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REACTIVE POWER COMPENSATION ANALYSES AND PLANNING PROCEDURE

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ANALYSES AND PLANNING PROCEDURE

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This report, prepared by Task Force 03 of CIGRÉ SC 38-01, is mainly based on work performed in Task Force sub-groups. Reports from the sub-group are presented as appendices. Some of them are, however, already published or presented as follows:

Appendix 1 WG38-01 TF3. Reactive Power Sources, presented at SC38 meeting in Stockholm 1985.

Appendix 2 WG38-01 TF3. Load Demand and Modelling.

Appendix 3 WG38-01 TF3. Planning Against Voltage Collapse, presented at SC38 meeting in Paris 1986 and published in Electra No. 111, March 1987.

Appendix 4 WG38-01 TF3. Methods for Reactive Power Optimization

Appendix 5 WG38-01 TF3. Use of Reactive Power Optimization Techniques in System Planning, answers to Questionnaire, August 1985. Presented at SC38 meeting in Stockholm 1985.

The report has been prepared by:

T. Johansson	WG38-01	Sweden, Former Chairman
M. Erche	WG38-01	Federal Republic of Germany, Chairman
J. Falck Christensen	WG38-01	Denmark
A.W. Grainger	WG38-01	Australia
Dai Jingchen	WG38-01	China
F. Kozak	WG38-01	Czechoslovakia
F.B. Pires	WG38-01	Brazil
G. Urdaneta	WG38-01	Venezuela
P-A. Chamorel	Expert	Switzerland
I.A. Erinmez	Expert	United Kingdom
N. Flatabø	Expert	Norway
N. Girard	Expert	France
H. Happ	Expert	USA
J. Van Hecke	Expert	Belgium
A. Invernizzi	Expert	Italy
B. Jansson	Expert	Sweden
J. Knudsen	Expert	Sweden
J. Lumbreras	Expert	Spain
G. Pels-Leusden	Expert	Federal Republic of Germany
T. Petersson	Expert	Sweden
G. Santagostino	Expert	Italy
M. Stubbe	Expert	Belgium
J. Verseille	Expert	France

REACTIVE POWER COMPENSATION ANALYSES AND PLANNING PROCEDURE

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1. INTRODUCTION

Planning of the reactive power resources in a power system is a comprehensive and complicated task. It involves determination of

- the total amount of reactive power resources to be installed in the system
- its distribution in the system, geographically and among voltage levels
- its subdivision into different kinds of reactive power compensation equipment.

The reactive power planning problem includes determination and allocation of reactive power reserve needed during disturbance situations.

In order to achieve optimal design, it is also necessary to compare reactive power installations with other network solutions. Investment costs for reactive power installations are low compared to the costs of active power generation or transmission lines. They have a much shorter construction time and also less influence on the environment.

Planning and optimization of reactive power compensation in a system is a part of the overall planning of the system and it should be based upon the same design criteria and system constraints as the planning and design of the whole system.

In this paper a stepwise procedure for planning of reactive power compensation is suggested and the planning process is described. A checklist for optimization of reactive power resources in a power system is presented.

2. REACTIVE POWER GENERATION AND ABSORBTION

Reactive power is produced or absorbed by all major components of a power system: generators, power transfer components, loads and reactive compensation devices.

- generators control the voltage by generation or absorption of reactive power. The generator is limited at full active load by the rated power factor, which usually lies within the range 0.75 to 0.95. Within a power factor range of 0.9-1 there are practically no additional costs for supply of reactive power. The capacity for absorbing reactive power is often limited by an underexcitation limiter, the setting of which is determined by synchronous reactance of the generator and its voltage regulator characteristics.
- the reactive power absorbtion of transformers usually lies between 5 and 20 % of the transformer rating at rated load, with low values for small and high values for large transformers at higher voltage levels.
- the line charging of overhead lines amounts to about 0.05 to 1.0 Mvar/km for 130-500 kV lines. For cables the charging is much higher, 0.7-18 Mvar/km for paper insulated cables of the same voltage range. For polyethylene or gas insulated cables the charging is lower. The reactive absorbtion of overhead lines depends upon the loading, and equals the charging at the surge impedance loading which ranges from 40 to 1100 MW for 130-500 kV lines. The reactive absorbtion of cables is much lower - less than 0.1 % of the cable rating per kilometer.
- the reactive power absorbtion of a HVDC converter station is 50-60 % of the active power converted and can be increased if needed for voltage control purposes.
- composite loads generally absorb reactive power in various proportions of the active power. The only type of individual load which can also produce reactive power is the synchronous motor.

The synchronous condenser, the shunt reactor, the shunt capacitor, the thyristor- controlled static var compensator and the saturated reactor static var compensator make up the shunt compensation devices.

- the synchronous condenser is the traditional means for continuous control of reactive power. In recent years it has been superseded by the thyristor controlled static var compensator, except in special applications such as at HVDC inverter stations in weak systems.
- the shunt reactor is usually the most economic special means for reactive power absorbtion. It is applied in conjunction with long EHV overhead lines or cables.
- fixed or mechanically switched shunt capacitors, which usually are the most economic means for reactive power generation, are commonly used in distribution systems for power factor correction and reduction of transfer losses. Shunt capacitors are also used in transmission networks under heavy load conditions.
- a Static Var Compensator (SVC) of thyristor-controlled type is a shunt reactive device, the reactive power of which can be varied rapidly by thyristors connected in anti-parallel. Two types of controlled elements are used, the Thyristor-Switched Capacitor (TSC) and the Thyristor-Controlled Reactor (TCR) or (TSR). The main purpose of most installations is high- performance voltage control, and sometimes damping of power oscillations or transient stability improvement.
- a Saturated-reactor Static Var Compensator is a shunt reactive device, the reactive power of which inherently varies with the applied voltage. Its characteristics are modified by shunt capacitors for range adjustment, series capacitors for slope adjustment and transformer tap changing for set point control.

Long transmission lines or cables can be disconnected during light load hours in order to reduce the reactive power input into the network. This method can only be used if it does not reduce reliability excessively. It will however increase network losses.

Series capacitors may be installed in long EHV transmission lines. Apart from the reduction in series reactive power losses the principal reason is to increase the transient stability limit and to improve load division between parallel circuits of different length of construction.

A comprehensive report on this matter is attached as Appendix 1.

3. REACTIVE POWER DEMAND AND MODELLING

3.1 Network Reactive Power Demand and System Representation

The reactive power demand in a power system results from the reactive consumption of the load and from the reactive losses in network. Therefore, the analysis of reactive demand cannot be dissociated from the representation of network in the models.

In LV and MV networks, the reactive losses are low and vary according to the load. These networks which are mostly unmeshed do not need to be represented and their losses can be incorporated in the load consumption.

In transmission networks on the other hand, the reactive power losses depend mainly on the real power transfer and network configuration. In this case, it may be necessary to model the network in detail.

Subtransmission networks can fulfill distribution and transmission functions. If only transmission planning is involved, and for steady state studies, subtransmission networks can be included in the load or represented by an equivalent.

For large interconnected systems, it may be necessary to divide the system into areas, and to study each area separately. This leads to the use of equivalents for the parts of the systems which are deleted. The choice of equivalents depends on the system configuration and the method of operation.

As an example, different equivalents are often used for main transmission and regional networks.

3.2 Load Characteristics and Modelling

"Loads" in main system reactive power studies are modelled as injections at the EHV or HV buses. In fact each injection is usually a combination of different components such as industrial loads composed of various kinds of motors and other types of equipment, commercial and air conditioning loads as well as residential loads. Included are many loads without reactive demand such as lighting and electric heating.

These loads are linked to the HV or EHV buses by HV, MV and LV networks and by transformers equipped with on-load tap changers used for automatic voltage control on the subtransmission and distribution networks. These networks, apart from any compensation equipment installed in them, are usually net consumers of reactive power, so that even a heating load will result in a reactive demand on the EHV or HV bus.

Although load also depends on frequency, the load dependency on voltage is more important for reactive compensation studies, due to the large range of voltage variation to be considered compared to frequency variations.

The most common representations of power system loads are:

- fixed P and Q model: load remains constant as the voltage changes
- fixed current: power is proportional to voltage

  $$P = P_o \left(\frac{V}{V_o}\right) \qquad Q = Q_o \left(\frac{V}{V_o}\right)$$

- fixed impedance: power is a function of the voltage squared

  $$P = P_o \left(\frac{V}{V_o}\right)^2 \qquad Q = Q_o \left(\frac{V}{V_o}\right)^2$$

Other models which are used include:

- composite load model, which is a combination of the three types listed above:

  $$P = P_o \left(A_1 + A_2 \cdot \frac{V}{V_o} + A_3 \cdot \frac{V^2}{V_o^2}\right)$$

  $$Q = Q_o \left(B_1 + B_2 \cdot \frac{V}{V_o} + B_3 \cdot \frac{V^2}{V_o^2}\right)$$

- exponential models:

  $$P = P_o \left(\frac{V}{V_o}\right)^a \qquad Q = Q_o \left(\frac{V}{V_o}\right)^b$$

The adequacy of the different models depends on the kind of study (steady state or transient) and on the methods used to solve the problem.

In steady state studies performed in order to define the amount of compensation devices necessary to obtain a satisfactory voltage profile in normal or emergency operating conditions, it is generally sufficient to assume that voltages applied to loads are held constant by transformer voltage regulation. Therefore fixed P, Q models are sufficient. However, in cases where the system has weak voltage conditions or where transformer tap changers are not properly coordinated at various voltage levels, special attention may have to be paid to short term load characteristics which could affect voltage stability.

In the seconds and minutes following a system disturbance the load which is imposed on a HV busbar will vary not only according to the chosen load/voltage characteristics, but also according to the operation of transformer tap changers at the various voltage levels. Modelling of this process can be critical to prediction of voltage stability.

It is important that tap changers at the lower voltage levels are appropriately delayed, so that voltage correction for main system disturbances takes place first at the highest voltage level, as this will result in the monotonic progression of loads to prefault values. If, instead, lower voltage transformers correct distribution voltages before higher voltage busbar voltages are restored, then distribution loads will be restored at an early stage. Subsequent higher voltage tap changes will cause the distribution voltage to rise above normal, resulting in "load overshoot". Some authorities block distribution tap changers following a severe voltage disturbance by telecontrol to avoid this.

The load overshoot condition is more onerous than constant power, and is further aggravated if shunt capacitor compensation is located at higher voltage levels. Where the tap change timing is known to be correct, it is sufficient to model the immediate post-disturbance condition according to the chosen load/voltage characteristic, and the final steady-state condition as constant active and reactive power.

In **transient studies** the load characteristics have great effects on system stability and simulation results can change significantly as different load representations are used. The classical model used for transient stability studies is fixed impedance representation. From a physical point of view, constant Q and constant active current often seems to be more realistic in long term studies.

There is much effort to improve knowledge of dynamic load behaviour, particularly the voltage dependence. The most common method of obtaining data is to measure the slopes dP/dV and dQ/dV within a rather limited range of voltage variation. Results may be available for individual components or for composite loads from measurements on the network buses after changing the transformer taps. However, these results based on a narrow range of voltage variation ($\leq$ 10 %) must be applied with caution to studies which involve wide ranges of voltage variation.

If voltage is expected to fall to below 80 % of nominal voltage or rise to above 110% of nominal special models of reactive power load should be used. Important non-linearities are caused by the stalling or tripping of motor loads at low voltage, and the saturation of iron-cored equipment at higher voltage.

3.3 Reactive Power Load Forecast

Reactive power load forecasting is usually based on the forecast of active load. One common method is to measure the Q/P ratio at the EHV/HV or HV/MV buses of the existing networks. The reactive load forecasting is then performed by extrapolation of the power factor. However, this often consists in assuming that the power factor is constant in the future.

In such investigations it is important to take into account the reactive power compensation devices connected in the systems below the point of measurement in order to deduce the natural reactive load. Measurements must also be made for different periods, such as peak load and light load conditions.

One way to improve reactive power forecasting is to divide the load into separate types. The evaluation of the power factor for each load type may then be studied and forecasted. This approach is more suitable for forecasting the reactive power load according to the evolution of the active load, but it requires more measurements on the network.

It appears that the reactive power forecast is an area which could generally be improved. Models and methods have to be based on knowledge of load composition.

More details can be found in Appendix 2: "Load Demand and Modelling".

4. PLANNING PROCESS

4.1 Introduction

4.1.1 General

The reactive power planning process does not in principle differ from active power planning, i.e. planning of the transmission network to transmit active power. Similar steps have to be performed in the planning process for both active and reactive power.

There is, however, one important difference between active and reactive planning: the capital cost. Investment costs related to reactive power usually reach only a few per cent of the corresponding cost for active power in a large system. Consequently, most resources in planning are devoted to active power, which always has first priority.

Satisfactory system operation needs both active and reactive power balance. But reactive power balance is a more local problem, because reactive power transport, especially in overhead line systems, is always associated with a voltage drop. However, reactive power plays an important part in the power system, and it is possible to gain improved system performance by optimizating the reactive power installations and operation.

The process of planning reactive power in order to handle voltage and reactive power problems is described in this chapter. Reactive power installations can also reduce investments for network components such as lines and transformers. This aspect is treated in paragraph 4.7.1.

4.1.2 Planning Aspects

In general the power system should be dimensioned in such a way that high security is obtained. The dimensioning criteria are determined with respect to security level and cost.

The criteria used for active power system planning are in most cases applicable also to reactive power planning. However, some changes and additions may be necessary.

The criteria should be chosen so that the network is able to withstand most common disturbances without exceeding specified voltage limits, loss of load,or breakdown of the network. Examples of dimensioning disturbances are: tripping of any generation unit, line or transformer, a transmission line fault, or a fault on a busbar section. These criteria are the basis for determining the transfer capability of the network. Voltage control, thermal limits and dynamic conditions must be taken into account when the criteria are applied to the network. In many cases, the latter will be critical. Voltage limits in different points of the system are also important.

The criterion might include a margin from voltage collapse conditions to allow for unforeseen load or transfer [5] .

4.2 Steady State Conditions

4.2.1 Voltage Quality

The purpose of the steady-state voltage control is to keep the distribution bus voltages within narrow limits, as the demand varies. The desirable voltage range could be a few per cent around the nominal voltage and the requirement might be for a higher voltage at peak load than at light load. The reactive resources must be dimensioned to maintain acceptable voltage levels under both high and low load conditions.

Narrow limits on voltage need to be applied only to customer busbars. Apart from sudden changes, much bigger overall range may be used on the transmission system without ill effect.

Both normal and outage conditions, according to the planning criteria, have to be examined. If there is an outage, either forced or planned, of one line out of a number of parallel lines, a great increase in reactive power demand may be created.

An important aspect in voltage quality is the voltage changes which are created when reactive power sources are switched in or out. Considerable experience is available on problems related to voltage changes at various repetition rates. The acceptable voltage change depends on how often they occur.

The voltage profile of a network is influenced by transmission design i.e. transmission capacity, active and reactive power losses as well as by additional reactive power installations. Consideration of cost in the planning stage will therefore give an optimal voltage profile, e.g. flat voltage or voltage drop.

4.2.2 Transfer of Reactive Power

From a technical point of view active power can be transferred over long distances. This is however not the case for reactive power, which preferably should be produced within a reasonable distance of the demand, since reactive power transfer incurs incremental transmission losses.

Consequently, subject to economic assessment, reactive power transfers should be minimized in order to reduce the current and to avoid voltage drops. Lower current results in reduced active and reactive losses. Lower active losses give direct economic gain due to reduced production cost. Lower reactive losses may reduce the total reactive power installations. Installation of some reactive power may, however, be justified. For example when it is available at lower cost at the sending end than at the receiving end of the system e.g. in generators rather than capacitors, or in larger sized banks of capacitors at higher voltage levels.

In some cases it may be possible to reduce power rating of equipment. Network elements such as transformers and cables can be operated at higher power transfer if they need to carry less reactive current.

In some systems dimensioning criteria are used to specify desired or permitted reactive power transfer. One criterion often used is to avoid transfers between different voltage levels. In these cases planning can be performed for example at the EHV-level without consideration of lower voltage levels. Another criterion can specify an upper limit for reactive power transfer between geographical areas which may correspond to the ownership of networks.

Such criteria should be based on an economic study which considers the cost of installing reactive compensation equipment at various voltage levels, and the cost of real and reactive power losses.

4.2.3 Specification of Equipment

When equipment mainly related to active power, such as generators, transformers and over-head lines, is specified special attention must be paid to reactive power. The reactance in network elements causes reactive power losses and voltage drop across the element.

The reactances must consequently be chosen taking reactive losses into consideration. This is often done by comparing the cost for reduced reactance with the cost for compensation of reactive power losses.

The voltage drop across elements will cause voltage variaton as the power flow through the element changes. Maximum permitted voltage variations may set a limit for the reactance. It is, however, often possible to compensate the voltage drop by means of transformer tap changers and in these cases the penalty is the cost of an increased range of taps and additional amounts of reactive power.

It must be kept in mind that choice of a low series reactance increases fault current levels which may result in a higher cost for higher rated equipment, or result in unacceptable operating arrangements.

It is therefore necessary to compromise between cost for high short-circuit current and transmission capacity.

In normal operation generators produce or absorb reactive power. In a network outage situation the generators may have to change reactive power production to control the voltage. The reactive power generation capability of a generator depends to a large extent on the rated power factor. In order to secure adequate voltage support during outage conditions, the rated power factor has to be chosen carefully when a generator is specified. For stability reasons, small generator reactances are preferred. The tap-ratios of generator step-up transformers have also to be chosen with serious attention.

4.3 Dynamic Conditions

4.3.1 Transient Stability

Transient stability (or first swing stability) can be improved by adding transmission lines between appropriate points in the system.

However, installation of reactive power equipment will also improve transient stability. The most efficient installation in this respect is often the series capacitor which reduces the total line impedance. The result is that the equivalent system impedance between different machine groups can be reduced. This is the same result as if more lines were added.

Shunt compensation can also improve transient stability by supporting the voltage in the system during disturbances. For greater effect a large part of the shunt capacity must normally be out of service but be connected quickly during the network disturbance. Both breaker switched capacitors and reactors, and especially SVC for fast acting, can be considered.

4.3.2 Steady State Stability

Power oscillations may occur between different machine groups in the system as a consequence of faults or small disturbances in the system. The initial disturbance can be a short-circuit on a busbar or on a line followed by tripping of the faulty component, or just minor fluctuations in load. Depending on the system layout, amount of power transfer, the kind of fault and its location, the power oscillations will be more or less severe. The oscillations are said to be undamped if the magnitude of the oscillations increases. Undamped oscillations may lead to tripping of lines and perhaps splitting of the system.

Proper voltage control can contribute to damping of the power oscillations. However, to contribute to damping, the voltage support source must have a special regulation facility. Sources which can improve damping include synchronous generators and thyristor controlled static var compensators. In some cases synchronous condensers which are primarily used for voltage control can be utilized.

Special modulation of the voltage control improves the damping of power oscillations by affecting the generator voltage and power output in the correct phase relationship to the rotor oscillations.

For generators, this can be achieved by the use of Power System Stabilizers, (PSS).

Static Var Compensators, SVC, can also have a significant influence on damping if controlled in the correct phase relationship with respect to generator oscillations, especially if they are located such that the resulting voltage changes moderate the power consumed by large loads.

If there are problems in a power system concerning bad damping or even undamped oscillations the following improvements should be considered:

1. Check the tuning of existing generator voltage regulators and power system stabilizers.
2. Install Power System Stabilizers on existing generator voltage regulators.
3. Install a controlled voltage device (static var compensator) that affects the voltage and thus the active output of oscillating generators.

Apart from these measures other network reinforcements such as adding transmission lines will of course improve the damping.

4.4 Voltage Collapse

4.4.1 General

Transmission of active power is dependent on the voltages at both ends of a transmission system and especially on the transmission angle between them. If the voltage, especially at the sending end, is not high enough to transmit the real power the voltage will break down and the system will be exposed to "voltage collapse". Voltage collapse may occur as a consequence of:

1. Contingencies which limit the local voltage control (i.e. unit tripping and excitation limiting of generators).
2. Contingencies which increase the transmission reactances (i.e. line and busbar faults, bypassing of series capacitor).

3. Contingencies which increase power transmission in the network due to the primary control of active power (i.e. unit tripping, network separation etc).

A disturbance sequence may start with a fault classified as any of the items mentioned above. If the fault is very severe it may cause a simultaneous voltage collapse (and/or other problem as well). However, if the system is able to survive the primary fault, a more critical period, in terms of voltage stability, will arise after a short time (up to some minutes).

This behaviour of the system is due to the fact that the excitation on synchronous generators will be returned either automatically or manually to levels within their capabilities, while at the same time the automatic tap-changer control on the load transformers will bring the load back towards its former value. Thus, with no increase in reactive support at the receiving end, the voltage continues to drop, and may reach the critical point where collapse occurs.

One method of calculating the margin of a network from voltage instability is to calculate successive ordinary load flows for the disturbed condition, in which the voltage at a particular node is varied over a range by attaching a fictious reactive power source. The plot of Q against voltage E will show a minimum critical Q at the critical voltage. Figure 1 illustrates the part of the curve where the system is voltage stable. It is important also to study the dQ/dE ratio. The process may need to be repeated at nodes in different areas of the system.

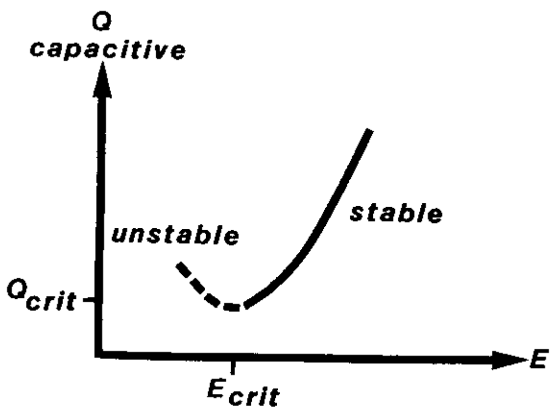

Figure 1. Plot of Q versus E

In modelling the system in these load flows it is necessary to correctly represent the excitation limiting behaviour of generators, and the behaviour of the load and transformer tap changers.

It is important to notice that in the period up to the time when the voltage collapse occurs there is balance between generation and load or even an excess of generation if voltages are low. The frequency will therefore be normal. When the voltage collapse occurs the system will suddenly lose its capability to transfer power. This indicates that frequency-activated load shedding cannot save a network from voltage collapse.

4.4.2 Load Characteristics

The load and its characteristics, especially the voltage-reactive load dependence, has a great influence on voltage stability. It should be noted that for large sustained changes there are loads with decreasing as well as increasing reactive consumption as the voltage decreases. A load which increases its reactive absorbtion will of course be more onerous than the opposite.

4.4.3 Reinforcement to Avoid Voltage Collapse

Apart from network reinforcements, such as building an additional line or providing sectionalising in an existing substation, the following solutions for avoiding voltage collapse should be considered in the planning stage.

1. Installation of shunt compensation in order to allow existing generators, synchronous condensers and static var compensators to be run with an increased reactive margin.

2. Installation of controlled sources (static var compensators, synchronous condensers).

3. Installation of series capacitors which will improve transient stability as well).

4. Installation of telecontrol so as to transmit new reference-values to transformer tap-changers, and signals to reactors, capacitors and SVC, in certain circumstances.

It should be noted that shunt compensation of a heavily loaded and overcompensated system by means of breaker switched capacitors will tend to decrease the voltage stable range of the system. This is due to the fact that the reactive power infeed to the grid from the shunt elements decreases with the square of the decreasing voltage. Thus voltage collapse occurs at higher voltage in such systems. For further details, see Appendix 3, [1] , [2] and [5] .

4.4.4 Voltage Rise

Voltage rise may origin from several causes. Reduction of load during parts of the daily load cycle will give a gradual voltage rise. If not controlled this high voltage would shorten the life time of insulation material. Sudden voltage rise can result from disconnection of loads or other equipment. High voltages caused by these events can often be taken care of by breaker switched shunt compensating devices. Generators or SVC will however give a more efficient voltage regulation.

4.5 Temporary Overvoltages

The connection between planning of reactive power and control of temporary overvoltages is most visible in the upper EHV region. Due to the high cost of the transmission lines, reduction of temporary overvoltages is a major economic concern.

The open end steady state voltage on an energized unloaded line can be expressed by the following formula:

$U = U_o \cdot k_s \cdot k_j$ where

U_o = the preswitch sending end bus voltage.

k_s is a multiplying factor for steady state voltage at the sending end
$k_s = 1/(1-X_s \cdot B_L)$

X_s is the source reactance
B_L is the line susceptance as seen from the sending end.

k_j = is a ferranti effect constant = $1/\cosh \Theta$ where
Θ is the electrical length of the line, which in turn is equal to the physical length of the line times the propagation constant.

The reduction of the steady state voltage on the switched line is particularly important if transformer termination is used as a means of postponing the costs of breaker installation. The saturation of the transformer produces current harmonics which are injected into the feeding circuit, consisting of the line, reactors, the source etc. The result is a temporary overvoltage including harmonics that might be close to system resonance. Shunt reactors are effective in reducing temporary overvoltages. SVC's can also reduce overvoltages, provided the design parameters are suitably chosen.

4.6 Resonance Phenomena

Reactive power compensation equipment can produce or reduce resonance overvoltages. Five areas are of major interest:

- Subsynchronous resonance created in a series compensated network at low load or no load.
- Harmonics generated by saturation of transformers.
- Harmonics generated by TCR and saturated reactor types of compensators.
- Power frequency overvoltages following unsymmetrical energization of a transmission line with line side connected shunt reactors.
- Resonance of capacitor banks with system impedances at particular harmonic frequencies causing high harmonic currents to flow and high harmonic voltages to occur locally.

The subsynchronous resonance can be dealt with by control actions on the series capacitor bank. When applicable, control actions on connected HVDC stations can also be used to eliminate subsynchronous resonance conditions.

Harmonics generated by saturation can be dealt with by specifying a satisfactory level of the saturation point or by control of shunt connected reactive compensation.

A particular problem concerns line side connected shunt reactors. If a line is energized unsymmetrically, caused for example by a single phase reclosing, a zero sequence voltage component is injected at the line terminal. If the degree of shunt reactor compensation is in the range of 60-90 % and the shunt reactors are directly connected to ground with no neutral circuit, dangerous temporary overvoltages can occur on the disconnected phase(s). This results from series resonance between the interphase capacitance and the resultant inductive admittance of the disconnected phase. The problem can be dealt with by avoiding line side connection of the reactors or by the application of a neutral reactor scheme which compensates for the interphase capacitance.

4.7 Economic Considerations

It would be ideal, but not achievable in practice, to plan and design electric power systems in a complete economic optimization process, where every variable of the system is expressed in monetary terms. However, it is often difficult, and sometimes impossible, to achieve a proper economic evaluation of every parameter and every quality concerned. Instead the design is often based upon a number of design rules which make special technical demands on the system and its behaviour in different operational situations and give it a reasonable reliability level. But, when working out these rules economic factors must be considered.

However, within the limits set by the design rules there is often opportunity for economic optimization. This also applies to the reactive power equipment which, as stated before, should be designed using the same rules as the entire system. Economic considerations can influence the choice between different technically equivalent solutions and the location and subdivision of reactive power equipment. System losses and investment and maintenance costs of installations are then the guiding economic factors.

4.7.1 Choice between Reactive Power Installations and Other Network Solutions

Transmission capacity and stability conditions can be improved by increasing and stabilizing network voltages and by reducing the transmission impedance. This can be done by installation of reactive power equipment, by increasing the number of transmission lines, by introduction of fast acting power system stabilizers on generators, and by other improvements in control technology. Economic comparisons often favour reactive power equipment from an overall cost point of view. In a developing system this means postponement of other system installations or even their replacement. SVC systems installed to increase damping and improve transient stability and voltage control, can also be economically utilized as alternative or supplement of reactive power reserve in generators.

When comparison between reactive power equipment and other transmission investments is undertaken, a cost reference for certain characteristics can be developed. For example, in a system with extensive use of series capacitors for improvement of transient stability the specific cost for series capacitors can be used to evaluate the penalty cost for the reactances of generators and transformers on the transmission level. This puts the optimization effort directly into the purchasing stage.

4.7.2 Choice between Different Types of Reactive Power Sources

As a general rule the choice of reactive power equipment is made based on costs of installation, maintenance and losses. However, in many applications the technical characteristics of the equipment will be decisive, and the choice will depend upon the function to be performed.

A cheap way of producing or consuming reactive power is to use the capability of the generators with rated power factor in the range of 0.9-1.0. Turbo generators which have a low short circuit ratio (high synchronous reactance) often have a low capability for absorbing reactive power due to stability limitations when underexcited. For units feeding long lines shunt reactors must often be installed to handle the line charging during light load and switching situations.

Static Var Compensators Comprising TSC/TCR equipment have both technical and economic advantages over synchronous compensators, so the latter have almost been driven out of the market except for special purposes, for instance for provision of reactive power to HVDC terminals. It is often necessary to use synchronous machines of a certain total rating for this purpose, particularly at a terminal predominantly used as inverter, in order to increase the short circuit power and self resonance frequency of the receiving AC system.

The high speed control that is available with thyristor-switched equipment makes this solution a necessity in some applications with pronounced control problems, involving risk of voltage collapse or other serious matters.

4.7.3 Location of the Installations

Transmission of reactive power causes a voltage drop which increases both active and reactive system losses. So there may be a gain in system economy by minimizing reactive power transmission. This can be achieved by proper location of the reactive power equipment both with respect to geographic areas and between voltage levels.

However, the low cost of reactive power in generators, and the ability to use larger bank sizes with lower specific cost at higher voltages often justifies economically the transmission of some reactive power to the load, and from higher voltages to lower voltages.

A matter of a technical nature is the choice between station side and line side connection of shunt reactors. The advantage with line side connection is in reduction of cost for the switching equipment. Line side connected reactors can be operated by load disconnected switches. The disadvantage is a loss of full flexibility in operation of the bank and the increase in unavailability of the line due to the contribution of the reactors.

4.7.4 Subdivision into Unit Sizes

Subdivision of reactive power equipment into many small units spread over the system solely to minimize reactive transmission increases the total installation costs and is not justified. Standard bank sizes are used for several reasons. Advantages of economy of scale in unit size and production costs, interchangability, supply of spare parts and build-up of experience are decisive.

The range of the system loading, together with consideration of contingencies decide the minimum amount of the reactive equipment which must be installed as switched units.

The largest size ΔQ of a breaker connected shunt compensator is determined by the voltage variation criterion.

$$\Delta Q = \Delta V \frac{S_c}{V_o}$$

where S_c is the short-circuit power at the point in question, and V/V_o is the resulting per unit voltage change.

If voltage control is desired in smaller steps the total required reactive power must be split into smaller sizes, or located at a point of higher fault current level.

Consideration of reliability and availability will influence the choice of unit sizes in favour of splitting into more and smaller units, if there are only a small number of units on the system.

4.7.5 Losses

Reduction of transmission losses is a significant economic factor in reactive power planning. The voltage criteria and the cost of active losses determine the degree to which the compensation should be increased in order to reduce losses. The gain is highest when improving the compensation from its minimum point and becomes smaller as the compensation approaches the point of minimum transmission losses. The gain is also higher in extended systems with long transmission lines than in compact networks with short transmission distances. Taking into account also the relative costs of reactive compensation plant an economic optimum is usually achieved when a small part of the reactive power is transmitted through the network.

With regard to the use of series capacitors on long parallel lines it is similarly found that losses have a predominant influence on the selection of capacitor bank sizes.

4.7.6 Conclusions

The reactive power installations should fulfil a number of system requirements and contribute to:

- Compensation of load growth

- Transmission capacity
- Voltage control
- System reliability
- Reduction of network losses

In planning of reactive power several different problems have to be treated, some of which are important for long term planning. The uncertainty of future development has to be considered carefully. The cost for reactive power equipment is only a small fraction of the total system cost. Deviations from an economic optimum have limited influence on the total costs. Sensitivity can be of greater interest than efforts to find a precise optimum.

It is far more important to find the correct technical solutions, because of the influence on the qualities of the supply, e.g. on reliability.

It is not possible to perform an overall economic optimization and the planner has to perform a number of sub-optimizations. In these sub-optimizations benefits of reactive power sources should be compared to their cost. The benefits are transmission capacity, system reliability and reduction of network losses. The cost for reactive power sources are investment, operation and maintenance cost [3] .

A single large scale mathematical model is not particularly suited to solution of the problem of reactive power planning. Several computer tools related to different problems have to be used.

5. SOLUTION TECHNIQUES

5.1 Introduction

The reactive problem is different for optimization of operating (short term or level 1) and planning (medium/long term or level 2). In the first case the best operation condition must satisfy the security constraints and guarantee the voltage stability with existing equipment. For real-time application in a control center, computation time has to be reduced to a minimum. In planning, optimization must consider additional reactive sources, determine the types, locations and sizes of these sources from an economical point of view, and must also guarantee security during the most severe foreseen operational conditions. Planning of reactive power has to be started with a thorough analysis of the existing system and its operational conditions.

Numerous techniques exist to solve efficiently the reactive optimization problem for steady state conditions. This chapter aims to point out the most usual methods capable of solving reactive problems; essentially optimal power flow and sensitivity techniques. These methods are generally suitable for solving some problems in both operation and planning with criteria and costs in objective functions related to the specific subproblem.

5.2 Load Flow and Optimal Load Flow

Traditionally, reactive power planning has been solved by a trial-and-error approach which uses an ordinary loadflow program in a very time consuming procedure. The solution found using this approach is not optimal, but the best of tried solutions. It is clear that in order to determine an optimal solution in an efficient way, the use of optimization techniques is necessary. If the network is well known to the planner, a more simplified method can be used.

In broad terms the reactive power planning is an optimal reactive source expansion problem formulated as a **mixed nonlinear-integer programming problem.** There exists no general mathematical programming technique for directly solving this class of problem, especially when applied to large scale systems. However, the optimum allocation of reactive sources can be studied by decomposing it using a two-level hierarchical approach. This approach takes advantage of the natural distinction between the reactive power dispatch of the available sources in system operation (level 1) and the reactive power allocation and sizing in system planning (level 2). The optimal reactive dispatch problem and the source expansion problem can be solved separately and alternatively in an iterative procedure. The general problem is thus transformed into a sequence of non-linear (level 1) and mixed-integer (level 2) programming problems.

Some of the level 1 problems can be treated as optimal power flow problems, which are formulated as non-linear problems. They can be solved by successive ordinary load-flows, non-linear programming methods or successive linear programming methods.

Non-linear programming techniques (differential injections, generalized reduced gradient, quadratic programming, etc.) are well suited for nonlinear cost functions and MW-loss minimization. These techniques give a good convergence and remain valid over a large region.

Linear programming techniques are well suited for security analysis with minor changes in the control variables. The objective function is approximated by a linear or piecewise linear function. L.P. methods provide fast and reliable solutions with low computer time. They are efficient tools for large systems with numerous constraints and small perturbations of the reactive variables. Several methods combine gradient techniques with linear programming.

The optimal reactive source expansion problem (level 2) is a **mixed linear-integer programming** problem with 0,1 variables and use branch and bound-type algorithms.

5.3 Sensitivity Methods

In order to determine critical voltage, several sensitivity techniques based on the ratio dV/dQgen can be used. Other voltage collapse indicators can be based on power flow solutions with additional sensitivity computations on dQgen/dQload. The representations of system components are very important in these cases.

5.4 Dynamic Problems

Static var systems, when properly controlled and located, are an effective way of damping both small and large electromechanical oscillations and extending transmission limits. Simulation by conventional methods and optimization methods based on **eigenvalues techniques** can be used.

5.5 Conclusions

Numerous techniques exist to solve efficiently the reactive optimization problem for steady state conditions. More tools should be developed for transient and dynamic studies. For instance, simulation techniques are essentially used in order to study the dynamic behaviour of the system.

Other problems remain in the application and implementation of these methods, such as:

- choice of objectives
- cost definition
- technical constraints and security criteria
- data acquisition
- exchange of information between control centres
- system modelling
- subsystem optimization (voltage level, geographic or ownership subdivisions)
- external equivalents
- reactive load forecasting

A more detailed description is given in Appendix 4 and in [4] .

6. UTILITY EXPERIENCE

In order to map the state of the art of reactive power planning and more precisely the extent of use of optimization procedures, a questionnaire was composed and distributed to a large number of utilities. Twenty utilities from fifteen countries participated. The majority of the utilities operate large meshed networks. Problems concerning the reactive power compensation of long radial transmission systems have therefore not been covered to the same extent in the survey. A short summary of the answers to the questionnaire follows:

6.1 Planning Objectives

Generally, the replies indicate that the main objective of reactive power planning is that future networks should be able to observe a set of technical constraints under both normal and emergency operating conditions.

Technical constraints of importance are:

- Observance of the limits of variation of steady state voltage, consequent upon load variations and the switching of network components. (This is the main constraint stressed by all utilities).
- Generator and transmission line loading limits.
- Reserve margin requirements.
- The risk of dynamic instability.

Many utilities also consider system economy improvement to be a main reactive power planning objective.

In order to achieve these objectives many utilities apply planning procedures that result in the optimization of different objective functions. Among these are:

- The amount of reactive compensation to be installed.
- The investment cost for reactive power equipment.

Following these procedures some utilities minimize the combined costs for reactive power equipment and total system losses.

The utilization of special objective functions, which refer to specific grid structures were also mentioned. For example:

- Maximization of voltage profiles.
- Minimization of reactive power flows on transmission and interconnection lines between different areas.

These two objectives are in part equivalent in that both result in flat voltage profile.

Additional material that is covered in the following sections shows that these objective functions can be dealt with in context rather than treated as individual objective functions.

With regard to economic evaluation all utilities but one stress that optimization is not limited to the observance of possible financial constraints.

The security requirement is generally met by applying certain criteria, which involve considering the loss of one line (single or double circuit) one transformer, or of one generator, or of one reactive power compensation device.

6.2 Planning Organization

In the overall planning procedures described by all the countries taking part in the survey, it appears that priority is always given to generation planning, some countries also stressing that generator power factors are fixed at this stage. The next thing to be planned is network development, an activity that is generally subdivided into two stages, the first taking into account active power transmission requirements, while the second is concerned with voltage control and reactive compensation requirements. Many of the replies received emphasize that the two stages are carried out with different timing and with different horizons: active power planning is developed over a longer period (for example, six years), while reactive power planning is studied over a shorter period (for example, two or four years).

Some replies, however, mentioned that active and reactive power planning are carried out at the same time, this procedure being applied when reactive compensation requirements may affect the selection of network development alternatives, or if they enable some active network reinforcement (new lines, new transformers, etc.) to be deferred.

Reactive power planning is carried out for different load conditions. Thus, all countries stated that their procedure took into consideration both peak load and light load situations. For some countries these conditions concern the same day; if so, the analysis is generally extended to other days of the year. For some other countries, these two load conditions concern different days. Moreover, a few countries stated that they examined the minimum load condition for the year, while others mentioned that they also studied intermediate load conditions (for example 0.85 of the peak) and others again emphasized the need to consider specific network configurations and generation dispatching such as to stress the transmission grid to the maximum.

Replies to the questionnaire indicate that the reactive power planning procedure is, in many cases, carried out for a horizon year that is generally that preceding the year considered in planning network development. In some cases only one or two years following the one in question are considered.

Many replies state in that the study is repeated for an intermediate year, especially when important changes occur the network structure. In some cases, reactive compensation analysis is extended to different load forecasts and to different network development alternatives.

6.3 Modelling of System

6.3.1 Subnetworks

Division into subsystems is done in many different ways. Most of the answers reveal that the network is geographically subdivided based on ownership, but division based on different voltage levels is also practised. However, organizational or technical reasons also decide the way in which utilities subdivide, if at all, for the purpose of modelling, but all items of some importance are considered.

The external system is represented in different ways. Some utilities make a reduction to an external equivalent while others do not make any approximation at all. About half of the utilities choose a representation with generators or loads as active and reactive power injections.

The most frequently used load model is a fixed P and Q representation, but fixed impedances are also used in some cases. Voltage dependent models ($P = f(V)$ and $Q = f(V)$) are used by a few countries.

Networks with voltage levels equal to or less than 130 kV are mostly represented as loads on the secondary side of the stepdown transformers.

6.3.2 Controlled Elements

The controllable reactive power sources are generators, synchronous compensators and SVC systems. In steady state the generators are in most cases represented as P,V nodes at the high voltage level. In some cases more detailed models are used. Sometimes the generators are represented as P,Q nodes. The limits on reactive power generation are in some cases taken into account by changing the P,V node to a P,Q node representing a more detailed capability curve. The synchronous compensators are modelled as generators with no active power output. This is also the most frequently used representation of SVC systems, although some countries place this node behind a reactance representing the steady state slope of the SVC.

6.3.3 Uncontrolled Elements

Reactors and capacitor banks are normally represented as fixed impedances. The non linearity of the magnetization characteristic of iron-cored reactors is not considered. However, switching of reactors and capacitors is included in many cases.

6.4 Analytical Solution Techniques Utilized in Reactive Power Planning

The most popular technique is successive ordinary load flow. Some utilities use optimal load flow, but in many cases this is in addition to ordinary load flow. A few utilities indicate that optimal load flow is under development.

The optimal load flow programs are based on either a reduced gradient method or linear programming. Quasi Newton and Quadratic programming methods are also used.

The size of the systems in the network model are in the range of 100-500 buses. A few use a larger number of buses, up to 1000.

As indicated in the previous chapter the optimization process often comprises investment cost and transmission losses in the function to be minimized. The contingency analysis is taken care of by successive optimization. The overall cost calculations are carried out manually by the majority - only in one case is a special VAR PLAN program mentioned.

Successive ordinary load flow is the most frequently used tool in the decisions on primary and secondary voltage control and very few have optimization methods in practical use.

A few utilities use sensitivity techniques. Those mentioned are:

1) (dQ_g/dQ_L) which is the resultant reactive power generation sensitivity in the network to variation of reactive load at a specific busbar.

2) A criterion based on the $\frac{U_i}{E_i}$ relationship where U_i is the actual voltage and E_i the voltage at zero load condition.

3) $(dV/dQ)_i$ which is the voltage to reactive power input sensitivity at a specific node.

Stability calculations are carried out by some utilities to choose between the different var-supplying devices being considered, to analyse the reactive power support from generators during an outage condition, and to analyse the ability of units to absorb reactive power during light load periods.

The reported experiences concerning the analytical techniques used in planning are very much dependent on the tool used. Ordinary load flow is most commonly used in planning, and experience in the use of this kind of program is mostly good, but is also indicated to be cumbersome and time consuming due to the manual work necessary, and is gradually becoming inadequate.

The optimization methods in use are considered adequate in terms of computing time, and handling of constraints, but improvements are necessary in the coordination of results, and modelling of the external system. LP-programs are useful in the study of big networks (1000 nodes), but the method is not well suited for loss minimization. In voltage stability studies more accurate load modelling is necessary to give greater understanding.

More automatic techniques to diagnose system performance are desirable, and automated techniques would also permit more alternatives to be investigated. See also Appendix 5.

7. SUMMARY AND RECOMMENDATIONS

7.1 Introduction

Planning and optimization of reactive power in a system is a part of overall planning and it should be based on the same design criteria and system constraints as planning and design of the whole system. In the initial phase of planning it is necessary to compare reactive power installations with other network solutions.

There are two important aspects which distinguish reactive power planning from planning of active power:

Firstly, transmission of reactive power over long distances will lead to both active and reactive power losses and voltage drop. Compensation to maintain reactive power balance in an area must consequently be provided in the vicinity. Reactive power is in this respect a more local problem than active power.

Secondly, investment costs related to reactive power reach only a few per cent of corresponding values for active power transmission equipment.

Deviations from the long term forecasts used in the planning procedure can easily be compensated for. A small deviation from the optimal solution has only a limited influence on the total system cost.

Depending on the technical solution a small increment of reactive power investment may defer significant line investments.

The basic problems related to reactive power are usually solved within power system planning, e.g. choice of system voltage. The rest of the reactive power planning involves the following main steps:

1. Decision on the regional need for reactive power compensation in the system. This comprises determination of a base installation which will handle high and low voltage limits, under both normal and outage conditions and under a number of system power transfer conditions. Often steady state calculations are sufficient.
2. Its location in the system, geographically and between voltage levels, which includes considerations of reactive power transfer and network configuration and cost of installation.
3. Its composition of different kinds of reactive power equipment which determines the amount of the base installation that needs to be controllable. Dynamic studies have to be performed. Aspects of reliability also have to be taken into account and the number of units and their sizes settled.

Optimization of reactive power, including economic considerations, is done in several steps. The solution techniques used are often ordinary load flows or in some cases optimal load flow.

7.2 Planning Procedure

7.2.1 General

Based on the conclusions in preceding chapters, procedures for planning and optimization of reactive power compensation are presented. The procedure is described here, in the form of a checklist. It is presumed that available models and programs are sufficient and no major development is necessary.

The main objective in reactive power planning is to plan the installations which can support energy supply during normal and outage conditions at a minimum overall cost.

Basically, reactive power planning is integrated in the overall system planning process. Reactive power solutions can often result in saving active power. In this respect reactive planning should not be separated from active power planning.

One specific characteristic of reactive power installations is the relatively small cost compared to active power. Another important aspect is the possibility of successively adding reactive power installations in order to improve system reliability and economy.

The technical solutions adopted are very important for system performance.

7.2.2 System Expansion

When an existing system has to be reinforced in order to meet an increased transmission demand the procedure is as follows:

- Different alternatives are compared in order to find the most economic solution including evaluation of the technical differences.
- Each alternative includes important and necessary reactive equipment, examples of which may be shunt or series capacitors, SVC, shunt reactors and other means for voltage control.
- The reactive load in the system is compensated to an estimated and perhaps not optimal level.

When an appropriate alternative solution has been chosen, optimization of the reactive power installations is performed including the geographical location of the equipment.

Following this approach reactive power planning can be regarded as a suboptimization process. It is possible to do it in this way because reactive power installations normally are less expensive than those for active power. The cost for reactive power is only a few per cent of the total cost for the system.

When purchasing equipment such as generators and transformers, reactances and other qualities related to reactive power have to be evaluated.

7.2.3 Dimensioning Criteria

Decision on dimensioning criteria is part of the whole problem of defining an appropriate level of network performance. Applied criteria should give consumers a reasonable availability of energy supply.

In a system planning process, dimensioning criteria are first determined. These form an overall planning principle, which characterize network design for a long time-period. Since they are often unchanged for decades, they are the predominant factor of system design. System voltage and insulation level constraints are also settled in this phase of the process.

Criteria are determined according to a technical-economic optimization taking into consideration system reliability versus investment cost.

Examples of dimensioning criteria are: maximum and minimum voltage; maximum voltage fluctuations due to normal load variations and switchings.

The planning criteria define the contingencies the system has to withstand without collapse, e.g. n-1 or n-2 criterion. The possibility of a single event causing multiple contingencies should be carefully considered. Criteria for emergency situations, others than in normal planning, may be taken into account. They will create a reactive power reserve, which is a relatively inexpensive way to improve system security.

7.2.4 Planning Procedure Checklist

Initial Work

Load and transmission demand has to be determined and system structure identified. If available, a special reactive power demand forecast should be used. Otherwise the active power demand forecast may be useful as a basis also for reactive power demand. It is important to determine the planning horizon, up to which several development stages have to be examined.

Modelling of load, generator characteristics and tansformer tap-changers must be carefully considered.

Reactive power or voltage problems are found by network studies taking the above described dimensioning criteria into account.

Before extensions are examined, improvements in the existing system should be studied. Operational experience must be taken into account. Improved or new methods concerning voltage control should be considered.

A number of economic factors have to be decided upon. Reactive power has an impact on system capacity, reliability, transmission losses etc. These factors have to be evaluated and included in the investigation.

Load Flow Studies

Load flow calculations should be performed for various load levels and transmission situations. This includes several stages as mentioned above, different load levels such as minimum, medium and maximum load situations. Critical transmission situations depend in many cases on power generation distribution, and the worst case may arise at a low load level.

Outage of network components such as lines, transformers, generators and reactive power equipment should be studied. Many load flow methods can be used, if available, optimal load flow program can be of great value.

These calculations give the minimum amount of reactive power installation within a region; exact geographical location and voltage level for connection of the equipment will not be determined here.

Voltage Stability Studies

Voltage stability margins are determined in order to check if more installations than those found above are needed. One method of doing this is to plot Q-E curves from successive load flow calculations. These studies also determine whether parts of the reactive installation needs to be controllable. An explanation is given in chapter 4.4. There are also other methods available.

Transient Stability Studies

The necessity of rapid control of reactive power sources will also be given by carrying out transient stability studies. Reactive power sources have to be modelled in an appropriate way in the programs which are used.

System Damping Studies

System damping studies, are carried out to examine oscillations in the range of 1 Hz. The aspects to consider here are the same as for transient stability studies. Suitable criteria have to be used to determine if the system is well damped or not.

Special Technical Demands

The ability to prevent excessive voltage rise due to load-rejection, load-shedding and self-excitation can determine the total amount of reactors and especially the control performance of the reactors.

In heavily loaded systems with transmission capacities very sensitive to voltage changes, emergency load-shedding based on voltage criteria instead of the more common frequency criteria, could be useful.

Reactive Power Sources

The need of reactive power can be fulfilled by a number of different sources. They have qualities with regard to control ability and rapidity. The cost per Mvar differs a great deal between different sources. A more detailed description can be found in chapter 2.

Sub-optimization

Given the regional amount of reactive power sources and its need for controlability, an economic sub-optimization follows. The benefits of the installations, which are transmission capacity, system reliability and reduction of network losses, has to be compared to the costs, which are investment, operation and maintenance costs.

The solution to the sub-optimization will give the location (geographically and voltage level), unit size (use of standardized unit sizes should be considered), and type of connection (fixed, breaker switches etc.)

Possibilities of coordination between proposed sources should be examined.

The process will be easier if rules of thumb or general rules can be used. For example if it can be stated that no transfer of reactive power between voltage levels should be allowed under normal conditions.

Check and Final Decision

A final study has to be carried out to confirm the results from all the analyses performed. Voltage fluctuations during switching, temporary overvoltages and resonance phenomena have to be checked.

A review of the dimensioning criteria, taking into consideration operational aspects, may be necessary in some cases.

The final solution from the planning process gives a long-term plan. Decision regarding investments or other actions, concerns only the next few years. Planning is a never ending process and plans created earlier have to be reviewed after some time.

Solution Techniques

A single large scale mathematical model cannot be used to solve the problem of reactive power planning. Consequently, the planning process has to be carried out as a number of sub-optimizations. Normal solution techniques are sufficient in most cases. Optimal load flow methods can be of great value in many studies.

8. REFERENCES

The list of references given here contains reports which have been of value to the work. Some of them have been published while others only exist as internal task force papers. References [1] - [2] are task force sub-group reports.

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APPENDIX 1
REACTIVE POWER SOURCES

by

M. ERCHE
Siemens AG
Fed. Rep. of Germany

T. PETERSON
ASEA AB
Sweden

Contents

The authors gratefully acknowledge contributions received from B. Ehmcke and H. Tyll, Siemens AG, Federal Republic of Germany.

Introduction

Reactive power is produced or absorbed by all major components of a power system:

- . Generators
- . Power transfer components
- . Loads
- . Reactive power compensation devices

Reactive power production or absorption of power transfer components depends mainly on operating voltage and current and can therefore hardly be changed during normal operation. Also changes in reactive power of generators and loads are limited. HVDC converter stations, especially with additional capacitors and reactors, can be operated in a reactive power control mode. Reactive power compensation devices are installed to improve

- reactive power balance
- voltage control
- system stability including damping of power oscillations.

They can be switched or continuously controlled. Their characteristics are described in this report.

Keywords:

Reactive power compensation, HVDC, static var compensator.

1. Generators

Power plants are installed to supply active power to the system. Additionally a generator is supporting the voltage, producing reactive power when over-excited and absorbing reactive power when under-excited. The reactive power output is continuously controllable. The step-response time in voltage control is from several tenths of a second and upwards, depending on different factors.

The rated power factor of generators usually lies within the range 0.75 to 0.95. Generators installed remotely from load centres usually have a high power factor; this is often the case with large hydro-power generators. It is not seldom justified to choose a rather low power factor when installing a new large steam-turbine generator close to load centres, with regard to severe outage conditions.

The allowable reactive power production or consumption is dependent on the active loading as illustrated by the Figures 1 and 2.

In case of pumped storage plants the synchronous machines are also used as motors. For these cases the diagram in figure 2 has to be extended to four quadrants.

2. Power Transfer Components

The major power transfer components are transformers, overhead lines and underground cables. HVDC converter stations are also discussed under this head-line.

2.1 Transformers

The reactive power consumption of a transformer at rated current usually lies within the range 0.05 to 0.20 p.u. as based on the transformer rating, with low values for small and high values for large transformers. The natural short circuit impedance of a transformer increases with the network voltage to which the transformer will be connected. Higher values of short circuit impedance can be required in special applications e.g. limitation of short circuit power at the secondaries in ac transmission systems or in connected HVDC back-to-back systems.

When two or more transformers operate in parallel the method of tap-staggering can be used for reactive power compensation and voltage control in addition to other means of compensation. Tap-staggering is limited by the step voltage change on the secondary side in case of switching off a transformer. Generally it will be controlled manually by the load dispatch centre. Tap-staggering is an usual reactive compensation method only in the UK practice.

2.2 Overhead Lines

The line charging of overhead lines amounts per 100 km to about 11 % at 50 Hz and 13 % at 60 Hz referring to the Surge Impedance Load (P_{SIL}) - see Table 1.

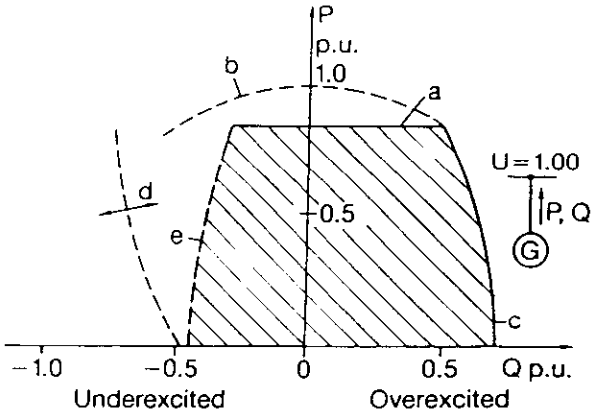

Fig. 1: Typical power chart for large turbo-generators

a - Turbine power limit
b - Stator winding thermal limit
c - Field winding thermal limit
d - Steady-state stability limit with proper AVR
e - Assumed intervention curve of under-excitation limiter

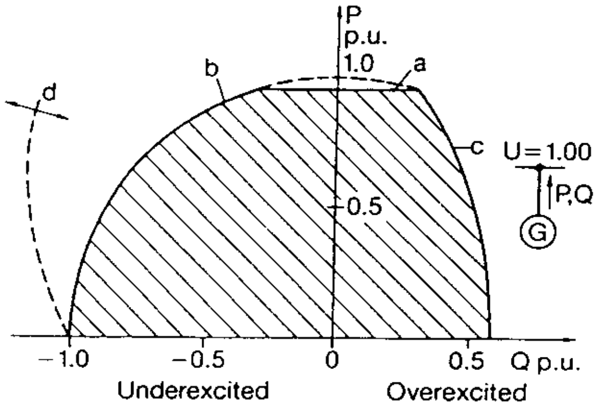

Fig. 2: Typical power chart for large hydro-generators

a----d, as in Fig. 1 above.

Table 1: Typical values of overhead line characteristics at 50 Hz

Operating voltage kV	SIL MW	Line charging Mvar/km	X_1 Ohm/km	No. of sub-conductors
130	50	0.05	0.40	1
220	130...180	0.14...0.19	0.40...0.3	1 ... 2
400	550...680	0.6...0.7	0.32...0.24	2 ... 4
750	2200	2.3	0.28	4

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2.3 Cables

2.3.1 Paper-insulated Cables

The capacitance charging of paper insulated cables amounts per 10 km to about 2 to 5.5 % at 50 Hz and 2.4 to 6.5 % at 60 Hz referring to the Surge Impedance Load (P_{SIL}), which is normally much higher than maximum load - see Table 2.

Operating voltage kV	SIL MW	Line charging Mvar/km	X_1 Ohm/km
130	350 ... 600	0.7 ... 4.0	0.10 ... 0.20
220	900 ...1400	2 ... 10	0.12 ... 0.25
400	2900...3300	8 ... 18	0.15 ... 0.30

Table 2: Typical values of underground paper-insulated cable characteristics at 50 HZ

2.3.2 Polyethylene-insulated Cables

The line charging of polyethylene-insulated cables, now being introduced in 100 kV systems (in few cases also 220 kV systems), is approx. 50 % of the line charging of paper-insulated cables.

2.3.3 Gas-insulated Cables

The line charging of gas-insulated cables is approx. 10 ... 20 % of the line charging of paper-insulated cables.

2.4 HVDC Converter Stations

HVDC converters always consume reactive power when in operation. The reactive power consumption of the HVDC converter/inverter is 50 to 60 per cent of the active power converted. The reactive power requirements of the converter and system has to be met by providing appropriate reactive power in the station. Mechanically switched filter banks, producing reactive power, are always installed, but one or more of all other types of reactive power compensation devices can also be found in converter stations. Also reactive control by means of the dc system itself is applied.

Figure 3a shows a general arrangement of a HVDC converter station.

Figure 3b shows a general operating diagram of a HVDC converter covering the reactive power consumption in terms of transmitted active power including the operating parameters of firing angle (extinction angle) and dc current.

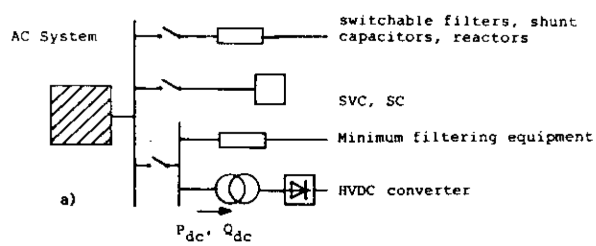
3. Loads

The reactive powers of loads considered in analysis and optimization of reactive power conditions of a power system are usually those of composite loads, not of individual loads. For the sake of completeness some typical values of reactive consumption of individual loads are, however, given below:

- Induction motors 0.5 to 1.1 kvar/kW at rated output
- Uncompensated fluorescent lamps 2 kvar/kW
- Uncontrolled rectifiers 0.3 kvar/kW
- Controlled rectifiers usually consume much more reactive power than uncontrolled ones and with dependence on the control angle
- Arc furnaces 0.7 to 1.4 kvar/kW at rated power.

Static power converters for rolling-mill DC motors, steel mills and in traction systems, have reactive power consumptions with a large average value and are subject to substantial rapid fluctuations, sometimes causing problems of voltage fluctuations.

The synchronous motor is the only type of individual loads which can produce or absorb reactive power depending on its excitation. Synchronous motors on the load side practically run with overexcitation.



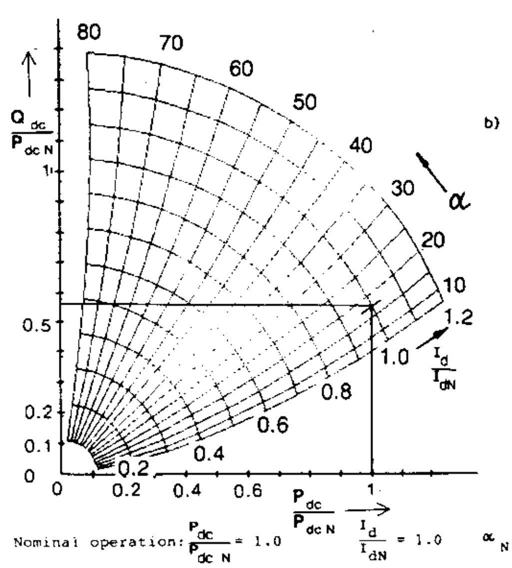


Fig. 3: HVDC converter station

a) General arrangement of shunt compensation devices and HVDC converter

b) Reactive power consumption of the HVDC converter

4. Reactive Power Compensation Devices

Capacitors and reactors are passive elements of reactive power compensation. They are incorporated in the system in series or in parallel connection. The different possibilities for the installation in a transmission are shown in Table 3. The main scopes are mentioned.

- The series capacitor is especially used to decrease the transmission angle and to increase the voltage at the receiving end. The degree of compensation must be less than 100 % to avoid ferroresonance, relay protection problems etc. Proposals have been made to change the degree of compensation by switching on and off parts of the capacitor e.g. by thyristor switches.

- A series reactor has no advantages in influencing the voltage at the receiving end. It is therefore only used for limiting the short circuit current especially in distribution and industrial systems.

- Parallel compensation with shunt capacitors is mainly used to increase the voltage at the receiving end in case of heavy load and to supply reactive power to the load directly. Transmission losses of the system will be reduced.

- Parallel compensation with shunt reactors is mainly used to keep the voltage down in case of light load and load rejection and to compensate the capacitive load of the line.

- A static var compensator can produce or absorb reactive power or both alternatively depending on the type and design. If a controlled reactor is included fine voltage control can be achieved.

The reactive power in series capacitors and series reactors is depending on the load current and therefore changing with the load. The reactive power in a shunt capacitor or a shunt reactor is depending on the voltage, which is practically constant.

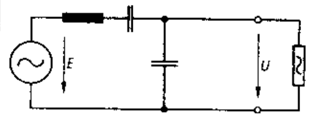
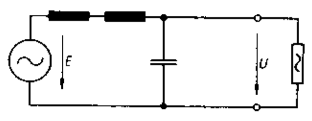
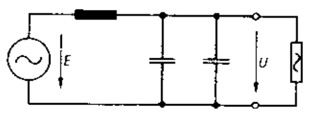
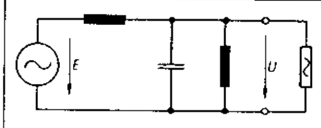
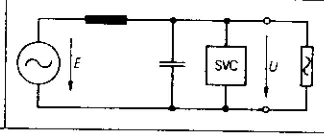
In the following subsections only shunt compensation devices will be described.

Nevertheless in the concept of reactive power optimization in the system, the series capacitor plays an important role and influences the size of shunt compensation devices.

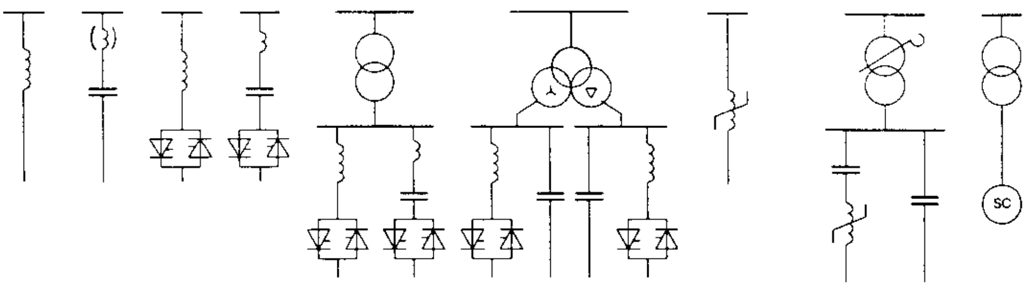
Series capacitors are mainly installed in EHV transmission systems with very long lines and for one or both of two main reasons. One of these is to increase the transmission load capability as determined by transient stability limits. The other reason is to obtain a desired load division among parallel circuits. Series capacitors, however, favourably influence the control of voltages and the reactive power generated in a series capacitor increases with increasing transmitted load. On the other side series capacitors introduce subsynchronous eigenfrequencies to the power system.

The series capacitor is not further treated in this paper.

Table 3: Use and influence of series and shunt compensation

	Equipment	Location	Parallel resonant frequency and short-circuit power	Voltage control	Transmission angle	Voltage rise at load rejection	Application
1	Series capacitor		Increased (see text)	Very good	Much smaller	(Very) low	Long distance transmission of high power
2	Series reactor		Decreased	(Very) poor	(Much) larger	(Very) high	Short distance, Limitation of short circuit current in distribution systems
3	Shunt capacitor		Decreased	Voltage increased	Slightly changed	High	Voltage support at heavy load
4	Shunt reactor		Increased	Voltage decreased	Slightly changed	Low	Reactive power compensation at low load Limitation of temporary overvoltages
5	Static var compensator		Increased or decreased	Voltage controlled	Slightly changed	Prevented by control	Reactive power and voltage control Damping of oscillations

Means of reactive power compensation and improvement of power system performance



1 2 3 4 5 6 7 8 9

Fig. 4: Examples of shunt compensation devices (with or without circuit breakers according to systems requirements)

1 Shunt reactor
2 Shunt capacitor (filter)
3 Thyristor controlled reactor
4 Thyristor switched capacitor
5 SVC for 6pulse operation of thyristor controlled type
6 SVC for 12pulse operation of thyristor controlled type
7 Saturable reactor
8 SVC of saturable type
9 Synchronous condenser

4.1 Descriptions

The shunt reactor, the shunt capacitor, the synchronous condenser, the thyristor-controlled static var compensator and the saturating-reactor static var compensator shown in fig. 4 make up the shunt compensation devices. The tables 4 to 8 list characteristics and features in a uniform way.

4.1.1 Shunt Reactors

A shunt reactor is a reactor connected in shunt to a power system for the purpose of absorbing reactive power.

In cases where a fixed or mechanically switched shunt reactor can be used with regard to the voltage control requirements, it is usually the most economic special means available for reactive power absorption. The majority of shunt reactors are applied in conjunction with long EHV overhead lines. They are also applied in conjunction with HV and EHV underground cables in large urban areas.

Shunt reactors in use range in size from a few Mvar at medium voltages and up to hundreds of Mvar at EHV.

See also Table 4.

4.1.2 Shunt Capacitors

A shunt capacitor is a single capacitor unit or, more frequently, a bank of capacitor units connected in shunt to a power system for the purpose of producing reactive power.

When a fixed or mechanically switched shunt capacitor can be used with regard to the voltage control requirements, it is the most economic means available for reactive power production. The majority of shunt capacitors are applied within distribution systems of different types: industrial, urban, residential and rural. They have a widespread use there for power-factor correction. Some shunt capacitors are installed in transmission substations. Very large shunt capacitors (usually filters) are to be found in HVDC terminal stations.

Shunt capacitors in use range in size from a single unit rated a few kvar at low voltage up to a bank of units, rated hundreds of Mvar of EHV.

Outstanding features of shunt capacitors are their low overall costs and their high application flexibility.

An unfavourable characteristic, most important in conjunction with major outages and disturbances is that they provide the least support at the very time when it may be most needed, because the reactive power output is proportional to the voltage squared. If used in a proper mix with other reactive power sources, this is, however, no obstacle to an extensive use of shunt capacitors.

See also Table 5.

4.1.3 Synchronous Condensers

A synchronous condenser is an idle-running synchronous motor, used for the generation or absorption of reactive power.

The synchronous condenser is the traditional means for continuous control of reactive power. Synchronous condensers are used in transmission systems: at the receiving end of long transmissions, in important substations and in conjunction with HVDC inverter stations. Small synchronous condensers have also been installed in high-power industrial networks of steel mills to increase the short circuit power.

Synchronous condensers in use range in size from a few MVA up to hundreds of MVA. The rated voltage usually lies below 24 kV.

The size of a synchronous condenser is referred to the continuous MVA rating for the generation of reactive power. In the generating mode of operation it usually has a rather high short-time overload capability. The inherent absorption capability is normally of the order of 60 per cent of the MVA rating, which means that the control range is usually 160 per cent of the MVA rating.

The reactive power output is continuously controllable. The step-response time with closed-loop voltage control is from a few tenths of a second, and up, depending on different factors.

In recent years the synchronous condenser has been practically ruled out by the thyristor controlled static var compensator, in the case of new installations, due to benefits in cost, performance and reliability of the latter. One exception is HVDC inverter stations, in cases where the short-circuit capacity has to be increased. The synchronous condenser can do this, but not the static var compensator.

See also Table 6.

4.1.4 Thyristor controlled static var compensators

A thyristor-controlled Static Var Compensator (SVC) is a static shunt reactive device, the reactive power absorption or generation of which can be varied by means of thyristors connected antiparallel. Two types of thyristor-controlled elements are used: the Thyristor-Switched Capacitor (TSC) and the Thyristor-(phase-angle-) Controlled Reactor (TCR). From a fundamental frequency point of view both can be considered as a variable reactance, the former being a step-wise variable capacitive reactance and the latter a continuous variable inductive reactance.

The main components of a SVC are static elements such as transformers, reactors, capacitors and thyristors. There is a variety of SVC main circuit arrangements; Table 7a shows some.

The main purpose for most installations is high-performance voltage control; some installations have been made for damping of power oscillations. The compensator is also used for balancing varying unbalanced loads.

Since its late transmission breakthrough, at the end of the 1970s, transmission SVCs with a total control range of around 22000 Mvar have been ordered in the world (May 1987).

SVCs in use range in size from a few Mvar up to 600 Mvar control range, and with nominal voltages up to 765 kV.

Both the rated reactive power production capability and the rated reactive power absorption capability must be specified. The reactive power output is usually continuously controllable.

The small-disturbance performance may be characterized by the step-response time, here defined as the elapsed time required to achieve 90 % of the called-for change in voltage, for step change in the reference voltage. The step change must be small enough for the SVC not to exceed its limit. The step-response time depends on the external power system impedance. It is usually only a few cycles at minimum fault level.

The large-disturbance performance is characterized by the actuating time of the SVC triggering and main circuits only. For a large voltage deviation the SVC response time approaches one half cycle (maximum one cycle).

See also Table 7.

4.1.5 Saturating-reactor Static Var Compensators

A saturating-reactor static var compensator is a static shunt reactive device the reactive power of which is inherently varying versus the voltage if using a self saturating reactor or is varied by means of a high-power transductor. Only the self-saturating reactor type has been employed in some cases of transmission compensators.

See also Table 8.

4.2 Costs for reactive power supply equipment

Generators are designed for supplying active power into the system. With the help of the voltage control there are practically no additional costs for the supply of reactive power within a power factor range of 0.9 ... 1. For lower power factors, figure 5 may give some ideas on incremental costs, compared to the capital costs of capacitors. If the reactive load has to be transmitted over longer distance, the costs of losses can be higher than the capital costs. The conclusion is, that a power factor less than 0.9 in a generator may not be economic in most cases.

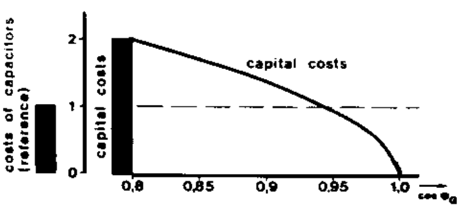


Fig. 5: Additional costs of reactive power prod. by generators

Synchronous condensers are designed for absorbing or supplying reactive power into the system. Generally their costs are higher than the costs for static var compensators. So they are reserved for special applications.

The costs for capacitors, reactors and static var compensators of different types are compared together (figure 6). Naturally capacitors and reactors without any control are less expensive than thyristor controlled reactors (TCR) or thyristor switched capacitors (TSC). Nevertheless, the costs are comparable at very high voltage levels, where transformer, breaker and other high voltage equipment are very expensive.

The most cost-effective type of SVC configuration depends on several factors and has to be found for each individual application. Among important factors are requested control range in Mvar and its subdivision on the inductive respectively capacitive side, voltage level, the evaluation of losses and harmonic requests.

The costs can, of course, only be approximate values, valid for standard equipment and for normal overload. They consider only the electrical part includings transformer and breaker on the high voltage side, but no additional equipment on the secondary side and no civil works, and especially, as stated before, not the losses, which vary depending on the different SVC-configurations.

4.3 Availability

Availability is defined as the proportion of time, in the long run, that a repairable device is in or ready for service.

Estimated values are given in Tables 4 to 8.

The availability indicated does not apply for the first year of operation and takes not account on teething troubles or design errors as may occur at a first design stage or due to incomplete network data. The values indicated have been achieved and will result in case of close co-operation between customer and manufacturer.

5. Future Development of Reactive Power Compensation Devices

No drastic development of shunt reactors and shunt capacitors is in prospect. Marginal improvements in efficiency, power density and specific investment cost might come.

No essential improvement of synchronous condensers is in sight. Moreover, during the recent years, the synchronous condenser has been practically ruled out by the thyristor-controlled static var compensator.

Thyristor-controlled static var compensators will be the subject of essential development in this area. Thyristors with higher power handling capability per unit, than of today thyristors, will decrease the costs. Light-triggered thyristors will be introduced. Force-commutated compensators, using normal thyristors or such with turn-off ability, will come into use, thus reducing the MVA amount of capacitors and reactors. This in turn might further reduce compensator costs.

6. References

1. Results of an International Survey on Reactive Power in Interconnected Power Systems
   Part I: Reactive Power and System Characteristics by I.A. Erinmez, Electra No. 87 (March 1983), page 65 - 96

2. Results of International Survey on Reactive Power in Interconnected Power Systems
   Part II: Voltage and Reactive Power Control Practices by A. Invernizzi

3. Use of Static or Synchronous Compensators in HVDC Systems by A. Le Du and others, Electra No. 91 (December 1983), page 51 - 82

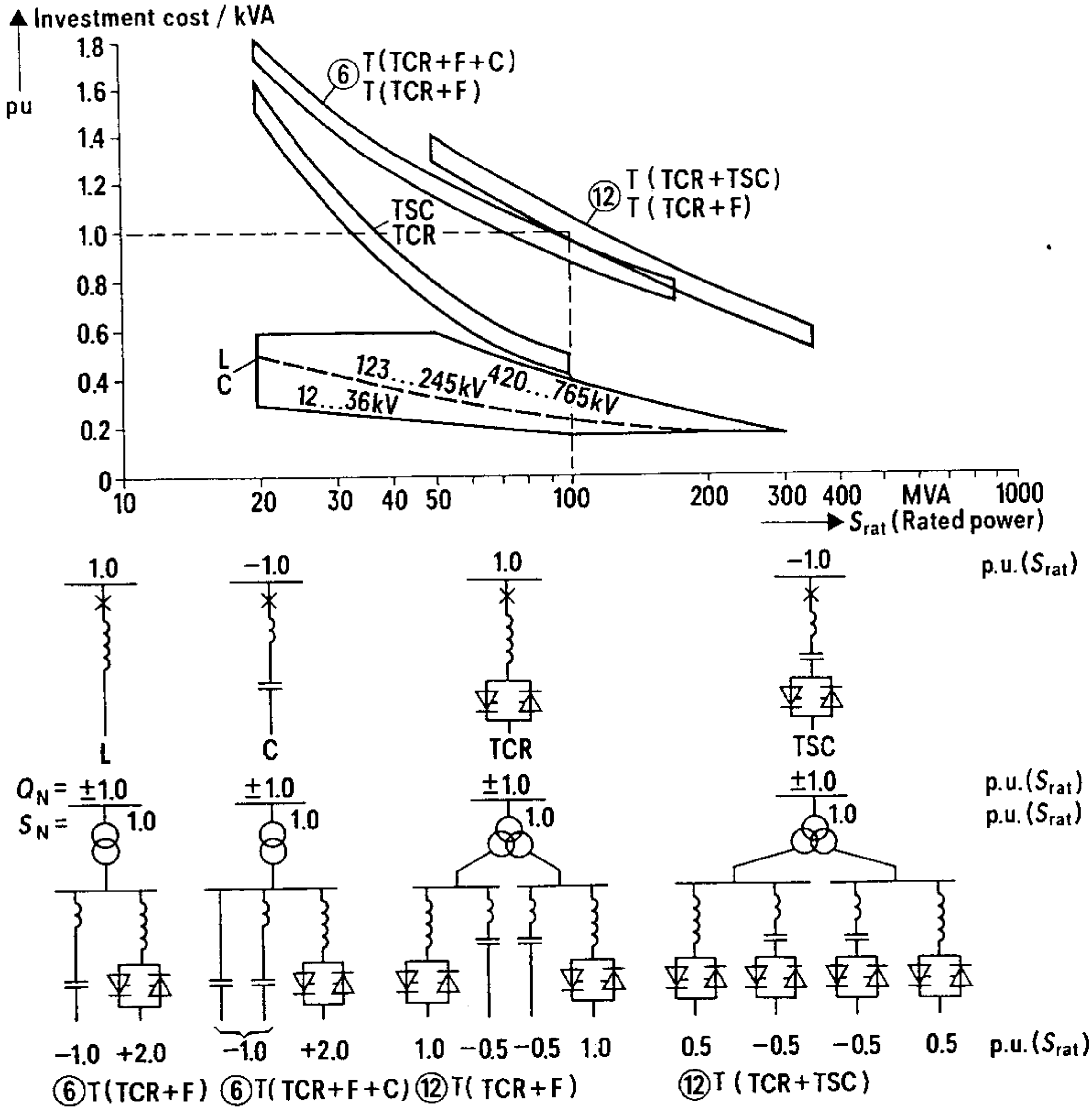


Fig. 6: Approximate investment costs for electrical equipment of reactive power compensation devices, including transformer and high-voltage switchgear, where relevant.
The SVCs with transformer are assumed symmetrical ($\pm Q_{rat}$):
the SVC rating referred to the transformer rating ($S_{rat} = Q_{rat}$).

Table 4a

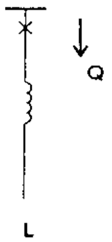
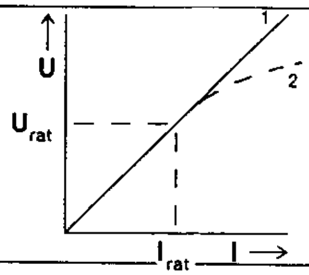
Equipment		Shunt reactor
Circuit Type		 3phase or 3 x 1 phase static elements
Alternatives		Air core / iron core 1) 2)
Characteristics		1) $Q = Q_{rat} \left(\frac{U}{U_{rat}}\right)^2$ 2) $Q \geq Q_{rat} \left(\frac{U}{U_{rat}}\right)^2$
Ratings		U_{rat}, Q_{rat}, U_{Knee} (rated voltage, rated power, kneepoint voltage)
Tasks	Voltage control steady state	Yes
	Voltage control transient	(Especially at saturation)
	Voltage stability	-
	Reactive power supply	Fixed reactance value only
	Damping of power oscillations	-
	Damping of SSR	-
	Influence on load flow	On reactive power load flow
	Stability improvement	(Indirect influence through higher excitation requirements of generators)
	Flicker compensation	-
	Correction of phase unbalance	-
Control system		Using a circuit breaker, decision of switching will depend on load flow requirements.
Response Time (time constants, gain, transfer function)		In case of switching ≈ 100 ms

Table 4b

Connection to the system	Directly to line bus or line or via transformer tertiary
Design criteria	Rated values U_{rat}, Q_{rat} Voltage range Load flow requirements Overvoltage limitation at load rejection Voltage changes at switching
Performance criteria	
Reaction	
Overload capability	High for limited time period
Variation of reactive power	Fixed reactance value only (except when switched)
Transformer	
Number of operation	Normally restricted to ≈ 2 ... 4 times daily
Maintenance	
Effects of switching	I_C/I_{rat} 3 ... 5 (I_C = Inrush Current)
Protection	Standard transformer protection
Losses	≈ 0.2 ... 1.0 %
Environmental factors	
Air conditioning	No
Space requirements	Low
Cooling requirements	Air-oil / natural-forced
Availability	ca.99 %
Maintenance	Negligible

Table 5a

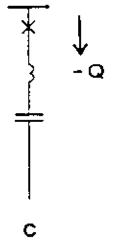
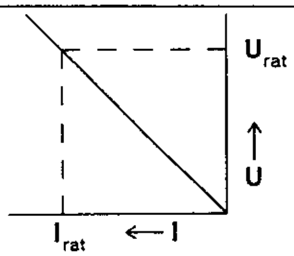
Equipment		Shunt capacitor (filter)
Circuit		
Type		Static elements consisting of various units in parallel/series connection
Alternatives		Paper or synthetic insulation
Characteristics		$Q = -Q_{rat} \cdot (\frac{U}{U_{rat}})^2$
Ratings		U_{rat}, Q_{rat}
Tasks	Voltage control steady state	Yes
	Voltage control transient	-
	Voltage stability	-
	Reactive power supply	Fixed capacitance value only
	Damping of power oscillations	-
	Damping of SSR	-
	Influence on load flow	On reactive power load flow
	Stability improvement	(Limited improvement due to decreased transmission angle)
	Flicker compensation	-
	Correction of phase unbalance	-
	Harmonic reduction	Yes
Control system		Using a circuit breaker, decision of switching will depend on load flow requirements
Response Time (time constants, gain, transfer function)		In case of switching about 100 ms

Table 5b

Connection to the system	Directly to line bus (or load) or via transformer (tertiary)
Design criteria	Fixed capacitance value Rated values U_{rat}, Q_{rat} Voltage range Load flow requirements Voltage support in special cases Voltage changes at switching Internally or externally fuses Increased voltage stresses due to harmonics
Performance criteria	
Reaction	
Overload capability	
Variation of reactive power	Fixed capacitance value only
Transformer	
Number of operation	Normally restricted to ≈ 2 ... 4 times daily
Maintenance	
Effects of switching	
Protection	Unbalance -, overcurrent -, overvoltage protection
Losses	≈ 0.02 - 0.06 %
Environmental factors	
Air conditioning	No
Space requirements	Extensive
Cooling requirements	No
Availability	> 99.5 %
Maintenance	Replacement of units in case of faulted units, depends on protection and fusing

Table 6a

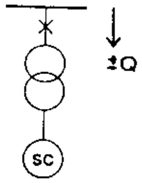
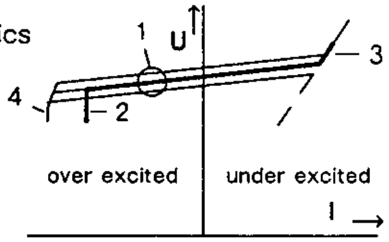
Equipment	Synchronous condenser
Circuit Type	 Rotating machine
Alternatives	
Characteristics	 1 Voltage-current-characteristic including slope and voltage range 2 Limitation in overexcited operation 3 Limitation in underexcited operation 4 Limitation at maximum exitation before action of limitation control 2
Ratings	U_{rat}, S_{rat}, operating range Overload (rating and duration)
Tasks: Voltage control steady state	Yes
Tasks: Voltage control transient	Yes
Tasks: Voltage stability	Yes
Tasks: Reactive power supply	Continuously controllable
Tasks: Damping of power oscillations	Yes, like PSS, but less effective than SVC of thyristor controlled type
Tasks: Damping of SSR	Possible
Tasks: Influence on load flow	On Reactive load flow
Tasks: Stability improvement	Improved in some cases
Tasks: Flicker compensation	Yes, but less effective than SVC (thyristor contr. type)
Tasks: Correction of phase unbalance	To a certain extent, due to rather low neg. seq. reactance, but less eff. than SVC
Tasks: Increase of short circuit capacity	(Wanted in HVDC application)
Control system	Voltage control (other control features possible)
Response Time (time constants, gain, transfer function)	Step-response time with closed-loop voltage control is from a few tenths of a second and up depending on different factors

Table 6b

Connection to the system	Via transformer secondary or tertiary
Design criteria	Rated values U_{rat}, S_{rat}, operating range Voltage range Load flow requirements Voltage support Stability improvement SCR-requirements
Performance criteria	
Reaction	Speed limited by machine constants
Overload capability	Cap. range high, ind. range low
Variation of reactive power	Continuously controllable
Transformer	Tap changer not always required
Number of operation	No limitation
Maintenance	
Protection	Standard generator protection
Losses	≈ 1 % not including auxiliary equipment
Environmental factors	
Air conditioning	
Space requirements	Medium
Cooling requirements	
Availability	ca.97 %
Maintenance	Extensive

Table 7a

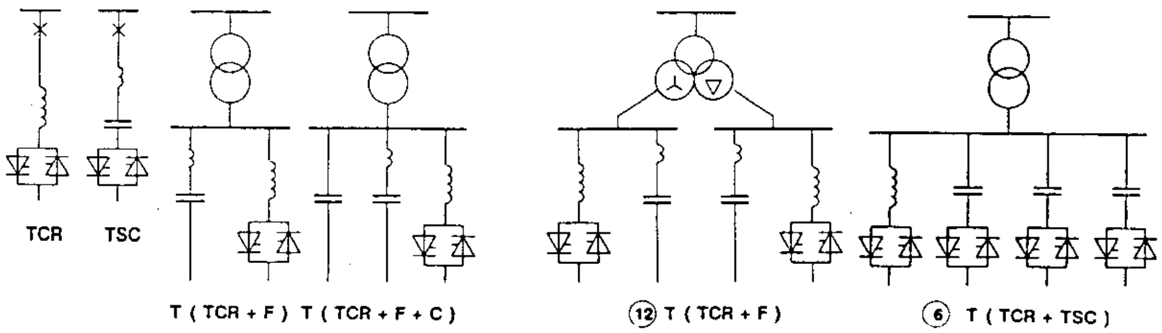
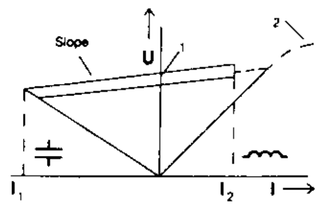
Equipment		Thyristor controlled static var compensators
Circuit Type		
Alternatives		12pulse operation e.g. ⑫ T (TCR+F) Additional capacitors e.g. ⑥ T (TCR+F+C)
Characteristics		1 Reference voltage 2 Overload range *) Can be manually adjusted or changed by additional signals e.g. at damping of power osciallations
Ratings		U_{rat}, $Q_{Crat}(I_1)$, $Q_{Lrat}(I_2)$, S_{rat} = Max $(Q_C(I_1),\ Q_L(I_2))$ with reference to point of connection Overload (rating and duration)
Tasks	Voltage control steady state	Yes
	Voltage control transient	Yes
	Voltage stability	Yes
	Reactive power supply	Continuously controllable within $I_1 - I_2$
	Damping of power oscillations	Yes (0.5 ... 2 Hz)
	Damping of SSR	Yes (10 ... 40 Hz)
	Influence on load flow	Esp. on reactive power load flow
	Stability improvement	Yes, depending on control sheme
	Flicker compensation	Possible, single phase control if required
	Correction of phase unbalance	Possible, with single phase control
Control system		Voltage control Additional signals for other control features (Damping of power oscillations, SSR)
Response Time (time constants, gain, transfer function)		Small-signal response time 3 to 10 cycles of supply frequency. Large-signal response time less than one cycle of supply frequency.

Table 7b

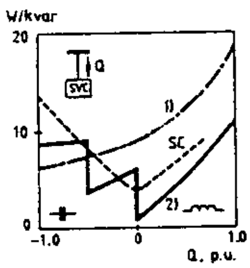
Connection to the system	Via transformer to the busbar Tertiary winding of the transformer for smaller size Circuit breaker preferred to disconnector
Design criteria	Rated Values U_{rat}, S_{rat}, control range Voltage range (time and deviation) Frequency range (time and deviation) Impedance of the system (pf to 25th harmonic) Higher harmonics in the system (voltage) Higher harmonics to the system (currents) Response at 1- and 3phase faults Response at load rejection (temporary overvoltages)
Performance criteria	
Reaction	Fast
Overload capability	High in inductive range (short-time)
Variation of reactive power	Continuously
Transformer	No tap changer required
Number of operation	No limitation
Maintenance	
Protection	Differential protection, overcurrent
Losses	 1) Type T(C+TCR) losses .5 ... .7 % of S_{rat} 2) Type T(2TSC+TCR) losses .3 ... .5 % of S_{rat}
Environmental factors	
Air conditioning	Sometimes air conditioned valve hall
Space requirements	Extensive space for filters and capacitors
Cooling requirements	Cooling water for large SVCs
Availability	> 99 %
Maintenance	Low

Table 8a

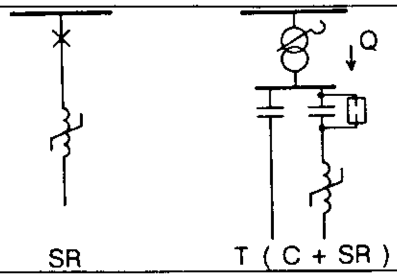
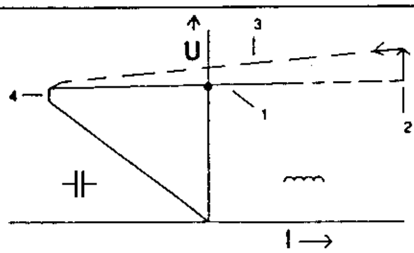
Equipment		SVC of saturable type
Circuit Type		
Alternatives		Compensation of air core reactance by series capacitor Control of saturation by dc premagnetization
Characteristics		 1 Continuous operation with reference voltage and slope 2 Spark gap operation at overload 3 V-I-characteristic after spark gap operation 4 Kneepoint voltage of SR
Ratings		U_{rat}, Q_{rat}, Control range, Kneepoint voltage Overload (rating and duration)
Tasks	Voltage control steady state	Yes
	Voltage control transient	Yes
	Voltage stability	Yes
	Reactive power supply	Continuously within the control range
	Damping of power oscillations	Possible in special cases
	Damping of SSR	No
	Influence on load flow	On reactive power load flow
	Stability improvement	Yes to a certain extent (no special control possible) Yes in case of dc controlled reactance
	Flicker compensation	Yes
	Correction of phase unbalance	No with 3phase equipment
Control system		Tap changer control for matching to the reference working point DC premagnetization used in very few cases
Response Time (time constants, gain, transfer function)		2 to 5 cycles of supply frequency for type T (C+SR). In case of tap-changer several seconds for 1 step.

Table 8b

Connection to the system	Via transformer to HV-busbar tertiary winding of transformers
Design criteria	Rated values U_{rat}, Q_{rat}, control range Voltage range Overload range Impedance of the system Damping of second harmonic resonance if necessary Cancellation of harmonic at symmetrical operation using multi-winding-reactor (up to 18 limbs)
Performance criteria	
Reaction	Fast
Overload capability	High in inductive range (short time)
Variation of reactive power	Continuously
Transformer	Tap-changer required
Number of operation	No limitation
Maintenance	
Protection	Standard transformer prot. Air-gap-protection of series capacitor.
Losses	Higher than SVC of thyristor controlled type
Environmental factors	
Air conditioning	
Space requirements	Extensive for T(C+SR)
Cooling requirements	Oil natural / forced
Availability	ca.95 %
Maintenance	

APPENDIX 2
REACTIVE POWER COMPENSATION ANALYSIS AND PLANNING PROCEDURE
SUB-ITEM : LOAD DEMAND AND MODELLING

by

J.F. CHRISTENSEN
ELKRAFT
Denmark

G. PELS-LEUSDEN
AVU
Fed. Rep. of Germany

J. VERSEILLE
EDF
France

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INTRODUCTION

There are three main aspects in analysis of the demand in regard to reactive power compensation:

- separation of the reactive demand related to the network from the one related to the loads,
- load modelling according to the kind of studies and to the models which are used,
- reactive loads knowledge and forecast.

These three items are described in the present report.

A summary of the present practices in the different companies has been established, according to the answers to the questionnaire on use of reactive power optimization techniques in system planning.

1. REACTIVE POWER DEMAND AND SYSTEM REPRESENTATION

The reactive demand in a power system results from the reactive consumption of the loads and from the reactive losses in the network; therefore, the analysis of the reactive demand can't be dissociated from the representation of the network in the models.

Whichever size is the studied system, it is impossible to keep the entire network, from the EHV to the MV or LV level, in the models. Some simplifications are necessary and two ways can be used for that, which are:

- using a vertical subdivision in voltage level,
- using a horizontal subdivision based on geographical considerations.

Both of them can be used simultaneously.

- The vertical subdivision: it leads to include the reactive consumption of the lowest voltage networks into the loads. The problem is to define the kind of network for which that approximation is a reasonable one.

  . distribution networks: the reactive consumption of these networks is low and vary according to the load level. For these reasons, they are mostly included into the load consumption.

  . transmission networks: on the contrary, the reactive losses in these networks can be high compared to the reactive flow; moreover, their variations depend not only on the load consumption, but also on the network configuration and operational conditions resulting from outages of network elements and power plants or, especially in a meshed grid, from measures to increase security or to limit short circuits currents. So, it is necessary to get a precise estimation of these losses that requires to represent these networks in the models.

  . Subtransmission networks: it isn't any obvious solution for these networks. Reactive losses can reach 30 % of the reactive flow.
  However, in many cases, owing to the size of the system, it is impossible to keep the entire transmission - subtransmission network. Then, two possibilities can be used depending on the system and on the problem to be solved.

  The first one consists in including these reactive losses into the loads; with appropriate load measurements and forecasts, this approximation is suitable for steady state studies on the transmission network in order to optimize the global amount of reactive compensation devices.

The second one consists in keeping the entire subtransmission network in a peculiar area and using a horizontal or vertical subdivision in the other parts of the system; a precise representation of this network is usefull to decide the characteristics of the reactive devices; some of these can be installed on the HV or on the MV network; their localization and their way of operation have to be chosen according to the reactive compensation requirements of the subtransmission network.

In another hand, it can be useful, for long term stability studies, to simulate the control of the on-load tap changers of the EHV/HV or HV/MV transformers, in order to analyse changes in the reactive demand after a disturbance.

- The horizontal subdivision: based on geographical or administrative criteria, it is used, in most cases, to separate the transmission network into subsystems.
  It leads to define equivalents of the parts of the system which are suppressed. The choice of the used equivalent is made according to:

  . the way of operation: the simplest example is when the exchanges between the different parts can be considered predefined; in this case it can be sufficient to use P, Q injections at the border nodes (the simplest case is when the studied system has to be internally fully balanced). Nevertheless, because the Q injections depend on the network operating conditions, such a representation is valid only if these variations are small.

  . the system configuration: there are different ways to obtain an equivalent for reactive power studies. The most common are:
  * considering the border nodes as P.V. nodes
  * compensations installed at the border nodes
  * REI equivalent
  * WARD equivalent

  In many cases it seems useful to keep a detailed representation of the system immediately surrounding the studied subsystem.

2. LOAD MODELLING

"Loads" in the reactive power studies are modelled as injections at the EHV or HV busses. In fact each injection is a combination of different components like industrial loads composed of various kinds of motors as well as residential loads including many constant impedance loads (lighting, heating ...).

These loads are linked to the HV or EHV busses by HV, MV and LV networks and by transformers equipped with on-load tap changers used for automatic voltage control on the subtransmission and distribution networks.

Despite the fact that load depends also on the frequency, we focus our attention on the load dependency on voltage, which is the most important for reactive compensation studies, because the frequency deviations are usually very small compared to the voltage deviations.

The most common representations of power system loads are:

- fixed P and Q model: load remains constant as the voltage changes
- fixed impedance: power is a function of the voltage squared

$$P = Po\left(\frac{V}{Vo}\right)^2 \qquad Q = Qo\left(\frac{V}{Vo}\right)^2$$

- fixed current: power is proportional to voltage

$$P = Po\left(\frac{V}{Vo}\right) \qquad Q = Qo\left(\frac{V}{Vo}\right)$$

Other models are used like:

- composite load model, which is a combination of these three types:

$$P = Po\ (A_1 + A_2\ V + A_3\ V^2)$$

$$Q = Qo\ (B_1 + B_2\ V + B_3\ V^2)$$

- exponential models:

$$P = Po\left(\frac{V}{Vo}\right)^{\alpha} \qquad Q = Qo\left(\frac{V}{Vo}\right)^{\beta}$$

The adequacy of the different models depends on the kind of study (steady state or dynamic) and on the methods used to solve the problem.

. Steady state simulation: according to the answers to the questionnaire on use of reactive power optimization techniques in system planning, load flow studies are the basis of the reactive planning. Because the purpose of these studies is to define the amount of compensation devices necessary for having a satisfying voltage profile in normal operation conditions, it isn't necessary to take into account the load dependency on voltage. Therefore fixed P, Q models are used at this step.

However, load flows can also be used in order to determine the state of the system following a major disturbance [1] (for example loss of a generation plant). These post-transient load-flows can be considered as a momentary picture of the system in a transient state, anywhere after the disturbance.

In this case, the sensitivity of the loads to the voltage has an important effect on the solution. It can be supposed that active and reactive power vary as some exponential power to the bus voltage (for example with a fixed impedance model) in order to get the state of the system in the first seconds after the disturbance.

On the other hand, a fixed P and Q model allows to simulate the effects of the transformer on-load tap changers which, after a time delay reaching till 1 minute or more, tend to restore the initial voltage at the load delivery points.

The solutions are different in both cases; fixed P and Q models are generally more pessimistic.

. dynamic simulations: dynamic studies are performed in reactive power planning in order to determine what type of reactive power device should be installed (e.g. static var compensator, switched capacitors ...) or to estimate the necessary reactive reserves during the dynamic sequence caused by a network fault.
The load characteristics have many effects on system stability and simulation results can change significantly as different load representations are used.

We can distinguish three main kinds of dynamic simulations:

Steady state stability

The purpose is to study the behaviour of the system after a "small" disturbance, for which linearisation of the equations is justified.

Simplified load modelling like fixed current or fixed impedance are often used.

However, there are some trends to improve the knowledge on dynamic load behaviour and particularly on the voltage dependency.

The most common way are measurements of the slopes dP (%)/dV (%) and dQ (%)/dV (%) within a rather limited range of voltage variations [2] that is justified for steady state stability. Many results are available for individual components [3] or for composite loads thanks to measurements on the network busses after changing the transformer taps [4]. All these results are based on narrow range of voltage variations ($\leq$ 10 %).

- The ΔP (%)/ΔV (%) factor varies between 0.2 and 2.0; the lowest values concern industrial loads predominantly composed of induction motors; the highest are related to residential and commercial areas composed of constant impedance loads such as heaters and lights; seasonal variations have been observed and winter values are higher than summer values.
- The ΔQ (%)/ΔV (%) factor is higher, varying from 1.5 to 4.0, but very high values are mentioned (7 to 12); however the effects of shunt capacitor compensation and of the reactive losses in the network have to be taken into account in such measurements.

In other respects, some models have been developed for special type of loads. The most common example is motor load. However, if it is easy to establish a dynamic model for one motor, it isn't so easy to find a single motor that will satisfactorily represent the aggregate motor load. Different methods have been proposed [5] and some of them have been compared in term of accuracy [6].

In the same manner, some models are developed in order to define an equivalent load describing the behaviour of the customer loads and of the lower voltage networks, as viewed from a specific network bus [7] [8].

The effects of the voltage dependency of active power can't be classified as leading to pessimistic or to optimistic results. Nevertheless the voltage stability limits often decrease when P(V) changes from constant impedance type toward constant power type, especially if loads are at load centers remote from generation. [See report on voltage stability].

Transient stability (up to a few seconds)

These studies involve wide ranges and fast gradients of voltage variations; therefore the non-linear behaviour of the loads has to be considered. In such cases, some of them (motors for example) can be disconnected; some other, on the contrary, can consume more active power than before the fault. Consequently, an accurate dynamic representation of the loads should be used.

However, it is difficult to get precise results in this field. Due to this lack of better knowledge, simplified models (often the same as for steady state stability studies) are used.

Long term stability (from a few seconds to a few minutes)

These simulations are performed in order to analyse the risk of voltage collapse or to study the coordination in time and space of the various control means. The numerical stepsize is one or more seconds as opposed to a fraction of a second for steady state stability or transient stability.

In this case, the problem, with regard to load representation, is to take into account the action of the tap changers which begin to operate after a few seconds and whose action continues during about one minute.

For voltage stability studies, it is important to model the response of automatic transformer tap changers which are in series between the main system and the load to ensure that their time grading is such that load overshoot does not occur (i.e. correction of the lowest voltage before the higher voltage) and to get a correct representation of capacitors (and the network shunt capacitances) connected between the load and the main system.

If the system contains an accurate representation of all tap changers, including their control characteristics (that means that the loads are considered at lowest voltage level which is controlled), the load models used for steady stability are suitable. For most systems, such a detailed representation of the system is too complex for simulation.

If the tap changers arn't described (loads viewed from the EHV level), it is necessary to make approximations; the most common one consists in using a fixed P, Q model.

This approximation is fairly good,if all tap changers are automatic controlled on constant voltage criteria. If some of the tap changers are manual or controlled by other criteria than constant voltage, a more detailed model should be considered.

3. REACTIVE LOAD KNOWLEDGE AND FORECAST

According to the answers to the questionnaire (see Appendix) reactive load forecasts are based on the active consumption forecasts and on the knowledge of Q/P ratios.

The most common method consists in measuring the Q/P ratio at the EHV/HV or HV/MV busses. In such investigations, it is important to know the reactive power compensation devices used at the time of the measurements in order to be able to compute the natural reactive consumption of the loads.

These measurements have to be made in order to know the Q/P ratio for the different periods which are studied (peak load and light load or other peculiar periods corresponding to special operation conditions).

For reactive power forecasting, it is necessary to make extrapolations of the power factor. However these extrapolations often consist in assuming that the power factor remains constant in the future.

An another method is a more analytical approach in which the compensation requirements are determined by type of use or type of network.

In this case, measurements have to be done in order to identify:

a) Special types of load groups regarding reactive power demand (e.g. mainly residential quarters with and without electrical heating, city areas with mainly shops and offices ...).

b) Reactive power demand of various types of MV and LV networks (e.g. mainly overhead lines or mainly cables, density of substations MV/LV and their rating).

c) For all possible combinations of item a) and b) the changes of reactive power demand (daily, weekly, seasonally).

This approach is more suitable to forecast the reactive consumption according to the evolutions of the active one, and to give indications about the evolutions of the Q/P ratio according to the load composition (for example how changes the power factor when the part of heating in the consumption grows?). It requires an extension of the measurements on the network which could also be used in order to analyse the dynamic behaviour of the loads. Such improvements in measurements are under way in a few companies. [8]

Finally, it appears that the reactive power forecasts aren't yet very precise. Due to this lack of accuracy, it is useful to complete the results of load flow models by analysing the sensitivity to the load level, especially in order to appreciate the risks of voltage instability.

4. CONCLUSIONS

Network representation

- The distribution networks don't have to be dissociated from the loads.
- Depending on the system, it can be more appropriate to consider the whole transmission network and to include the subtransmission network into the loads, or, on the contrary, to use geographical subdivisions in order to keep the subtransmission network in a limited area.

Load modelling

- For load flow studies fixed P - Q models are sufficient.
- For dynamic studies, dependency of the loads with the voltage is important; however it is difficult to obtain accurate models and also to know the effects on the results of the approximations which are done.

Reactive power forecast

- Reactive power forecast is, at the moment, based on extrapolation of Q/P ratio measurements on the existing networks and on active load forecasts.
- Identification of Q/P ratios for different types of loads or networks seems to be more suitable for forecasting; however that requires improvements in measurements and knowledge on load composition.

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Appendix: Table collecting informations about reactive power demand (questionnaire of Reactive Power Optimization Techniques in System Planning)

	country company	network limits		load cases considered	reactive demand knowledge		load modelling		additional remarks
		vertical	horizontal		currently	forecast	size	estimation	
A	EdF	≥ 225 kV	-	peak/low each for summer, winter mid-season	tg φ -meas. for all load cases	tg φ =const.	P,Q	suff., for dynamics P,Q=f(v) can be important	reactive forecast uncertain, because load structure is unknown
B	Belgian (combined)	≥ 70 kV	-	peak 85 x peak (sensitive to loss of generation, because predominantly in 400 kV)	cos φ -meas.	cos φ = const.	P,Q	suff. due to tap changer action	
C	Chubu	≥ 154 kV	ownership	peak (summer), low (winter night)	Q-meas.	Extrapol. ?	P,Q	-	
D	Osaka	≥ 275 kV	-	as C	?	tg φ -extrapolation	P,Q	more detailed seems useless	growing tendency of tg φ -extrapolation
E	Tokio	≥ 275 kV	-	peak/low	?	?	$P = P_0V^{\alpha}$ $Q = Q_0V^{\beta}$	suff.	
F	Czechoslovakia	≥ 220 kV	-	winter peak winter night summer peak summer night summer min.	according to the structure of the load (active consumption forecasts)	cos φ =0,95	P,Q		load definition at II.V or I.V terminals of transformers 400/110 and 220/110
G	TVA (USA)	≥ 115 kV	-	summer peak winter peak min.load of the year, min.load at peak day, 80 % summer peak	cos φ -meas. for all load cases	extrapol. according P-forecast	P,Q (load flow) Z(trans stab.) P,Q or I=const (sensitivity)	suff., measurements have been improved recently	
H	Switzerland (combined)	lower voltage levels = fixed load (≥ 220 kV)	WARD-equival. at interconn. busses of surrounding network	peak/low February (Wednesday) August (Sunday)	measurement	acc. to P-forecast	P,Q and Z	-	
I	Swedish State Power Board	≥ 130 kV (> 70 kV)	for stab. studies all Nordic countries included	peak/low medium with special transmission from hydro resources	?	acc. to P-forecast	P,Q (load flow) P_0V^{α} Q_0V^{β} (stab.)	suff. for load flow	

	country company	network limits		load cases considered	reactive demand knowledge		load modelling		additional remarks
		vertical	horizontal		currently	forecast	size	estimation	
J	Norwegian (combined)	⩾ 132 kV	geographical	peak/low	?	acc. to P-forecast	P,Q and Z	-	intention to limit reactive power flow between voltage levels
K	Romania (Nat. power board)	⩾110 kV	REI-DIMO equivalent (?)	peak winter evening, peak summer morning, low summer holiday night	measurement	acc. to P-forecast	P,Q	suff.	
L	CEGB	⩾132 kV	-	peak/low, 85 % peak due to North-South-transmission	measurement of tg φ	tg φ =const.	P,Q some loads sensitive to volt.	suff. but pessimistic for voltage step changes	interconnection between 132-kV-busbars often represented as equivalents. Measurement program is intended to improve knowledge of tg φ of loads
M	ENEL	⩾400/220kV and some 150- and 132-kV-networks	equivalents at interconn. busses	peak/low at summer and winter working day, abs. low, noon of summer working day	measurement	cos φ - extrapolation	P,Q (possible P=const $Q=QV^2$)	suff. due to tap changer	noon of summer working day is examined because all shunt capacitors in servcie but no peak load
N	Siemens (Germany)	-	active equivalents	peak/low, energizing of system after breakdown	measurement	acc. to P-forecast	P,Q Z for spec. industrial loads	suff.	more exact representation with use of exponents can be applicated if data available
O	New York Power Pool	-	equivalents of surrounding networks	winter peak summer peak summer min.	measurement of identified load groups	tg φ =const.	P,Q recently $Q=Q_0 \cdot (\frac{V}{V_0})^\beta$	insufficient reactive power measurement, improvement is intended for better forecast	load modeling recently as function of voltage in reactive power planning
P	Northern State Power (USA)	⩾ 115 kV (⩾ 69 kV for local studies)	equivalent MAPP (Mid continent area power pool)	peak/low	-	cos φ -forecast in connection with P-forecast	P,Q (for dyn. studies I=const or a comb. of I=const. and Z=const.	improvement intended	distribution networks should maintain cos φ =1 to minimize losses

	country company	network limits vertical	horizontal	load cases considered	reactive demand knowledge currently	forecast	load modelling size	estimation	additional remarks
Q	Iberduero (Spain)	≥ 145 kV	intercon-nections as fixed P,Q	peak/low	Q-measure-ment	acc. to P-forecast corrected by extra-polation of Q-meas-urements	P,Q (Z pos-sible)	-	
R	Hidro-electrica Espanola (Spain)	≥66 kV	load flow: full exter-nal II.V system re-presented. Opt. load flow: fixed Z for net-work, fixed load	peak/low each for one day in winter and summer	measure-ment (survey)	acc. to P-forecast using tgφ - measure-ments	P,Q	suff.	improvement of data col-lection is intended for better know-ledge of load types
S	ELKRAFT (Denmark)	132 kV busses	neighbour-ing sys-tems de-tailed re-presented	peak/low medium load case (crit-ical in re-active re-serve)	measure-ment at peak	acc. to P-forecast and tgφ - extrapola-tion	P,Q (sta-bility: PoV0,8 QoV1,8	probably not suffi-cient, im-provement by measure-ment pro-gram in-tended	tgφ =0 in-tended at I.V terminals of 400/132 kV transformers
T	Australia + New Zea-land (combined, 7 utilities)	respons. 66 kV to 6.6 kV	into sys-tems with small mu-tual in-teractions	peak/low	measure-ments	acc. to P-forecast tgφ =const.	P,Q (trans P,Q= t (V)	suff. for LF, to be improved for tran-sient studies	

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APPENDIX 3

PLANNING AGAINST VOLTAGE COLLAPSE

J.F. CHRISTENSEN
ELKRAFT
Denmark

A.W. GRAINGER
ECNSW
Australia

G. SANTAGOSTINO
CESI
Italy

M.STUBBE
Tractebel
Belgium

J. VERSEILLE
EDF
France

ABSTRACT

Several systems have experienced voltage collapse, and the Task Force's questionnaire |4| indicates a need for a widely accepted procedure for dealing with the voltage collapse problem in system planning. The object of this report is to present a procedure and to establish guide lines for the use of system planners in order to prevent voltage collapse.

The report contains an explanation of the voltage collapse problem, and how it is influenced by transmission system characteristics, the steady-state and the dynamic behaviour of the load, as well as the overall system control. Experiences from actual system disturbances are examined together with conclusions from the questionnaire. Prefault conditions are discussed, and it is suggested that the use of n-2 security in reactive planning could be justified in order to obtain a probability of failure due to voltage collapse consistent with normal practice regarding transient stability. A planning procedure based on a normal load-flow program is established, and practical guide lines for planners are drawn up. This procedure is much faster than procedures based on dynamic calculations. Finally an example to illustrate the method is given.

1. INTRODUCTION

It is well known that transmission of active power is dependent on the voltages at both the sending and receiving ends of a transmission system.

The most well-known steady-state limitation to power transmission on a system occurs when the electrical angle between the voltage sources at the two ends reaches 90 degrees.

However, at this transmission angle there is a very high requirement for the supply of reactive power at both the sending and receiving ends. For example, while at 90 degrees the maximum real power transmission possible in the system of figure 1A is EU/X_L, at the same time the reactive power requirement is U^2/X_L at the receiving end and E^2/X_L at the sending end, both directed into the line. The reactive power to be supplied at each end of the line is therefore of the same order as the power transmitted.

Generators at the ends of a system might be able to supply this requirement, and hence to maintain voltages, for short times during power swings (by field forcing), but there are very few situations in which such high reactive power supply could be maintained for any length of time. With realistic types of voltage support the reactive power supply will be limited, and voltage will collapse at steady-state angles much less than 90 degrees.

After the voltage has collapsed, the power transfer capability of the system disappears (because $EU/X_L = 0$), and loss of synchronism between generators at the two ends will follow. However, it is an important characteristic of this kind of system failure that loss of synchronism is a result of voltage collapse rather than a cause.

As stated, voltage collapse can occur at quite low transmission angles and, when the system is heavily overcompensated at the receiving end, at receiving system voltages which are not much lower than the normal operating range. The failure process can be illustrated by using a transmission line performance chart for the receiving end of the line, as shown in figure 1B. On the abscissa is the reactive power supply or absorption at the receiving end of the line and on the ordinate the power transmission. Circles showing the relationship between the power transmission and the reactive power supply are drawn with U/E as parameter. As seen in figure 1B, there is an absolute power limit which is highly dependent on the resources available for reactive power supply at the receiving end. The equations relating to these circles are given in appendix 1 in the extensive report |7|.

The explanation of voltage collapse, referring to figure 1B, is as follows:

At an initial per unit voltage of 1.0 in the receiving network, reactive power Q_0 must be supplied to the line to support the power transmission.

Now one of the machines P_1 in figure 1A is tripped, and we assume that the missing active power is delivered from the remote machine. To support this increased transmission, additional reactive power must be supplied to the line, if the same voltage is to be maintained. If this is not available (especially

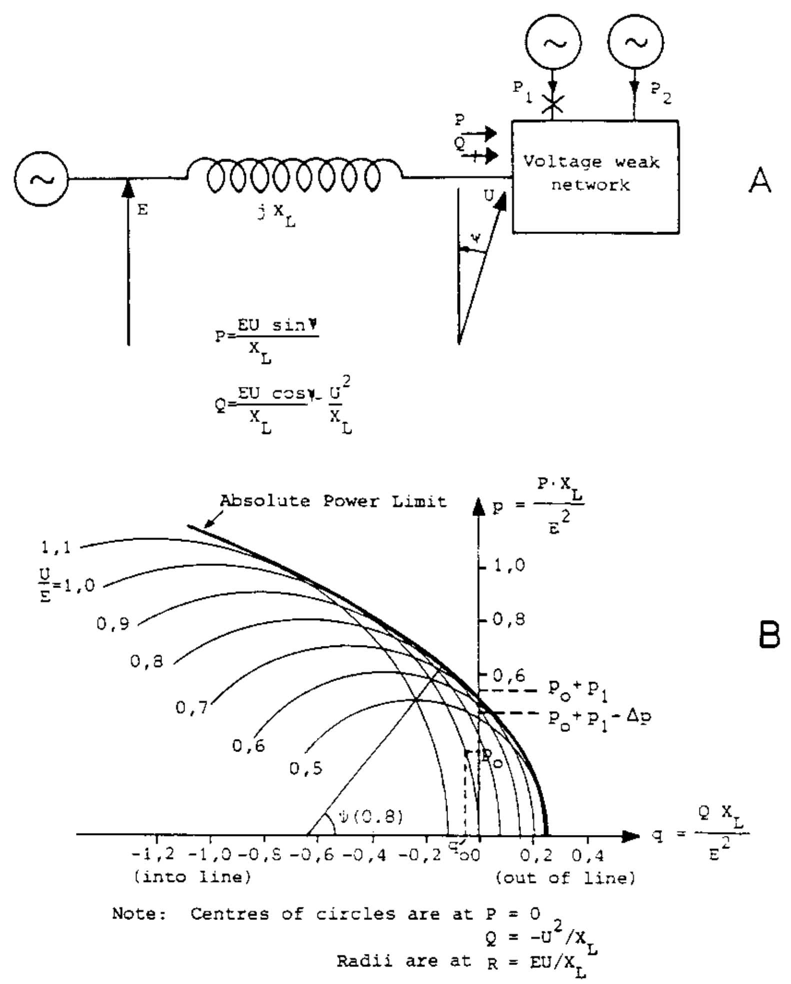


Figure 1. Receiving end line performance chart.

when the reactive power generating capacity of P_1 is lost), equilibrium will be established at a lower voltage and with a lower transmission $P_0 + P_1 - \Delta P$, where ΔP is the reduction in load due to the lower voltage.

In the following period, typically 1/2 to 5 minutes, the excitation on synchronous generators will be returned either automatically or manually to levels within their capabilities, and the automatic tap-changer control on the load transformers will bring the load back towards its former value, and the transmission from the remote machine will increase towards $P_0 + P_1$. With no increase in reactive support at the receiving end, the voltage must drop further. It can be seen from the figure that there exists a limit to the power, which may be transmitted irrespective of voltage, and that an attempt to exceed this will result in a voltage collapse. The transmission angle at which this occurs is far less than 90^o. For instance, the transmission angle for $U/E = 0.8$ is shown by the designation ψ (0.8) in figure 1B.

It is also important to notice that in the period, before the voltage collapse occurs, the frequency will be normal or even slightly high (due to ΔP) for some contingencies. This indicates that frequency-activated load shedding cannot save the network from voltage collapse.

The additional power transmission also draws additional reactive power from the sending end system. If the supply there is also limited (and this is made worse by the need to supply additional real power), the sending end voltage may also begin to fall. The transmission limitation will then occur at an even lower power transmission.

It should be noticed that the risk of voltage collapse is connected to:

1. contingencies which weaken the local voltage control (i.e. unit tripping)

2. contingencies which weaken the transmission system (i.e. line and busbar faults)

3. contingencies which increase the power transmission in the network due to the primary control of the active power (i.e. unit tripping, network separation, etc.).

Further, it should be noticed that voltage collapse often (not always) will happen after a time period determined basically by the timing of the automatic transformer tap-changer control and of the reduction in generator excitation levels.

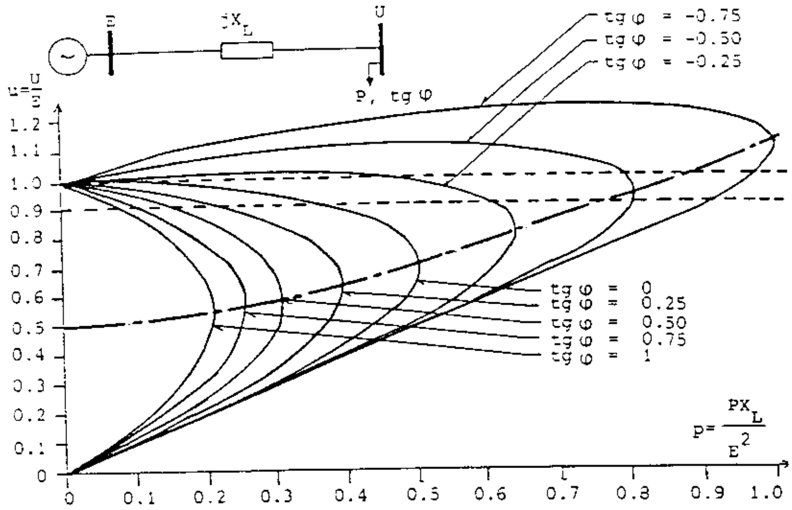


Figure 2.

U-P curves illustrating the relationship between the voltage and the load with tgφ as parameter.
—·— Curve connecting points with maximum power.
===== Operating range

2. INTERACTION BETWEEN TRANSMISSION SYSTEM CHARACTERISTICS AND LOAD BEHAVIOUR

When system conditions change, the behaviour of the load interacts with transmission system characteristics to determine successive operating points on the performance chart of figure 1B. It is of interest to separately examine in more detail the transmission system characteristics and both the steady-state and dynamic load behaviour.

2.1 Transmission system characteristics

Alternative charts can be derived from figure 1B to illustrate some fundamentally important properties of AC transmission. The first such chart is the U-P curve (|7|), App. 2), which shows the relationship between the voltage and the load at the receiving busbar, with the assumption that load power factor is constant. This can be devised from first principles or by examining the intersections of straight lines through the origin, representing various tgφ, with the voltage circles of figure 1B. Examples of U-P curves are shown on figure 2.

For each load power factor there is a maximum transmissible power. For any value of P below the maximum there are two possible solutions for U. Normal operation of the power system is always at the upper value, within narrow limits around 1.0 p.u.

The load tgφ has a strong influence on the receiving-end voltage. For voltages in operating range 0.9 to 1.0 p.u. loads with positive tgφ, with zero, or with low negative tgφ tend to reduce U as the load P increases. With large negative tgφ increases until P reaches a much higher value. This represents an unstable operation condition for the assumed constant tgφ load.

For studies of prevention of voltage collapse U-P curves are not easy to use, because the technique of adding variable reactive power sources (for example SVC's) means that load tgφ is not constant.

A more useful chart is the Q-U curve, which can be drawn to show the characteristics of a line alone or of an entire transmission system including severable lines and the load plus compensation. Figure 3 shows an example for a purely inductive transmission line alone with active load as parameter. These curves correspond to intersections of horizontal straight lines with the voltage circles of figure 1B.

Only the parts of the curves to the right of the minima are stable |7| unless supported by additional reactive power from an automatic source (static var compensator, synchronous condensers, etc.) in which case stable operation can be maintained as long as the source has a sufficiently high Q versus U gain and is within its control range. It is also only true provided the automatic reactive source controls the voltage faster than the actions that return the power to a constant value, for instance tap-changer control. This is normally the case, although it may not be the case in special applications. For instance large induction motors may consume a fairly constant power, but abruptly increase their reactive power absorption when the voltage decreases. This response of induction motors for voltage variations may be faster than the controls of automatic reactive sources.

2.2 Load characteristics

Loads whose real and reactive parts vary with voltage interact with the transmission characteristics by changing the flow through the system. The load and transmission effects can be summated to show the overall response at the load busbar to variations in voltage associated with changes in reactive power injected.

The voltage dependence of the load has a tremendous influence on the stable part of the curves in the

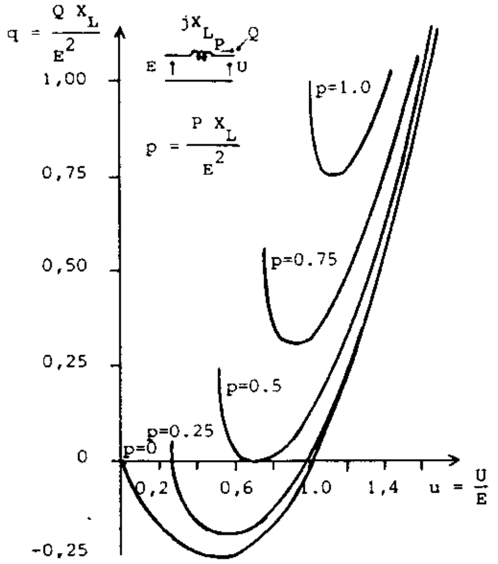


Figure 3 Q-U curves for a transmission line with active load as parameter.

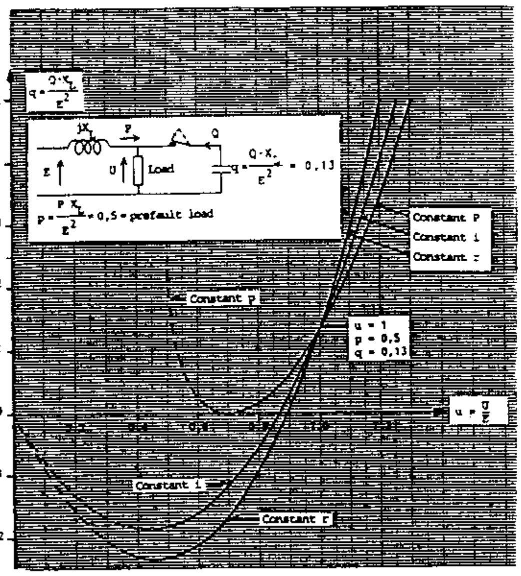


Figure 4 Q-U curves showing the influence of the load VS voltage characteristic on voltage stability.

period before the action of primary controls. Figure 4 shows the simple case, where a purely active load of 0.5 p.u. is fed through a purely inductive line. A reactive power injection of 0.13 p.u. at the receiving end results in a voltage of 1 p.u. If the reactive power injection of 0.13 p.u. is lost, the voltage at the receiving end will decrease. If the load is purely resistive, the voltage will settle at 0.89 p.u. If the load has constant current characteristic, the voltage will settle at 0.86 p.u. But if the load is constant, the system will reach the limit of voltage stability at a voltage of about 0.7 p.u.

A description of the voltage dependency of the load and characteristic values are given in |1|.

When making calculations on a transmission network it is normal to represent the load at a high voltage level. The dynamic behaviour of the load in such calculations comes from two different causes. The former is the dynamics of the consumers. These dynamics will sum up as a voltage-dependent load at the consumer voltage level and be transformed up to the voltage level at which the load is represented in the calculations. The latter is the dynamics of the system control, principally the automatic tap-changer control of the transformers. This will be dealt with in the following section on system control.

3. INFLUENCE OF SYSTEM CONTROL ON VOLTAGE COLLAPSE

Only the planning aspects of system control are to be considered.

Discussion has been divided into three parts, namely system voltage control, system power-frequency control and undervoltage load shedding control.

3.1 System voltage control

Referring to CIGRE SC 38-02 TF03 |2|, system voltage control is organized in the form of a structured system (automatic, to varying degrees), comprising three operational levels (which we shall refer to as "Primary, Secondary, and Tertiary"), and a forecasting level (referred to as "Security Forecast").

From this work it can be concluded that it is necessary to represent all primary voltage control actions correctly in planning calculations to prevent voltage collapse. The primary voltage control actions are due to AVR's of generators and synchronous compensators, static var compensators, automatic tap-changers, and capacitors and reactors switched automatically on voltage criteria.

A description of the reactive power sources including their response and control range is given in |3|.

The planner should consider the actual transformer control hierarchy, which controls are automatic and which are not, and be careful in representing the effect of the voltage control on the reactive power losses and generation of the elements in the sub-transmission and distribution network. Further the planner must investigate if the time grading of the transformer tap-changer control will result in a temporary overshoot of the load. In this case there could be a higher temporary demand for injection of reactive power than after action of the primary controls.

Referring further to the voltage control structure |2|, the aim of the secondary and tertiary voltage controls and also the security forecast studies is to find an optimal V-Q security-conditioned track in the daily operation of the system. One should therefore not include these control actions in the initial planning calculations to prevent voltage collapse. But it should be checked that these control actions will not result in a situation, which is worse than that which applies after action of the primary controls. Changes in the future secondary voltage control also have to be taken into account.

Further, it should be remembered that it is always easy for the planner to fix an optimal pre-fault condition, but it is not possible for the secondary and tertiary voltage control, whether automatic or manual, or by use of security forecast studies, at any time to operate the system exactly on the

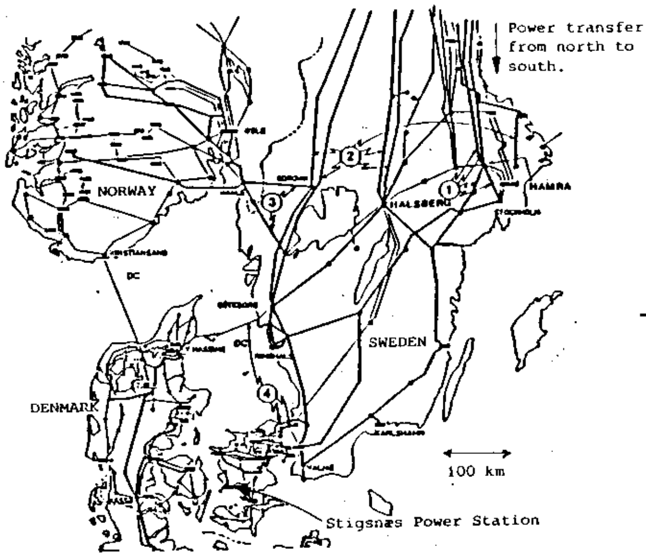


Figure 5

The southern part of the NORDEL-network showing the 400 kV lines, which were tripped in connection with the fault on 27th December,1983. See also the text of figure 6.

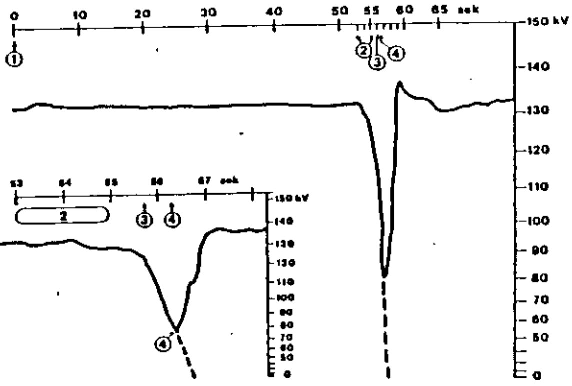


Figure 6

132 kV voltage measured at Stigsnæs Power Station on Sealand in Denmark during the disturbance on 27th December,1983, at 12.58 o'clock.

(1) Busbar falt at Hamra trips four 400 kV lines, of which 2 northward.

(2) Five 400 kV, seven 220 kV and all 132 kV lines, at 61° northern latitude, are tripped.

(3) Two 400 kV lines between the South of Norway and Sweden are tripped.

(4) One 400 kV line and two 132 kV lines between Sealand and Sweeden are tripped. About this time the Kontiskan line HVDC is tripped.

---- The voltage in the South of Sweden (collapses).

optimal track. This could call for a certain margin when planning reactive power resources.

Finally, demand on reactive power reserve for equalizing the deficit between an area and its surroundings, within a certain time (for instance 15 minutes), can influence the necessary reactive power resources.

3.2 System power-frequency control

What has been said about voltage control also applies to power-frequency control.

It is important to represent all primary power-frequency controls (fast automatic governor actions based on measurement of the local frequency) correctly in planning calculations to prevent voltage collapse.

Secondary power-frequency control (area control, automatic generation control (AGC), etc.) can come into planning in the sense that it has to be checked that the secondary control actions will not result in a situation, which is worse than that which applies after action of the primary controls. Changes in the future secondary power-frequency control also have to be taken into account.

3.3 Undervoltage load shedding control

Undervoltage activated load shedding can be used as an emergency means of counteracting the influence of tap-changer control. It is not normal practice to prevent voltage collapse for faults which are equal to or less severe than the chosen planning criterion, although in cases where there are reasons for delay in needed system augmentations it can be used temporarily. Its application would be to contain a local disturbance, perhaps in order to prevent a major network voltage collapse.

Whatever planning criterion is chosen, it is usually possible for multiple contingencies to occur which are more severe than it, although with a very small probability of occurence. There might not be sufficient justification to install transmission plant to prevent voltage collapse in such cases. However, it might be consistent for the utilities, who use underfrequency load shedding to cover severe generating capacity loss, also to use undervoltage load shedding, although the probability of it being used may be less in the latter case. The consequences of a major network collapse occuring need to be weighted against the costs of such controls.

The effectiveness of load shedding in an overloaded system can be seen in figure 3, where a reduction of p = 0.25 p.u. from p = 0.75 to 0.5 p.u. reduces the reactive power requirement by about 0.3 p.u.

A special case is industrial plants with local generation, which disconnect from the network under severe disturbances. This may be taken into account in the planning.

4. EXPERIENCES FROM SYSTEM DISTURBANCES LEADING TO VOLTAGE COLLAPSE

4.1 Example of a disturbance leading to voltage collapse

The Swedish contingency on 27th December, 1983 (figure 5) is a good example of how a voltage collapse develops.

Figure 6 shows the 132 kV voltage at Stigsnæs Power Station in Sealand in Denmark during this system disturbance, which started with a busbar fault at Hamra about 60 km northwest of Stockholm (figure 5).

The fault disconnected both sections of the 400 kV busbar. This fault is not considered as a dimensioning fault in planning.

As will appear from the description in figure 6, no other lines of importance are tripped immediately after the Hamra fault in the first 53 seconds. Then during the next 2 seconds a cascade tripping of all northerly lines takes place, and 1 second later the lines to Norway are tripped. The reason is the following: After the outage at Hamra, Halsberg is the most important feed-in substation to the Stockholm area (figure 5). Here a heavy voltage drop occurs, which reduces the load in the area. The automatic upward adjustment of the 10 kV voltage involves a gradual rise in load towards the normal value during the following period. Because of this the transmission from the north is increased, causing a further drop in the 400 kV voltage at Halsberg.

After 53 seconds the voltage is so low and the current so large that all northerly lines, and shortly after the lines to Norway, are tripped by the impedance relays. Hereby the southern parts of Sweden and Sealand are isolated with a relative production deficit between 50 and 60%.

As appears from figure 6, the voltage collapses first at Halsberg at t = 53 seconds and 3 seconds later in Sealand.

Fortunately, the interties between Sealand and Sweden are tripped by the impedance relays after 56.3 seconds, after which the network voltage in Sealand is restored (figure 6). At this time the network frequency is 49.0 hz, i.e. higher than the first frequency-activated load shedding step (48.5 hz).

What can the planner learn from this incident?

Firstly, if correctly planned, power systems only reach a condition of voltage instability after a large disturbance.

Secondly, the voltage collapse is a process, which often takes some time (55 seconds on this incident) after the initiating disturbance. It is, therefore, the objective of planning to specify the necessary local reactive supply or emergency controls in this period to cope with the actual contingency.

Thirdly, this local reactive supply has to be activated automatically by the local voltage, because the operator has no time to interfere in the developing voltage collapse.

Fourthly, behaviour under multiple contingencies is very important, when planning the response of reactive power sources and emergency controls.

This appears from figure 6 where, after t = 55.7 seconds, (point (3)) voltage collapse spreads the disturbance to a very large area. This happens, when South Sweden and Denmark/Sealand are isolated with a power deficit of 50 to 60% from the powerful systems in North Sweden and Norway. The generators in the isolated area have to deliver both the real and the reactive power deficits, until the frequency-activated load shedding has equalized the power deficit in the isolated area. The result is a very low system voltage in the island, where the generators are unable to control voltage, because their excitation systems are overloaded, and they lose stability due to small synchronizing forces before function of the frequency-activated load shedding. For the planner, when considering the response of the reactive power sources and emergency controls, it should be taken into account that these will help such an islanded system to survive.

Finally, the planner must not either forget that all (maybe even more) reactive resources, which are activated automatically when the voltage in the island is low, may need to be removed promptly a few seconds later, when the frequency-activated load shedding has equalized the active power deficit |6|.

4.2 Main results of the analysis made at EDF of 20 major disturbances in the world leading to voltage collapse

Before the disturbance: The system is weakened due to outages (lines or plants), maintenance or temporary operating conditions (for example due to the installation of new equipment). Moreover, the network is generally highly loaded.

The disturbance:

- In many cases (more than the half) the loss of only one more element (line or power plant) is sufficient to initiate the disturbance. In the other cases, successive faults have lead to loss of more than one element.
- In several cases the initial fault has been a busbar fault during maintenance operations in a substation.
- In all cases there is at least one event "which should never occur", e.g. human fault or misworking of equipment. These situations are difficult to forecast, because such events have very low probabilities.

Reconstruction of the system: Problems of high voltage levels are often mentioned.

5. PLANNING PROCEDURE AND GUIDE LINES TO PREVENT VOLTAGE COLLAPSE

The questionnaire on "Use of Reactive Power Optimization Techniques in System Planning" |4| indicates a need for a widely accepted procedure for dealing with the voltage collapse problem in system planning.

If correctly planned, power systems only reach a condition of voltage instability after a large disturbance. The process is essentially non-linear in that it involves limiting of generator excitation systems and SVC's and usually the attempted restoration of load by transformer tap-changing.

Therefore, a correct representation of all important system controls, including the control limits, is essential when planning against voltage collapse.

The objective of such planning is to specify the amount and response of the needed reactive sources at each busbar in the transmission system.

Special cases like for instance a far away large local motor load feed through a radial line, where the rapid response of the voltage dependency of the load, mentioned at the end of section 2.1, may lead to a rapid voltage collapse, are outside the scope of this paper. Such cases have to be treated separately by dynamic simulations, representing the fast time response of the load and the system control correctly.

5.1 Selection of contingencies and pre-fault conditions

The first problem is to identify the operation

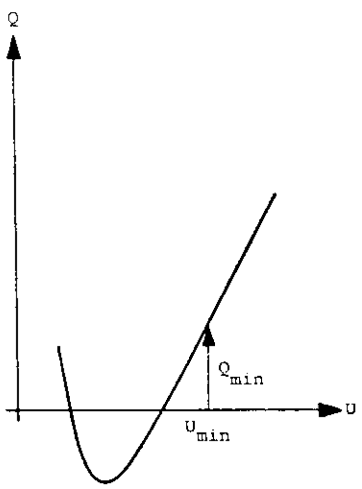


Figure 7. Post-fault constant power Q-U curve with intersections of the U-axis.

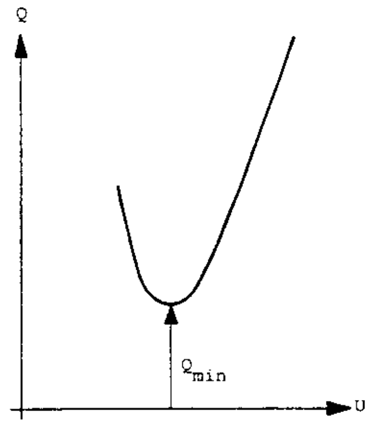


Figure 8. Post-fault constant power Q-U curve without intersections of the U-axis.

situation and the contingencies which may lead to voltage collapse. For small networks the situation can be well defined. For bigger networks it is not so easy, and systematic checking must be used to define the worst cases.

It should be noted that 3 to 4 utilities (|7|), App. 4) use n-2 security criterion in reactive power planning (i.e. generator plus line or transformer or two lines, whichever is more severe). When planning for transient stability, many utilities assume the most serious fault (3-phase) on the faulted component in spite of the fact that this has a low probability. When planning against voltage collapse, the fault severity (1-, 2-, or 3-phase) is of no importance. Therefore, using n-2 security criterion, when planning against voltage collapse, could be justified in order to obtain the same probability of failure in the system as one tries to obtain against transient instability, when using the most serious type of fault together with a n - 1 security criterion. In any case many utilities consider the loss of both circuits of a double-circuit line, or on a common corridor, to be a single contingency for reactive power planning.

The planner should be very careful when choosing the generators at low excitation by keeping as many capacitors as possible connected without exceeding the maximum network voltages, because increased reactive reserve on the generators reduces the risk of voltage collapse after the contingency. Other than high system voltage the only limitation is due to the underexcitation limiters on the generators. But operators will never run a network in that way. Therefore, the number of capacitors in the pre-fault conditions should be based on a realistic estimate of the operational practice with an adequate margin, for instance due to clock-switched capacitors etc. As a minimum it must be ensured that natural changes in the load, switching of capacitors, etc. and contingencies will not bring any generator to the limit of underexcitation with an adequate margin.

Further, it should be noticed that a relatively high pre-fault excitation on the generators gives a better transient stability margin and the most efficient voltage control in many other serious system disturbances (network separation, load rejection, load shedding, etc.) |6|. This can lead to the conclusion generally not to operate the system with low excitation on the generators.

In a long distance EHV transmission system generators often have to absorb reactive power. This condition is inadvisable due to reduced synchronizing power, and in such systems it is generally preferred to install shunt reactors close to the generators in order to load them with reactive power. During disturbances (line tripping, generator tripping, etc.) the shunt reactors may be switched out. In long distance systems it is necessary to achieve a near balance between reactive power sources and loads separately at the sending and receiving ends, because transmission of reactive power over such distances is very inefficient or, at high transfers, technically impossible.

5.2 Planning procedure

A practical procedure can be based on the Q-U curves, (figure 4 and |7|, App. 3), because these curves can be determined by means of a normal load flow program for a normally meshed network with the actual power units connected.

For the normal planning problem of finding the necessary reactive compensation to handle a contingency (i.e. busbar faults etc.) at or near a certain busbar, the procedure could be the following:

1. Starting from the pre-fault system make a series of load flow calculations for the steady-state post-fault system to find the Q-U curve for the busbar with all manual controllers frozen in the pre-fault settings. The method is to set the busbar to be P, U type with P = 0, and determine Q in or out of busbar to achieve a range of U values. The load should be the pre-fault load and the distribution of generation and contingency the worst case. The influence of all automatic primary controllers, especially automatic tap changers, should be taken into account. Special care has to be taken to correctly represent the action of generator AVR's in keeping voltage constant, while this is within the generator's capability, and further to limit the generator's Mvar production correctly. A suggestion for representing the response of the generators is presented in |7|, App. 5. A description of the

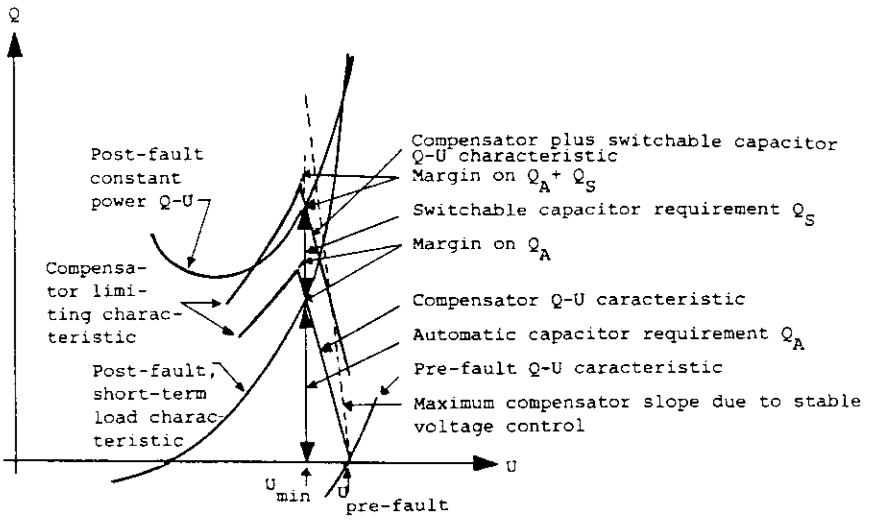


Figure 9. Procedure to determine the total need and the proportion of automatic and switchable reactive power injection at a certain busbar.

reactive power sources, including their response and control range, is given in |3|.

Figures 7 and 8 show two different Q-U curves.

2. The right hand intersection of the Q-U curve with the U-axis gives the "natural" voltage at the busbar. If the Q-U curves cut the U-axis, as shown in figure 7, with an adequate margin, it is an indication of no need for any further automatic infeed of reactive power to cope with the contingency in order to prevent voltage collapse. In such a case the necessary reactive reserve has come from existing sources (generators and/or SVC's). If there is a requirement for a minimum post-fault voltage, it might be necessary to supply a certain reactive power (Q-min in figure 7) automatically after the fault in order to keep the voltage above this minimum value.

   If the Q-U curve is above the U-axis, as shown in figure 8, it is an indication of need for an additional automatic infeed of reactive power Q-min to just prevent voltage collapse, and a greater amount to achieve a margin or to achieve a minimum post-fault voltage.

3. To determine the proportion of the required reactive power injection to be automatic (e.g. SVC or synchronous compensator) and the part to be switched with a small time delay, the following method can be used:

   Plot another Q-U curve, as shown in figure 9, for the short-term post-fault condition and therefore with the following changed assumptions:

   1) Load transformer taps locked at pre-fault settings

   2) Load vs voltage characteristic represented by measured values, e.g.

$$P = P_o \left(\frac{U}{U_o}\right)^a \qquad Q = Q_o \left(\frac{U}{U_o}\right)^b$$

   The faster acting generator voltage and excitation controls must, however, be represented as before and also, if important, the primary active power control.

   For practical load-voltage characteristics, this curve will be less onerous than the constant power curve and may give an intersection with the U-axis (which will show the immediate post-fault voltage).

   The tap changing of the load transformers will cause a gradual transition from this short-term Q-U characteristic to the steady-state constant-power characteristic. The time co-ordination of the tap changers at the various voltage levels should be examined to ensure that this transition will occur without overshooting the constant power characteristic.

   If the immediate post-fault voltage is not satisfactory or, indeed, if there is no intersection with the U-axis, then an automatic infeed of reactive power to the busbar must be considered. The required response of this compensation can also be represented on the Q-U plot, starting at the pre-fault voltage on the U-axis and intersecting the short-term characteristic at or above the required minimum voltage U_{min} on figure 9. The limiting behaviour of the compensation must also be considered, because this will determine the margin which is required.

   Summarizing and referring to the definitions in |5|, one could, for instance, plan the system shown in figure 9 by installing at the actual busbar a static var system (SVS) consisting of a static var compensator (SVC) with the value Q_A plus some margin and mechanically switched capacitors with the value Q_S, both controlled by a common SVS co-ordinator. Both Q_A and Q_S are values at U_{min} and must be converted to nominal voltage.

   One should be very careful about using a correct representation of the load vs voltage characteristic. The knowledge of this is often very uncertain, and in some cases it could be justified to choose the pessimistic value, constant power. This leads to the conclusion that the whole amount $Q_A + Q_S$ in figure 9 should be automatic, and indeed that some margin should be added to this amount.

The slope of the SVC must be such that it intersects with the Q-U curve well to the right of the minimum of the Q-U curve, and must not be steeper than allowed by stable voltage control under minimum short-circuit conditions. A check must also be made that the fast voltage-controlled mechanically switched capacitors will not cause excessive overvoltages, for instance in connection with system disturbances leading to load-rejection or load-shedding |6|. Further it has to be checked that the natural frequent changes in the transmission network due to load variations, system controls and system oscillations will not cause too frequent switching of the mechanically switched part of the static var system.

4. The amount of margin to be allowed from the minimum of the Q-U curve should be considered. Some possible guide lines are as follows:

   (a) Operation at or too near the minimum of the Q-U curve will be unsatisfactory, because small variations in system loading, tap-changing, etc. will cause large voltage variations with possible "hunting" of tap-changers.

   (b) A minimum slope of the Q-U curve at the final operating point could be chosen so that the switching of a capacitor bank would not cause too large changes in voltage.

   (c) It is possible for the voltage at the minimum point of the curve to be so low that maintenance of an adequate post-fault voltage (e.g. 95%) might give an adequate margin.

   (d) A fixed Mvar margin based, for instance, on some percentages of the total load of the area and on consideration of possible errors in forecasting this load might be appropriate.

   (e) Consideration of the sensitivity of the movement of the Q-U characteristic with changes (errors) in the system MW load might lead to an equivalent Mvar margin.

5. An alternative to the Q-U procedure for planning against voltage collapse which could be used in densely meshed networks with local generation on the primary network (|7|, App. 4, Belgium) is to install enough mechanically switched shunt capacitors to prevent any generator from overloading its excitation system under all planned contingency conditions. In such networks, voltage collapse can be avoided simply by releasing enough primary reactive reserve (excitation margin) on the generators by installing enough mechanically switched capacitors in the network.

5.3 Planning guide lines

In order to obtain a correct planning against voltage collapse, the following guide lines could be of value:

1. Define the criteria to be adopted regarding operation conditions and the contingencies to be taken into account in the planning.

2. Select potential dangerous operating conditions in accordance with the criteria. A way to rank the cases of interest is to calculate the busbar voltage sensitivity to the reactive power injections. Depending on the network, two ways can be followed:

   - to choose the contingencies to be studied and to define the worst operating conditions for each contingency.

   - to choose the operating conditions and to identify the contingencies which lead to a voltage collapse.

3. Carefully consider the possibility of a single event causing multiple contingencies. For instance line loading under worst possible power flow and voltage conditions should be checked against protective settings. It is necessary to develop a policy to either accept the consequences of a contingency more severe than planned or adopt a control strategy for dealing with this event (for instance, undervoltage-activated load-shedding may be a way to contain a local disturbance in order to prevent a major network voltage collapse).

4. Find out for one set of contingencies, by means of an optimal load flow program or by hand, the best and most economical location of compensation equipment in order to avoid voltage collapse. It should be noticed that, depending on whether the purpose of a substation is to transmit power through the high voltage network or to the low voltage network, the effectiveness of a Static Var System can depend highly on whether it is connected to the high voltage or the low voltage side of the transformers in the substation. The dimensioning in size and response of the reactive equipment can be done using the Q-U methodology.

5. Coordinate different solutions for different sets of contingencies.

6. Consider contingencies after action of the primary controls, and even in certain cases the influence of the secondary controls.

7. Carefully model the response of generators on an overexcitation demand from the system.

8. Carefully model the response of automatic transformer tap changers which are in series between the main system and the load to ensure that their time grading is such that load overshoot does not occur (i.e. correction of the lowest voltage before the higher voltage).

9. Consider the effect of the manual and automatic transformer tap changers which are in series between the main system and the load to ensure a representation of capacitors (and the network shunt capacitances) connected between the load and the main system.

10. Maintain practical margins from Q-U limits.

An example to illustrate the use of the Q-U method is given in Appendix 1.

6. REFERENCES

|1| CIGRE SC 38 WG 01 TF03: Load demand and modelling

|2| CIGRE SC 38 WG 02 TF03: Improvement of voltage control

|3| CIGRE SC 38 WG 01 TF03: Subitem 4. Reactive power sources

|4| CIGRE SC 38 WG 01 TF03: Answers to questionnaire on use of reactive power optimization techniques in system planning. August 1985.

|5| CIGRE SC 38 WG 01 TF02: Report on static var compensators.

|6| Planning a network with appendix structure to become an integrated part of a large transmission network.
J. Falck Christensen, J.S. Christiansen, T. Østrup, 1985. IEE Conference Publication, 255, 51-56.

|7| CIGRE SC 38-01 TF 03: Planning against voltage collapse (extensive version with all appendixes) October 1986.

APPENDIX 1

Example to show the use of the Q-U method to determine the reactive power infeed at a certain busbar

The example is the 400 kV system shown in figure 10A with five 400 kV lines feeding two substations equipped with one transformer (500 MVA) and two transformers (700 + 500 MVA) respectively with a short-circuit reactance of 25%. Both substations are connected to a common meshed 132 kV system with some generation. The reactive load in the 132 kV system is compensated, so there is no transfer of reactive power on the low voltage side of the 400/132 kV transformers. As regards voltage collapse the worst operating condition occurs, when the 650 MW unit is running at full load together with 700 MW power infeed from the larger neighbouring system. (In this operating condition trip of a single transformer will result in overload of the remaining transformers. This overload can be handled in due time by active power reserve in the 132 kV network). The worst contingency is a busbar fault indicated by "fault 1" in figure 10A. This fault disconnects the 700 MVA transformer and two 400 kV lines. The fault increases the reactive power losses by about 400 Mvar, which has to be supplied by generators far from the faulted busbar. The problem is to determine the necessary infeed of reactive power in this substation to prevent voltage collapse after the contingency. The infeed of reactive power is done on the low-voltage side of the transformers, which in this case has proved to be the most effective place.

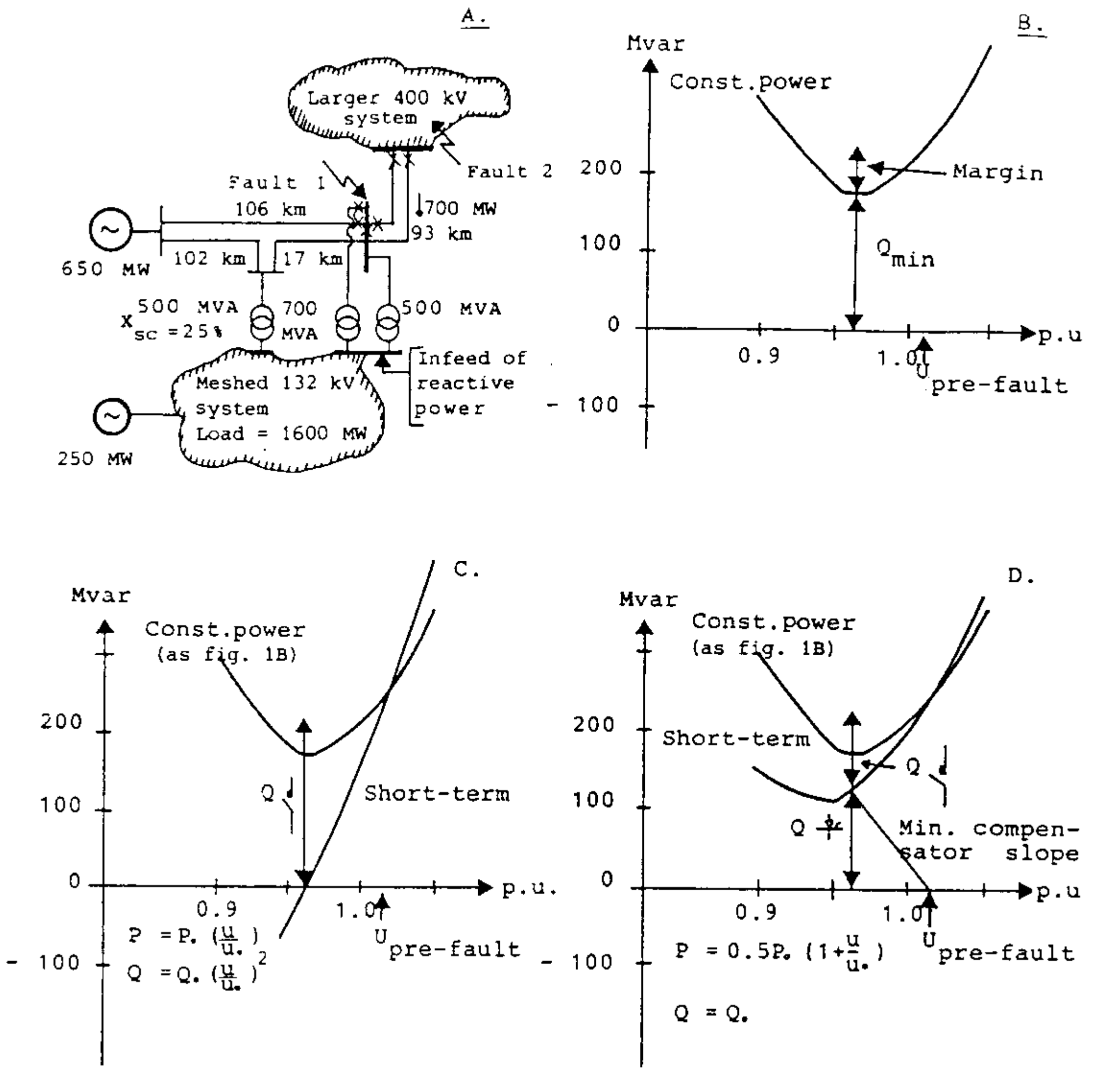
The post-fault constant power Q-U curve is shown in figure 10B, and it indicates a need for automatic infeed of about 200 Mvar at 0.96 p.u. voltage. In other examples the minimum can be at a lower value, maybe under an acceptable minimum voltage. In such cases the necessary reactive power infeed may be larger than the minimum value of the Q-U curve.

Figures 10C and 10D show two alternative short-term characteristics with the two different voltage dependencies of the load indicated in the figures. These short-term characteristics include neither initial transients nor the longer-term tap-changing. The curve after tap-changing is also shown in the figures and is similar to the one in figure 10B.

From figure 10C it appears that there is no need for thyristor-switched capacitors at all, but with the alternative load response in figure 10D a thyristor-switched part of about 120 Mvar is needed. The minimum slope of the compensator is also indicated, and it must be checked that the SVC is not unstable with this slope under minimum short-circuit condition.
As mentioned, the mechanically switched condensers can cause excessive voltage excursions. To check for this the system must be investigated under other operating conditions and contingencies. This is illustrated in figure 10E, which shows the voltage due to "fault 2" in the neighbouring system, which decreases the voltage at t = 0, resulting in automatic switching in of the capacitors. At t = 2 seconds the fault results in a load rejection due to tripping of the lines to the neighbouring system, resulting in an increase of the voltage.

As illustrated in figure 10E, the delayed switching of the mechanically switched capacitors can result in very high temporary overvoltages.

Very often such calculations will determine the part of the SVC, which has to be thyristor-switched.



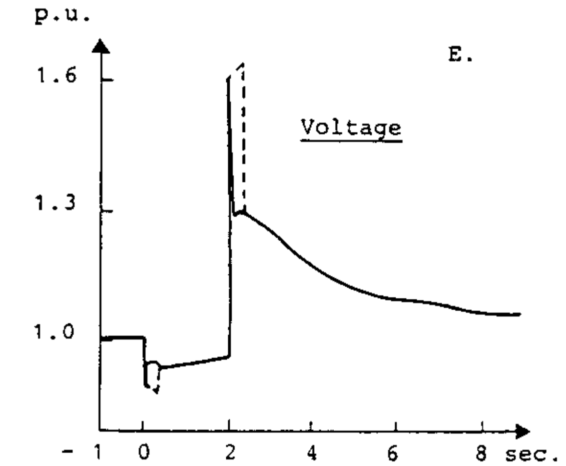


Figure 10
Example showing how the thyristor-switched and the mechanically switched parts of a SVC are determined.

A: The system

B,C, and D: Post-fault Q-U curves due to fault 1

E: Voltage due to fault 2 under other operating conditions

—— with all capacitors thyristor-switched

---- with all capacitors mechanically switched

APPENDIX 4
METHODS FOR REACTIVE POWER OPTIMIZATION

by

P.-A. CHAMOREL

Swiss Federal Institute of Technology,
Lausanne, Switzerland

1 - INTRODUCTION

Three questions arise with regard to the problem of optimization techniques and modelling :

a) Which methods are available for solving an optimization problem ?

b) How can these methods be used in reactive power planning ?

c) Are these methods sufficiently efficient for solving the general reactive problem, or is there any need for new methods and tools to be established ?

The reactive problem is fundamentally different for optimization of operation (short term or level 1) and planning (medium/long term or level 2) [1,5]. In the first case, the best operation condition must satisfy the security constraints and guarantee the voltage stability with existing equipment. For real-time application in a control center, computation time has to be reduced to a minimum. In planning, optimization must consider additional reactive sources, determine the types, locations and sizes of these sources from an economical point of view, and must also guarantee security during the most severe foreseen operational conditions.

During the last twenty years, numerous methods have been proposed for solving the reactive problem, such as successive ordinary loadflows, optimal power flow, sensitivity techniques, etc. The next section wants to point out the most typical methods capable of solving the reactive problem , essentially optimal power flow and sensitivity techniques. These methods are generally suitable to solve both operation and planning problems, but with different criteria and different costs in objective functions. However, the major problem remains the modelling and the application of these methods (definition of objectives, investment cost or priorities of reactive generation, reactive load forecasting and modelling, response of external systems, etc..)

2 - EXISTING METHODS

For optimization of steady state problems, J. Carpentier defines two main method families in his survey publication [1], based on the compactness of the method. A method is noncompact or sparse if it uses all the state and control variables in the optimization process. The method is compact if it provides an intermediate reduced model of the system, where objectives and constraints are only expressed in terms of control variables. Compact methods generally involve greater complexity, but allow wider applications, specially for large systems.

2.1 - Noncompact (or sparse) methods

In the noncompact methods, we can mention the **injections method** which was first proposed twenty years ago, where the optimality conditions were found using the Kuhn and Tucker theorem. Compared to present-day algorithms, this method was slow and had convergence difficulties. We can mention as well the **Hessian methods** [7-8] where inequality constraints are taken into account through penalty functions, the **Dommel-Tinney reduced gradient** family [9-11] where the gradient is expressed in terms of the control variables, the application of the **Wolfe reduced gradient**, which is a general mathematical programming method with linear constraints and a convex objective, the application of the **generalized reduced gradient** [12], which is a general convex programming method, and the application of **quadratic programming** [23].

2.2 - Compact methods

In the compact methods, we distinguish linear and nonlinear methods. The nonlinear model is generally solved using a general nonlinear programming method. We can mention the **differential injections method** [13-15], where the reduced model is built with first and second order sensitivities and is solved through the application of the **generalized reduced gradient**. The quadratic character of this technique remains valid over a large region with good convergence. Other compact nonlinear methods based on **gradient technique** or **quadratic programming** are proposed in [16-25].

In linear methods, the principle consists of linearizing the objective functions and the network equations. The reduced model is solved by using **dual or primal simplex algorithms** [26-42]. These methods may be improved by performing successive linear programming and by iterating with an AC loadflow. L.P. techniques are well suited for security in short term operation with minor changes of the control variables. Several methods combine **gradient techniques with linear programming**. Different objectives can be used, such as minimum var deviation, minimum MW-losses, maximum voltage profile, etc... However, minimum investment cost and MW-losses are difficult to handle by L.P. due to the nonlinearity of this problem. For var planning, capacitors are not continuous variables and the problem necessitates a discrete solution with **mixed integer programming techniques** [41,43].

2.3 - Sensitivity methods

A **Sensitivity method** based on the ratio $\delta V/\delta Qgen$ is proposed in [44] to determine critical voltage. **Voltage collapse indicator** methods are proposed in [35,36,45-48], based on a single optimal power flow with additional sensitivity computations on $\delta Qgen/\delta Qload$ (1 = perfect voltage stability, infinite = voltage collapse).

2.4 - Dynamic problems

Static var systems properly controlled and located are an effective way of stabilizing both low and high frequency electromechanical oscillations and extending transmission limits. A method based on **eigenvalues techniques** is proposed in [49].

3 - EXTERNAL REACTIVE EQUIVALENTS

In interconnected systems the results obtained from steady-state system analysis studies strongly depend on the representation of the external system behaviour. Therefore, an external equivalent reflecting the quasi steady-state response of the external system has to be added to the studied system. Numerous papers describe the theory and application of active and reactive external equivalent reported to boundary busses of the study system [50-55]. These equivalents are capable of simulating the external reactive response in case of modifications or disturbance in the studied system.

4 - CONSTRAINTS AND OBJECTIVES OF OPTIMIZATION

The following constraints and objectives can be handled by existing methods, principally based on steady state constrained optimal power flows. Several methods simultaneously perform a full coordination with active power. Others consider separetely the two problems by decoupling active and reactive power with some minor loss of optimality. Various publications are mentioned proposing solution techniques of each specific objective.

4.1 - Control variables

a) Location, size, limits and regulation range of control variables such as :
- generator reactive power output according to real power output
- switchable reactive compensation devices (serie and shunt capacitors, serie and shunt reactors)
- continuous controllable compensation devices (synchronous compensators, static var compensators)
- LTC transformer tap positions

4.2 - Security constraints

b) Equality constraints on active and reactive power balance

c) Inequality constraints or limits on :
- steady-state bus voltage magnitude
- steady-state branch real power/reactive power/current flow
- reactive power reserve

4.3 - Economical criteria

d) Postponement of new investments [general]

e) Minimum investment cost of new units (planning only) with:
- linear cost function [17,27-29,32-36,38-40]
- piecewise linear cost function [27,29,38,39]
- quadratic/convex cost function [6-15,18,22-25]
- discrete cost function [41,43]

f) Medium/long term expansion planning, and comparison of energy saving with new device capital costs, including choice of power factors of planned generators, choice, location and timing of new reactive compensation devices (planning only) [17,40,41]

g) Minimum MW losses with reactive sources [7-10,12-17,19,21-25,30,31,38-42,45]

h) Minimum MW losses with optimal setting of transformer ratio [10,12-15,19,20,22-25,30,31,41]

4.4 - Voltage control and stability

i) Minimum total reactive production or absorption of existing equipment and maximum reactive spinning reserve (operation only) [22,23,25,38,39].

j) Minimum Mvar change for preventative or corrective rescheduling or minimum number of units rescheduled (operation only). [27-29,31-34,37-39,42]

k) Minimum tap changers deviation (operation only) [27,28,31,37-39]

l) Secondary control with eventually proportional reactive production or
absorption of existing equipment (operation only) [26]

m) Sensitivity computation to prevent voltage collapse [35,36,44-48]

n) Reduction of steady-state and transient overvoltage after load ejection or switching operation

4.5 - Maximum transmission capacity

o) Maximum voltage profile for MW-losses reduction and transmission capacity increase [12,35,36,49]

4.6 - Optimal stability and damping

p) Increase of transient stability, damping of electromechanical oscillations [49]

4.7 - Voltage quality

q) Optimal choice of reactive compensation devices for quality of the voltage (HVDC converters, flicker problems at mills or furnaces, etc.)

5 - CONCLUSION

Numerous techniques exist to solve efficiently the reactive optimization problem for **steady state conditions**. Traditionally, the VAR planning has been solved by a trial-and-error approach which uses an ordinary loadflow program in a large time consuming procedure. The solution found using this approach is not optimal, but the best of tried solutions. It is clear that in order to determine an optimal solution in a efficient way, the use of efficient optimization techniques is necessary.

Generally speaking, the var planning is an optimal reactive source expansion problem formulated as a mixed nonlinear-integer programming problem. There exists no general mathematical programming technique for directly solving this class of problems, especially when applied to large scale systems. However, the optimum allocation of reactive sources can be solved by decomposing it into a two-level hierarchical approach [5]. This approach takes advantage of the natural distinction between the VAR dispatch of the available sources in system operation (level 1), and the VAR allocation and sizing in system planning (level 2). The optimal reactive dispatch problem and the source expansion problem can be solved separately and alternatively in an iterative procedure. The general problem is thus transformed into a sequence of non-linear (level 1) and mixed-integer (level 2) programming problems.

The level 1 problem is a conventional optimal power flow problem formulated as a non-linear problem. It can be solved by successive ordinary load-flows, non-linear programming methods and successive linear programmings.
Non-linear programming techniques are well suited for non-linear cost functions and MW-losses minimization. These techniques present a good convergence and remain valid over a large region.
L.P. techniques are well suited for security analysis with minor changes of the control variables. The objective function is approximed by a linear or piecewise linear function. L.P. methods provide fast and reliable solutions with low computer time. It is an efficient tool for large system with numerous constraints and small perturbations of the reactive variables.

The optimal reactive source expansion (level 2) is a mixed linear-integer programming problem with 0,1 variables and use branch and bound-type algorithms.

More techniques should be developed for **transient and dynamic** studies. For instance, simulation techniques are essentially used in order to control the behavior of the system. Sensitivity methods give good indications on critical voltage.

The major problems remain the **application** and the **implementation** of these methods, such as :

- choice of objectives,
- cost definition,
- technical constraints and security criteria,
- data acquisition,
- exchange of information between control centers,
- system modelling,
- subsystem optimization
  (voltage level, geographic or ownership subdivisions)
- external equivalents,
- reactive load forecasting, etc...

Answers to the questionnaire concerning the analytical techniques, objective functions and technical constraints are summarized in figures 1 and 2.

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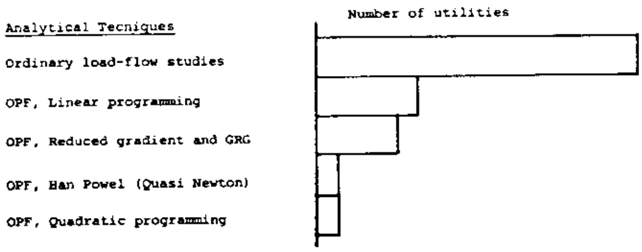
Utilities	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Analytical techniques :																				
Ordinary load flow		x	x	x		x	x		x	x	x	x		x	x	x	x	x	x	x
OPF, linear programming	x							x					x				(x)			
OPF, Generalized RG		x							(x)											
OPF, Reduced gradient					x						x							(x)		
OPF, Quasi Newton (Han Powel)													x							
OPF, quadratic programming															x					
Objective functions :																				
Minimum investment or compens.	x	x	x		x	x	x	x	x	x	x		x	x	x	x		x	x	x
Minimum transmission losses	x		x		x		x	x	x				x			x		x		x
Maximum voltage profile	x																			
Minimum reactive interchange												x								
Technical constraints :																				
Steady state voltage	1	4	-	1	2	2	1	1	1	1	1	1	1	1	3	2	1	1	1	1
Line energisation overvoltage	-	-	-	-	-	-	2	-	4	3	2	6	2	3	-	1	-	-	-	-
Switching of compens. plant	-	-	1	2	3	-	4	-	5	6	-	4	-	-	5	3	-	-	2	2
Generator loading limits	2	1	-	3	1	1	3	3	3	2	4	3	-	2	2	6	2	2	3	3
Reactive power reserve	-	2	-	-	4	-	5	-	2	4	5	2	3	-	-	5	4	3	4	4
Transmission line overloading	-	3	-	-	-	3	6	2	6	5	3	5	-	-	1	4	3	4	-	5
Dynamic problems	3	-	-	-	-	-	-	-	7	-	-	-	-	-	4	-	-	-	5	6

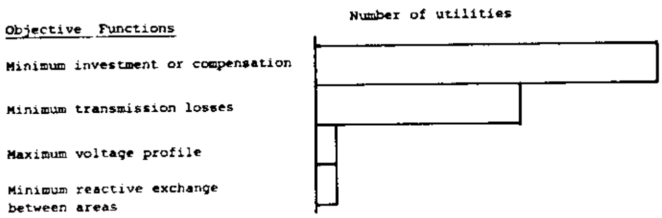
x ---> in operation

(x) ---> under development

Figures represent the order of priority

Fig. 1 - Answers to Questionnaire - Appendix 5





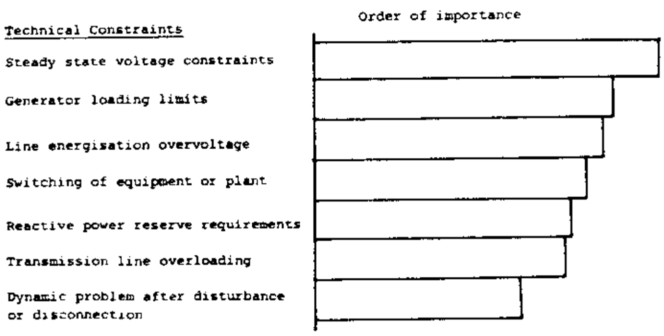


Fig.2 - Answers to Questionnaire - Appendix 5

APPENDIX 5

USE OF REACTIVE POWER OPTIMIZATION TECHNIQUES IN SYSTEM PLANNING

by

N. FLATABØ
EFI
Norway

A. INVERNIZZI
ENEL
Italy

INTRODUCTION

The Study committee No. 38 on "Power System Analysis and Techniques" was set up at the Paris session in 1982.

The scope of work for Working group No. 1 "Reactive Power Analysis and Modelling" has been defined as follows:

> "To study the characteristics of reactive generation and compensation requirements of network as they impact the performance of electrical power systems."

WG No. 1 has organized its work into different Task Forces.

The term of reference for Task Force No. 3 on "Optimization Techniques and Analysis of Reactive Power Compensation" has been defined as:

> "To examine criteria and techniques available for optimal reactive compensation levels in networks including assessment of different networks, different reactive compensation devices, optimization objectives and techniques for analysis, including non-linear and linear programming approximations. The work includes such constraints as unit costs, technical performance, reliability, variable demand and generation patterns and reserve allocation, in order to meet selected technical or overall cost objectives. The work will conclude in guidelines for optimal planning and utilization of reactive power compensation."

TF3 started its work with a survey of optimization methods and tools used by power companies in practical planning of reactive power compensation equipments.

The questionnaire was seeking information about the organisation and objectives of reactive power planning within the overall system planning cycle, the extent of power system representation, and methods/techniques used to solve the planning problem. Based upon the observed trends further work will be carried out by TF3 to provide guidelines on the use of such techniques for optimal planning and utilisation of reactive compensation within the system. Possible improvements to the techniques will also be considered.

Some twenty utilities of fifteen countries replied to the questionnaire. The replies of some countries refer to a group of several utilities, as in the case of Australia, Belgium, Switzerland and Norway.

Table 1 lists the utilities taking part in the survey, together with some data of their own electric system.

It should be emphasized that since replies generally concern the planning of reactive compensation requirements in large meshed networks (with several hundred buses and lines), problems concerning the reactive power compensation of long radial transmission systems (a.c. or d.c.) are not considered, except in a few minor cases.

1. SUMMARY

1.1 Planning objectives

Generally, the replies to the questionnaire indicate that the main objective of reactive power planning is that future networks should be able to observe a set of technical constraints, under both normal and emergency operating conditions.

All the countries participating stressed that observance of the limits of variation in steady-state voltage, consequence upon load variations and the switching of network components, is the main technical constraint. In addition to this constraint, many countries also mentioned observance of generator and transmission line loading limits and of reserve margin requirements, during both reactive generation and absorption.

Replies to the questionnaire also indicate that in planning reactive power, some countries obeserve both line energization overvoltage constraint and maximum voltage step changes after switching of compenation plants. A few replies also stress the need to forestall the risk of instability.

Many of the countries taking part in the survey also consider system economy improvement to be a main planning objective. This objective is in some cases indentified with the reduction of network losses.

In order to achieve the aforementioned objectives, many countries stated in their replies to the questionnaire, that they applied planning procedures that consist in the optimization of different objective functions. Many replies indicate the minimization of the amount of reactive compenation to be installed, or of the investments required is practised by the countries that took part in the survey. Some countries after the optimization procedure referred to above, evaluate the amount of compensation that enables losses to be minimized. A few other countries state they use more sophisticated objective functions by which investment cost and cost of losses are minimized at same time.

The utilization of special objective functions, which probably refer to specific grid structures, is also mentioned. For example:

- maximization of voltage profiles;
- minimization of reactive power flows on transmission, and interconnection lines between different areas.

The replies received generally stress the fact that optimization is not limited to the observance of possible financial contraints; only in one case is reference made to the need to establish job priorities, not forgetting budget ceilings.

The replies to the questionnaire indicate that, in order to ensure observance of the technical constraints described above, N-1 security criteria are generally applied, which involves considering the loss of one line (single or double circuit), or of one generator, or of one compensation plant. The procedure in respect of the loss of the largest generator and the most heavily loaded transmission line (security criterion N-2) is sometimes applied in some countries. On the other hand, the application of probability criteria to reactive power planning (probability of outages, energy not supplied) is also mentioned in few replies.

1.2 Planning organization

In the overall planning procedures described by all the countries taking part in the survey, it appears that priority is always given to generation planning, some countries also stressing that generator power factors are fixed at this stage. The next thing to be planned is network development, an activity that is generally subdivided into two stages, the first taking into account active power transmission requirements, while the second is concerned with voltage control and reactive compensation requirements. Many of the replies received emphasize that the two stages are carried out with different timing and with different horizons: active power planning is developed over a longer period (for example, six years), while reactive power planning is studied over a shorter period (for example, two to four years).

Some replies, however, mentioned that active and reactiver power planning are carried out at the same time, this procedure being applied when reactive compensation requirements may affect the selection of network development alternatives, or if they enable some active network reinforcement (new lines, new transformers, etc.) to de deferred.

Reactive power planning is carried out for different load conditions; thus, all countries stated that their procedure took into consideration both peak load and light load situations. For some countries, these conditions concern the same day; if so, the analysis is generally extended to other days of the year (for example, a winter peak day and a summer peak day). For some other countries, on the other hand, these two load conditions concern different days. Moreover, a few countries stated that they examined the minimum load condition of the year, while others mentioned that they also studied intermediate load conditions (for example 0.85 of the peak) and others again emphasized the need to consider specific network configurations and generation dispatching such as to stress the transmission grid to the maximum.

Replies to the questionnaire indicate that the reactive power planning procedure is, in many cases carried out for a horizon year that, as has already been said, is generally that preceding the year considered in planning network development. In some cases only one or two years following the one in question are considered.

Many replies state in that the study is repeated for intermediate year, especially when important changes of the network structures occur. In some cases, reactive compensation analysis is extended to different load forecasts and to different development network alternatives.

1.3 Modelling of system

In reactive power planning the network might be divided into subsystems. Most of the answers indicate that the network is geographically subdivided based on ownership. Many answers also indicate a division based on different voltage levels. A few answers indicate subdivisions due to organizational or technical reasons. In some countries the whole network is taken into account when planning reactive power compensation.

The external systems are by about half of the contributors represented as generators, loads or as active and reactive injections. Some of the answers indicate that the external system is represented exactly, while external equivalents are used by others.

The most common load model is a fixed P and Q representation, but fixed impedances are also used in some cases. Voltage dependent models ($P \cdot V^{\alpha}$ and $Q \cdot V^{\alpha}$) are used by few of the utilities answering the questionnaire.

The lower voltage networks are mostly represented as loads on secondary side of the transformers, which are connected to voltage levels above 130 kV.

The reactive load forecast is in most cases connected to the active load forecast by assuming a Q/P ratio. The forecasts are mostly carried out for high and light load in summer and winter periods.

As the load models are rather simple they give good accuracy on steady state load flow analysis, while model improvements are needed and wanted in transient and voltage dependent analysis.

The controllable MVAr supplying devices are generators, synchronous compensators and SVC systems. In steady state the generators are in most cases represented as P, V nodes on high voltage level or behind a rectance on low voltage level. Sometimes the generators are represented as P,Q-nodes. The limits on reactive power generation are in some cases taken into account by changing the P,V-node to a P,Q-node representation when the limits are reached. One answer indicate that the Q-supply is represented as a fixed reactive or capacitive impedance beyond limits of Q, while others indicate that limits are handled manually. The synchronous compensators are represented as generators without active power production, and that is also the most common representation of the SVC systems.

The uncontrollable MVAr supplying devices are saturated reactors, normal reactors and shunt capacitors. By the utilities answering the questionnaire the use of saturated reactors are indicated by one for temporary overvoltage reduction. The most common representation of normal reactors and shunt capacitors are fixed impedances, while P,Q- and P,V-node representation is mentioned in some cases. The reactors and shunt capacitors are switchable in many cases.

1.4 Analytical solution techniques utilized in reactive power planning

The most common analytical technique used in reactive power planning is successive ordinary load flow. Optimal load flow is used by some of the utilities, but in many cases in addition to ordinary load flow. A few answers indicate that optimal load flow is under development.

When successive ordinary load flow is used, very few of the answers indicate that additional features are included, but some are mentioning limit checks on reactive power, voltage and line flow.

The optimal load flow programs are based on either a reduced gradient method or linear programming. Quasi Newton and Quadratic programming methods are also used.

Very few have indicated other optimization methods, but penalty function methods and special optimization program for radial feeders are mentioned.

The size of the systems in which optimization techniques are used, were in most cases in the range of 100-500 buses with less than 75 generator buses and 100 compensation buses. A few answers indicate network sizes up to 1000 busbars and above with the same number of generator busbars.

In the optimization process the investment cost and transmission losses are in many cases included in the criterion to be minimized, while reactive power reserves, voltage limits, and transmission capacities are handled as constraints or taken care of manually. The contingency analyses are carried out by successive optimization and the overall cost calculations are carried out manually, but a special VAR PLAN program is mentioned in one case.

Primary voltage control is taken care of by a P,V-node representation of generators, synchronous compensators and SVC busbars. In optimization the secondary voltage control can be a result of calculations, and handled by the programs. Tap changer positions can be calculated by the optimization programs, but manually adjustments are also mentioned. The division of reactive power generations between generators and other VAr-supplying devices can be decided upon the basis of loss minimization. Use of successive ordinary load flow is, however, the most common tool in the primary and secondary voltage control because very few have optimization methods in practical use.

Optimization methods are often developed for medium and long term expansion planning purposes, but frequently used in operation planning also.

The future network stages are mostly taken into account by separate studies, but one answer indicates that the optimization is carried out by one study covering the whole planning period.

As ordinary load flow is used in reactive power planning, this is also the most common tool in the study of voltage variations, voltage stability, and reactive power reserve conditions. Sensitivity techniques are used by few. The sensitivity techniques mentioned are:

1) (dQ_g/dQ_r) which is the resultant reactive power generation sensitivity in the network to variation of reactive load at a specific busbar.

2) A criterion based on the

$$\left| \frac{U_i}{E_i} \right|$$

relationship where U_i is the actual voltage and E_i the voltage at zero load condition.

3) $(dV/dQ)_i$ which is the voltage to reactive power input sensitivity at a specific node.

Stability calculations are carried out by some utilities to choose between the different VAr-supplying devices to be installed, to analyse the reactive power support from generators during outage condition, and to analyse the ability of units to absorb reactive power during light load periods.

The reported experiences of the analytical techniques in planing are very much dependent on the analytical tool used. Ordinary load flow is most common in planning, and the experience from the use of this kind of program is mostly good, but also indicated cumbersome and time consuming due to manual work necessary, and gradually becoming inadequate.

The optimization methods in use are considered adequate in terms of computing time, and handling of constraints, but improvements are necessary in the coordination of results, and modelling of the external system. LP-programs are useful in the study of big networks (1000 nodes), but the criterion is not well suited for loss minimization. In voltage stability studies a more accurate load modelling is necessary to give greater understanding of the problem.

More automatic techniques to get network diagnostics are desireable, and automated techniques would also permit more alternatives to be investigated.

The analyses are in most cases carried out on big computers, but minicomputers are used in some cases.

1.5 Names of utilities participating in the questionnaire

* Electricité de France (A)
* Combined answers of Belgian Utilties (B)
* The Chubu Electric Power Company (Japan) (C)
* The Kansai Electric Power Co, Inc.(Osaka,Japan)(D)
* The Tokyo Electric Power Co, Inc. (Japan) (E)
* Czechoslovakia (F)
* Tennessee Valley Authority (USA) (G)
* Combined Swiss Utilities Network (H)
* Swedish State Power Board (I)
* Combined Norwegian Utilities Network (J)
* The National Power System of the Socialist Reublic of Romania (K)
* Central Electricity Generating Board (CEGB,UK) (L)
* ENEL (National Authority for Electr.) (Italy) (M)

TABLE 1 Survey of utilities

NAME OF UTILITY	INSTALLED CAPACITY [MW]	TOTAL AMOUNT OF ENERGY PRODUCTION [TWH]	COMPENSATION INSTALLED				CHARACTERISTICS OF NETWORK	
			SHUNT CAPACITORS [MVAR]	SHUNT REACTORS [MVAR]	SYNCHRONOUS COMPENSATORS [MVAR]	SVC [MVAR]	VOLTAGE LEVEL [LV]	N. OF BUSBARS IN LOAD-FLOW
EDF	85000	310	11600	2400	-860/+1600	0	400 225	160 760
BELGIAN UTILITIES	11700	52	900	0	0	0	400 225/150 70	26 191 274
CHUBU E.P.C.	16177	77.3	4909	3860	0	0	500 275 154	8 62 250
KANSAI E.P.C.	23518	93	4837	9145	90	0	500 275 154	17 73 9
TOKYO E.P.C.	41000	157	14300	8730	50	0	500 275 154	30 100 30
CZECHOSLO-VAKIA	18000	81.5	128	1080	740	0	400 220	35 26
TVA	32077	114	4961	1640	240	0	500 161 115	27 323 17
SWISS UTILITIES	[illegible]100	55	60	198	-110/+144	0	400 220	35 137
SWEDISH S.P.B.	30070	120	2040	5550	-345/+670	-200/ +200	400 220 130	100 100 50 - 600
NORWEGIAN UTILITIES	22000	100	1640	250	1657	570	420 300 132	70 100 150
SOCIALIST REPUBLIC OF ROMANIA	18000	71	1000	780	540	0	400 220 110	22 75 900
CEGB	51000	212	575	8970	-250/+575	-510/ +570	400 275 132	130 190 230
ENEL	50000	180	10000	150	200	0	380 220 150/132	110 280
NORTHERN STATES POWER	6412	28.7	930.5	660	10	0	500 345 230 161 115	1 17 6 16 123
NEW YORK POWER POOL	21186	122	1625	2150	364	0	765 345 230 138 115	2 72 33 111 607
IBERDUERO S.A.	5720	15	0	1140	0	0	400 220 145	16 78 99
HIDROELEC-TRICA ESPANOLA S.A.	7318	14.7	932	760	610	0	400 220 132	13 31 77
ELKRAFT	3596	11	790	150	0	0	400 132	33 217
AUSTRALIA AND NEW ZEALAND (5 UTILI.)	29530	97.5	3062	1935	950	-60		

* Siemens AG, (West Germany) (N)
* New York Power Pool (USA) (O)
* Northern States Power (USA) (P)
* Iberduero, S.A. (Spain) (Q)
* Hidroeléctrica Española, S.A. (Spain) (R)
* ELKRAFT Power Company Ltd., Copenhagen(Denmark) (S)
* Comb. response from Australia and New Zealand (T)

2\. BACKGROUND INFORMATION

2.1 Name of Utility. (A)
Electricité de France

2.2 System size - General Information.

2.2.1 Installed capacity .... 85000 MW

2.2.2 Total amount of energy production .... 310 TWh (1984)

2.2.3 Total amount and type of reactive power compensation installed

Shunt capacitors .... 11600 MVAr
" reactors .... 2400 MVAr
Synchronous compensators 860/+1600 MVAr
SVC .... 0 MVAr

2.3 Characteristics of Network.

2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow

Voltage levels	No. of busbars in loadflow
400 (X) kV	... 160 .....
225 (Y) kV	....760 .....
90/63 (Z) kV	... - .....

2.1 Name of Utility. (B)
Combined answers of Belgian Utilities

2.2 System size - General Information.
2.2.1 Installed capacity .(1st Jan.-84)... 11700 MW
2.2.2 Total amount of energy production .. 52 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 900 MVAr
" reactors .... MVAr
Synchronous compensators .... MVAr
SVC .... MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 400-150/225 -70kV.

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	... 26 .....
150/225 (Y) kV	... 191 .....
70 (Z) kV	... 274 .....

2.1 Name of Utility. (C)
The Chubu Electric Power Company (Japan)

2.2 System size - General Information.
2.2.1 Installed capacity .... 16177 MW
2.2.2 Total amount of energy production .. 77.3 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 4909 MVAr
" reactors .... 3860 MVAr
Synchronous compensators .... MVAr
SVC .... MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).500-275-154-77-33 kV

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
500 (X) kV	... 8 .....
275 (Y) kV	.... 62 .....
154 (Z) kV	... 250 .....

2.1 Name of Utility. (D)
The Kansai Electric Power Co.,Inc.(Osaka, Japan)

2.2 System size - General Information.
2.2.1 Installed capacity (March 1984) ... 23518 MW
2.2.2 Total amount of energy production . 92.793 TWh (1983)
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .....(March 1984) 4837 MVAr
" reactors ...."..... 9145 MVAr
Synchronous compensators ..."..... 90 MVAR
SVC ...."..... 0 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).
500, 275, 154, 77, 33, 22, 6.6, 0.2, 0.1 (kV)

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
500 (X) kV	... 17 .....
275 (Y) kV	... 73 .....
154 (Z) kV	... 9 .....
Generator	... 31 .....

2.1 Name of Utility. (E)
The Tokyo Electric Power Co., Inc. (Japan)

2.2 System size - General Information.
2.2.1 Installed capacity .... 41000 MW
2.2.2 Total amount of energy production . 157 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 14300 MVAr
" reactors .... 8730 MVAr
Synchronous compensators .... 50 MVAr
SVC .... 0 MVAr
(As of March 31, 1984)

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmissission system (in descending order).
500 kV -275 kV -154 kV -66 kV - 22 kV

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
500 (X) kV	... 30 .....
275 (Y) kV	....100 .....
154 (Z) kV	.... 30 .....
66 kV	.... 40 .....

2.1 Name of Utility. (F)
Czechoslovakia

2.2 System size - General Information.
2.2.1 Installed capacity .... 18000 MW
2.2.2 Total amount of energy production . 81.5 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 128 MVAr
" reactors .... 1080 MVAr
Synchronous compensators .... 740 MVar
SVC .... 0 MVar

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 400-225-110- 22 kV

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	.... 35 .....
220 (Y) kV	.... 26 .....

2.1 Name of Utility. (G)
Tennessee Valley Authority (USA)

2.2 System size - General Information.
2.2.1. Installed capacity .... 32,077 MW
2.2.2. Total amount of energy production 114 TWh
2.2.3. Total amount and type of reactive power compensation installed *)
Shunt capacitors .... 4961 MVAr
" reactors .... 1640 MVAr
Synchronous compensators .... 240 MVAr
SVC .... 0 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 500,161,115,69,49kV

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
500 (X) kV	... 27 .....
161 (Y) kV	... 323 .....
115 (Z) kV	... 17 .....
69/46 kV	Radial Studies Only

Tot. No.of busbars in loadflow - 2293

*) TVA delivers power to 160 distributors at the wholesale level. This figure only represents the reactive power devices installed on the TVA system. Section 3.2.1 describes the reactive power requirements imposed by the distribution system that TVA supplies.

2.1 Name of Utility. (H)
Combined Swiss Utilities Network

2.2 System size - General Information.
2.2.1 Installed capacity .... 10133 MW
2.2.2 Total amount of energy production . 50473 TWh (1983)
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... +50 MVAr) at 380
" reactors .... -172 MVar) and
Synchronous compensators .. +144 MVAr) 220 kV
SVC .... 0 MVAr) levels
Synchronous generators -3240 to +4545 MVAr)

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
380 (X) kV	... 35 .....
220 (Y) kV	... 137 .....

2.1 Name of Utility. (I)
Swedish State Power Board

2.2 System size - General Information. (1983)
2.2.1 Installed capacity .... 30070 MW
2.2.2 Total amount of energy production .... 120 TWh/year
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 2040 MVAr
" reactors .... 5550 MVAr
Synchronous compensators ..... +670/-345 MVAr
SVC .... +200/-200 MVAr
Synchronous generators .... MVAr
(An additional +170 MVAr at industries)
Series capacitors .... 3600 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).
400 kV/220 kV/130 kV and limited consideration tp 70 kV.

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	... 100 .....
220 (Y) kV	... 100 .....
130 (Z) kV	.. 50-600 ...

2.1 Name of Utility. (J)
Combined Norwegian Utilities Network

2.2 System size - General Information.
2.2.1 Installed capacity .... 22000 MW
2.2.2 Total amount of energy production ... 100 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 1640 MVAr
" reactors .... 250 MVAr
Synchronous compensators .... 1657 MVAr
SVC .... 579 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 420, 300, 132

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
420 (X) kV	... 70 .....
300 (Y) kV	... 100 .....
132 (Z) kV	... 150 .....

2.1 Name of Utility. (K)
The National Power System of the Socialist republic of Romania.

2.2 System size - General Information.
2.2.1 Installed capacity .... 18000 MW
2.2.2 Total amount of energy production ... 71 TWh
2.2.3 Total amount and type of reactive power compensation installed *)
Shunt capacitors .... 1000 MVAr
" reactors .... 780 MVAr
Synchronous compensators .... 540 MVAr
SVC .... MVAr

*) In the networks of the power supplier.

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 400 kV,220 kV, 110 kV.

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	... 22 .....
220 (Y) kV	... 75 .....
110 (Z) kV	... 900 .....

2.1 Name of Utility (L)
Central Electricity Generating Board (CEGB, UK)

2.2 System size - General Information
2.2.1 Installed Capacity 551,000 MW
2.2.2 Total energy production 212 TWh (1983/84)
2.2.3 Total amount and type of reactive power compensation installed:
Shunt reactors at 400 kV 2000 MVar
Shunt reactors at 275 kV 1900 MVar
Shunt reactors at 132 kV 120 MVar
Shunt reactors connected to 13 kV tertiary windings of 400/132 kV and 275/132 kV transformers 4740 MVAr
Reactive absorption capability due to tap-staggering groups of MVar 400/132 kV and 275/132 kV transf. 1960 MVAr
Shunt reactors at 33 kV and 11 kV 210 MVAr

Shunt capacitors at 400 kV Nil
Shunt capacitors at 275 kV Nil
Shunt capacitors at 132 kV 270 MVAr
Shunt capacitors connected to 13 kV

tertiary windings of 400/132 kV and 275/132 kV transformers 260 MVAr
Shunt capacitors at 33 kV and 11 kV 45 MVAr

Series capacitors Nil

Total reactive power absorption capability from shunt reactors 8970 MVAr (not incl.tap stagger)

Total reactive power generation capability from shunt capacitors 575 MVAr

Synchronous compensator absorption capability 250 MVAr

Synchronous compensator generation capability 575 MVAr

Declutched gas turbines absorption capability 768 MVAr

Declutched gas turbines generation capability 1305 MVAr

Static variable compensator absorption capabililty 60 MVAr

Static variable compensator generation capability 120 MVAr

Saturated reactor type compensator absorption capability 450 MVAr

Mechanically switched capacitor (assosiated with the saturated reactor compensators) generation capability 450 MVAr

These items will be commissioned 1985/6.

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).
400, 275, 132 kV (33 kV is sometimes modelled)

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	... 130 .....
275 (Y) kV	... 190 .....
132 (Z) kV	... 230 .....

2.1 Name of Utility. (M)
ENEL (National Authority for Electricity, Italy)

2.2 System size - General Information. *)
2.2.1 Installed capacity .... 50000 MW
2.2.2 Total amount of energy production . 180 TWh
2.2.3 Total amount and type of reactive power compensation installed *)
Shunt capacitors .... 10000 MVAr
" reactors ..(only one plant).. 150 MVAr
Synchronous compensators .... 200 MVAr
SVC .... / MVAr
*) In the networks of the power supplier.

2.3 Characteristics of Network. *)
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 380 kV, 220 kV, 150-132 kV. The last voltage level issued only for regional networks.

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
380 (X) kV	... 110 .....
220 (Y) kV	... 280 .....
150-132 (Z) kV	... / .....
	(For national network)

No. of busbars in loadflow
... 20 .....
... 30 .....
... 290 .....
(For regional networks)

*) The figures are given for the planned network development (year 1988).

2.1 Name of Utility. (N)
Items of utilities. SIEMENS AG (West Germany)

2.1 Name of Utility. (O)
New York Power Pool (USA)

2.2 System size - General Information.
2.2.1 Installed capacity .... 21186 MW
2.2.2 Total amount of energy production.. 122 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 1625 MVAr
" reactors .... 2150 MVAr
Synchronous compensators .... 364 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).
(765, 345, 230, 138, 115)

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
765 (X) kV	2
345 (Y) kV	72
230 (Z) kV	33
138 kV	111
115 kV	607
Less than 115 kV	453
	1278 TOTAL NYPP

2.1 Name of Utility. (P)
Northern States Power (USA)

2.2 System size - General Information.
2.2.1 Installed capacity
.... Summer 5,950 MW - Winter 6,412 MW
2.2.2 Total amount of energy production 28,675 GWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors ....930.5 MVAr
" reactors .... 660 MVAr
Synchronous compensators .... 10 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).
500, 345, 230, 161, 115, 88, 69, 34.5 kV.

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
500 (X) kV	1
345 (Y) kV	17
230 (Z) kV	6
161 kV	16

115 kV	123
88	3
69	379
34.5	3
24	2
23	2
22	2
20	3
18	1
13.8	10
7.2	1

2.1 Name of Utility. (Q)
Iberduero, S.A. (Spain)

2.2 System size - General Information.
2.2.1 Installed capacity .... 5720 MW
2.2.2 Total amount of energy production... 15,0 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... MVAr
" reactors .... 1140 MVAr
Synchronous compensators .... MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	16
220 (Y) kV	78
145 (Z) kV	99

2.1 Name of Utility. (R)
Hidroeléctrica Espanola, S.A. (Spain)

2.2 System size - General Information.
2.2.1 Installed capacity .... 7318 MW (1984)
2.2.2 Total amount of energy production... 14,7 TWh
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 932 MVAr
" reactors .... 760 MVAr
Synchronous compensators .... 610 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order).

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Voltage levels	No. of busbars in loadflow
400 (X) kV	13
220 (Y) kV	31
132 (Z) kV	77
66	161

2.1 Name of Utility. (S)
ELKRAFT Power Company Ltd., Copenhagen (Denmark)

2.2 System size - General Information.
2.2.1 Installed capacity .... 3596 MW
2.2.2 Total amount of energy production... 11 TWh (incl. 2.3 TWh import (1983))
2.2.3 Total amount and type of reactive power compensation installed
Shunt capacitors .... 1983: 450 MVAr
1985: 790 MVAr
" reactors .... 150 MVAr
Synchronous compensators .... 0 MVAr

2.3 Characteristics of Network.
2.3.1 Voltage levels (X,Y,Z kV) of transmission system (in descending order). 400/132 kV

2.3.2 Number of busbars included in your load flow analysis at each voltage level.

Own network	90 nodes (3 on 400 kV)
Neighbouring areas	160 nodes (30 on 400 kV)
Primary network of rest of NORDEL	400 nodes (220-400 kv)
Rest of NORDEL transmission	600 nodes (130 kV)
Total	1250 nodes

Of course both size and details of the network used for calculation differ with the nature of the problem investigated.

2.1 Name of Utility. (T)
Combined respons from 5 Australian generation/transmission authorities, 1 New Zealand generation/transmission authority and 1 Major Australian/International consultant.

The numbers in front of the anwers (4/7) means 4 out of 7 utilities have given this answer. Utility (T).

3. REACTIVE POWER PLANNING

3.1 Objectives of planning.

3.1.1 Describe the main objectives of reactive power planning in your system, (technical or security requirements, economical achievements).

A: Observance of the technical constraints (defined in 3.1.3) in most of the operation conditions that can be encountered, in normal and emergency case.

B: The main objectif of reactive power planning is to get a sufficient power reactive reserve on generators in order to avoid their overloading in case of tripping.

C: 1) Adjustment of voltage level of electric power system in case of usual or unusual times.
2) Supply of reactive power of consumers and power system.
3) Loss minimization by reactive power flow adjustment.

D: It is a technical requirement. That is to maintain proper voltage of system.

E: 1) To maintain the adequate voltage at each part of the system.
2) To reduce the transmission losses.

F: Technical requirements - the main requirement is the preservation of voltage in technical limits ($\pm$ 5% U_{nom}).

G: 1) Voltage Control - Steady State
- Switching Voltage Control
2) Reduction of Real Losses.
3) Limit Reactive Absorbed by Generators (For Stability Reasons)

H: - Security (constraints of voltage and branch current).
- Minimum cost investment and minimum MW losses.

I: The primary objective with reactive power

planning is to build a system which is technically sound and secure. This encompasses the application of reactive power equipment that is necessary from the technical point of view as the first step and secondly solution of system technique problems in which the use and control of reactive power is compared to other means and methods.
The second priority is economic considerations including optimizations.
The result is a system solution that should be considered as secure.

J: Maintain satisfactory voltage levels during normal and (n-1) outage conditions.

K: The objective of reactive power planning is to achieve safe operation for the transmission system and to minimize the power transmission and distribution costs.

L: Main objectives:

1) To enable steady state voltages to be maintained on 400 kV system between 0.975 p.u. and 1.025 p.u. (when planning 4 yr. ahead), and between 0.95 p.u. and 1.05 p.u. on the 275 kV system.
2) To ensure that voltage step changes following double circuit fault outages are within 12% of the starting voltage.
3) To ensure sufficient reactive power reserves.

M: The overall planning process is dividen into two main steps:
- The objective of the first step is to meet technical and security requirements.
- The one of the second step is to improve system economy.

N: Voltage regulation in all load conditions of system, including contingency. Economic load flow.

O: The main objective of reactive power planning for the NYPP system is to provide acceptable voltage reponse for pre- and post-disturbance conditions and to maximize economic transfer capability.

P: The main objectives of reactive power planning in our system are voltage control, system security and economic savings (occasionally transient voltage control). This is accomplished by:
a) Providing sufficient capacitive or reactive support to allow operating control during normal operations.
b) Providing sufficient reactive power to maintain the system voltage during severe disturbances when a major import of emerggency power is required.
c) Using capacitors to defer expensive transmission facilities.
d) Reducing losses and capital expenses by placing reactive sources as close as feasible to the reactive loads.

R: 1. To maintain the voltages within their limits during normal and (n-1) outage conditions.
2. To minimize the active power losses and satisfy as much as possible a given voltage profile.
3. To maintain the stability with the margin of reactive power available in the generatting units.

S: The system has to withstand certain contingencies. 'Extreme' economic dispatch situations will stress the system most. Thus we find the economic optimum between installation of reactive power and the matching limitation of the economis dispatch.

T: (7/7) Recognise that economy is important in some form.
(4/7) Also recognise security as a constraint.
(6/7) Mention the achievement of technical objectives (eg voltage regulation).

3.1.2 <u>Describe the objective functions used in optimization of reactive power installations. (minimum losses, minimum compensation, minimum investment cost, etc)</u>

A: Minimum compensation + highest voltage profile.

B: Minimum compensation.

C: Minimum losses. (Within the satisfactory good. Minimum investment. Adjustment of system voltages.)

D: The reactive power flow on 500 kV backbone lines to be zero.

E: Minimum investment.
Minimum losses.

F: Minimum investment cost.

G: Attain satisfactory voltage levels with minimum compensation and minimum investment costs (including the effects of losses).

H: Minimum investment cost and MW losses.

I: The main objective function used in optimization of reactive power installation is minimum life cycle cost. This includes consideration to the following items:
1. Investment cost
2. Operation and maintenance
3. Reactive power reserves
4. Network and equipment losses

J: Minimum investment cost.

K: The objective function is to minimize the investment cost of the transmission network and the operation costs for supplying active and reactive power.

L: Objective functions:
The system is divided into zones, and it is prefered that each zone has a reasonable balance between reactive power generation (by the network) and reactive power absorption. Hence it is desired to keep inter-zonal reactive power transfer to a minimum. The cheapest overall solution is normally sought.

M: - First step: Minimum investment cost.
- Second step: Minimum losses.

N: Minimum compensation under consideration of contingencies.

O: The objective function is to achieve the security and economic objectives with minimum investment cost.

P: The two major objective functions used in choosing reactive power installations are mini-

mizing losses and minimizing investments. Losses are minimized by:
a) Placing capacitors as close as possible to the reactive loads
b) Requiring the distribution system to maintain unity power factor
c) Using small dispersed capacitive sources spread around the system.
Investments are minimized by: a) above process to reduce losses; and b) siting capacitors at specific locations to defer major transmission developments.

Q: Minimum generation cost for a given demand.

R: Minimum losses adding penalty functions (these include voltage and reactive generation constraints).

S: See 3.1.1.

T: (4/7) Use minimum overall cost (capital + discounted losses) - (1/4) also include cost of load not supplied in equation.
(2/7) Use minimum investment cost.
(1/7) Use minimum compensation.

3.1.3 <u>Describe the technical constraints applied (in order of priority), such as:</u>
* steady state voltage contraints
* line energisation overvoltage constraints
* constraints due to switching of compensation plant
* generator loading limits
* reactive power reserve requirements
* transmission line overloading

A: 1) Steady state voltage constraints (insulation levels, statutory voltage levels, nuclear power plants auxiliaries supply).
2) Respecting generators loading limits.
3) Preventing the risks of unstability.

B: - Generator loading limits
- Reactive power reserve requirements
- Transmissiion line overloading
- Steady state voltage constraints

C: Transmission line overloading less than 2% of voltage change in case of opening or closing of voltage adjusters.

D: 1) Steady state voltage constraints
- required voltage at customers
- insulation strenght of machines in system
2) Constraints due to switching of compensation plant: Change of voltage by switching must be less than 2%.
3) Generator loading limits: P.F. must be more than 95%.

E: 1) Generator loading limits
2) Steady state voltage constraints
3) Constraints due to switching of compensation plant
4) Reactive power reserve requirement

F: 1) Generator loading limits.
2) Steady state voltage constraints.
3) Transmission line overloading.

G: 1) Steady State Voltage Constraints
2) Line Energization Overvoltage Constraints
3) Generator Loading Limits
4) Constraints Due to Switching of Compensation
5) Reactive Power Reserve Requirements
6) Transmission Facility Overloading

H: 1) Steady state voltage constraints (particularly at light load, voltage profile to high).
2) Tranmission line overloading.
3) Generator loading limits.

I: The technical constraints applied are in order of priority:

1. Steady state voltage. Limits: +5%, -5%. In exceptional cases -10%.

2. Reactive power reserve.
This is important at the receiving end of long transfer system from hydro resources to consumption area.
3. Generator loading limits.
Small cosφ at units in the load area (=0.85). Correspondingly at hydro resources cosφ is larger (~0.9).
4. Line energization overvoltage.
5. Switching of compensation plant.
<0.6% at frequent switching.
<2% at rarely occurring switching.
6. Transmission line overloading.
7. Network stability at disturbances.

J: 1. Steady state voltage constraints
2. Generator loading limits
3. Line energisation overvoltage constraints
4. Reactive power reserve requirements
5. Transmissison line overloading.
6. Constraints due to switching of compensation plant

K: The technical constraints considered are:
- to observe the steady state voltage constraints
- to avoid energisation overvoltages of the 400 kV lines.
- to avoid transmission line overloading
- to maintain the generator steady state stability
- to assure the required reactive power reserve.

L: Order of priority:
1. Steady state voltage constraints
2. Reactive power reserves
3. Generator loading limits
4. Constraints, due to switching compensation plant, including automatic switching due to faults
5. Transmission line overloading
6. Line energisation over voltage constraints

M: A. steady state voltage contraints
B. line energisation overvoltage constraints
C. constraints due to switching of compensation plant
D. generator loading limits
E. reactive power reserve requirements
F. transmission line overloading
First "A" and "B", then "E".

N: 1. steady state voltage contraints
2. generator loading limits
3. line energisation overvoltage constraints
Dependent on actual transmission project.

O: The technical constraints applied in the analysis are:
1. Transmission line overloading
2. Generator loading limits
3. Steady state voltage constraints
4. Transformer tap settings
5. Dynamic voltage response to disturbances

6. Switching surge overvoltage constraints

P: The technical constraints applied are:
1) Line energization overvoltage constraints.
This constraint applies only to a few long EHV lines on our system. In these cases reactors are added to the line to reduce both transient and steady-state voltages on the open end of the line during energization. The constraint is to keep the voltage levels below 80% of the breaker's or transformer's BIL and within the energy dissipation capability of the equipment's surge arresters.
2) Steady-state voltage constraints.
Our voltage constraint is based on our ability to control our distribution voltage with LTC transformers. On any transmission voltage bus that has a distribution transformer connected to it, our voltage constraint is to stay within +5% and -10% of the transmission busses nominal voltage.
3) Constraints due to switching of compensation plants.
This is limited to a ± 3% change in voltage for any one switching event except for installations used to prevent system voltage collapse after a major system emergency.
4) Transmission line overloading.
Compensation will be added if a line's overloading is a result of excessive reactive power flow.
5) Reactive power reserve requirements.
Sufficient reactive support is provided to meet system voltage criteria upon the loss of the largest reactive power source (a generator) with a major system disturbance. This is both for capacitive capability during system peak load and inductive capability during the system minimum load.
6) Generator loading limits.
The capability of our generation to provide reactive power is included in our analysis of reactive power needs. We assume our generation can provide a specific amount of reactive power without significantly impacting its real power output. This capability is then included as part of our system reactive reserve requirement.

Q: a. Steady state voltage constraints
b. Generator loading limits
c. Transmission line overloading
d. Reactive power reserve requirements

R: 1) Steady state voltage constraints
2) Generator loading limits
3) Reactive power reserve requirements
4) Transmission line overloading

S: Steady state voltage constraints.
Constraints due to switching of compensation plant.
Generator loading limits.
Reactive power reserve requirements.
Voltage control in connection with load shedding.
Voltage control in connection with frequency activated load shedding.

A certain priority between these is unjustifiable.

T: (7/7) include steady state voltage constraints
(6/7) include switching limits
(5/7) include generator loading limits
(5/7) include reactive power reserves
(1/7) added transformer overloading to list.
(1/7) added voltage rise due to disconnection of generator.
Most considered that all technical constraints included should be met by the planned system without compromise.

3.1.4 Describe the financial constraints applied, and the background for these.

A: Calculation of the amount of additional shunt capacitors which could be economically installed (profitability rate).

B: Nihil.

C: Comparison of loss reduction and compensator's installation determination of installation points with refer to scale merit.

D: There is not a clear financial constraint.

E: -

F: Minimum investment cost for new compensation means. There are no financial constraints if additional shunts are needed from technical point of view.

G: Accomplish job in most economical manner considering budget ceilings and priority of jobs needing to be done.

H: -

I: Minimum life cycle cost is desired (see point 3.1.2). The investment cost will in most cases be no constraints.

J: None.

K: Paying off the expense for the reactive power compensation by the time specified in the norms for the national economy or earlier.

L: Financial Constraints:
There are no direct constraints (budgetry etc.). The economic case is subordinate to the technical need for the scheme proposed. However, consideration is given to re-siting existing plant if justifiable, to reduce costs.

M: Usually not applied, since new installations regard only shunt capacitors that require investments distributed in time.

N: Avoidance on HV-switchgear whenever possible.

O: No specific finacial constraints are applied to the analysis of reactive compensation requirements. However, recommendations for reactive compensation must be economically justifiable with minimum investment cost.

P: The financial constraints applied to reactive compensation are no different than those applied to any new capital facility. Reactive compensation is considered one alternative to solving system concerns.

Q: The cost is only considered in the objective function.

R: -

S: No.

T: (2/7) Require to demonstrate a real rate of return on investment (8% and 10% resp).

(2/7) Minimises total cost (investment - discounted savings).
(1/7) Minimises investment cost only (ie immediate tariff effect).

3.1.5 Describe the security criterion used (n-1 security, loss of load probability, others).

A: n-1 security:
For each studied situation of the network, technical constraints have to be satisfied in case of outage of any 400 kV line or any generator, after the acation of the secondary voltage control, the voltage evolutions due to such an outage can be computed (see 4.10). So it is possible to define the reactive power reserves required in normal case (see 4.6).

B: a) N-1: Tripping of one line (or transformer) or one generator.
b) N-2: Tripping of one generator + another generator or one line (or transformer). We accept 10% overloading on lines and transformers but no steady state overloading generators.
c) Tripping of a 400 kV busbar. In this case we accept 10% overloading on lines bu 15% on transformers.

C: (n-1) security.

D: We didn't consider security criterions. But our planning has some room for actual system operation.

E: To maintain the adequate voltage at the single contingency (n-1 security).

F: (n-1) security. In special cases (n-2) security

G:
1. N-1 security.
2. Probability of occurrence
3. Stability considerations
4. Limit reactive output of nuclear generating units to increase security of transmission system for offsite power supply.

H: n-1 security.
n-2 for some particular cases.

I: In planning for shunt capacitors and reactors, a safety margin is included allowing one unit to be out of operation. Transmission planning is based on certain design criteria e.g. busbar faults shall not cause load shedding. In combination with this an other method is also used i.e. evaluation of the estimated interruptions of supply.

J: n-1 security.

K: The security criterion used is the loss of the largest generator unit and of the most important transmission line for the subsystem considered.

L: Security criteria: For the main inteconnected system the credible fault outages are defined as:
1) a single circuit overhead line
2) a double circuit overhead line
3) a designated pair of single circuit overhead lines concurrently during the defined winter season
4) a single circuit cable
5) a section of busbars or mesh corner
6) a supergrid transformer
7) a reactive compensator
8) the most onerous single system infeed

For reactive power planning we normally simulate condition (2) for several double circuits, selected from past experience, and consider this to be the "worst credible" fault outage for all demands. Other conditions may also be simulated as circumstances dictate (e.g. 6) and 7)).

M: A n-1 security criteria is applied in implicit form by providing suitable reserve margins on generators and by limiting the permitted variation range of voltage.

N: N-1 criterion.

O: The voltage criteria used the NYPP system states that "No bus voltage shall fall below its pre- and post-contingency low limit or rise above its pre- and post-contingency high limit. Generally the low voltage limit is .95 per unit and the high voltage limit is 1.05 per unit.

P: Security criterion used.
We do not use any probability based criterion with reactive power planning. Any reactive power planning is conducted as one alternative out of many to keep the system operation within established criteria.

Q: n-1 security.

R: n-1 security criterium.

S: The NORDEL dimensioning criteria.

T: (6/7) Use n-1 criterion, (2/6) allow for prior outage of specified reactive plant. These (2/6) also require n-2 security at low load levels or for specified duration to allow maintenance. (1/6) also includes loss of load probability.
(1/7) Uses cost of energy not supplied.

3.2 Organizing of planning.

3.2.1 How is the reactive power planning coordinated with the planning of active power.

A: The horizons of planning are
- n+8 for the power plants
- n+6 for the 400 kV network
- n+5 for reactive power

B: Generation planning is studied separately. Cos phi of generators are fixed at these stage. Reactive problems are studied together with active problems when planning the network.

C:
1) Calculation of reactive power demand by correlation factor of forecasted active power.
2) Installation of compensation plant among system.

D: We plan acative power at peak load time in each ten year. And, we plan reactive power at peak load time in the two year future using the active power planning of that time.

E: The reactive power planning is usually carried out on a year-by-year basis according to the planning of active power. Both are implemented by the same section.

F: The active power planning has the priority.

The reactive power planning is one kind of the planned network control.

G: 1. Key loads are maintained at constant power factor to enhance power transfer capability of transmission lines. Reactive power planning is an integral part of planning active power needs.
2. Plan to require 0.95 power factor of customers for peak conditions and not higher than unity during monthly offpeak periods. This will be put in the rate structure and, in effect, encourage TVA distributors to install and properly operate switched shunt capacitors.

H: Reactive power planning is separately achieved.

I: Primary concern is the generator cosφ. Reactive power planning is secondary.

J: Planned separately.

K: Power plant and electric network planning on the one hand and reactive power planning, on the other hand, are actually decoupled. For decoupling the respective planning operations, some basic principles were observed concerning the influence of the reactive power on the system development.
For the generation and transmission network development established in accordance with the active loads, the required reactive generation and consumption means are forecasted for 5-year horizons.

L: Reactive power planning is coordinated with the overall annual planning cycle, which looks up to six years ahead for the transmission system. Reactive compensation is planned four years ahead, since this is the minimum "lead time" for such plant to be commissioned on the system. System reinforcements required to satisfy active power constraints are conducted over the whole planning period.

M: Active power is planned 5-8 years before, reactive power is planned 3-4 years before. Thus reactive power is planned after active power. In the case of particular projects (very long-lines), active and reactive power are planned at the same time.

N: According to increase of active power. Consideration of outages of most important lines.

O: Reactive power planning assumes a deterministic load and dispatch load and dispatch which is economically dispatched (active power) so that all transmission facilities are within their thermal constraints.

P: When reviewing system problems, adding reactive support is considered along with other alternatives in correcting potential voltage or overload problems. Usually, because adding reactive support only works for a couple of years, it is used to defer major cost alternatives.

Q: First at all the needs of generation and transmission are considered to satisfy the active demand forecasted. After that, the needs of reactive compensation are studied with the results of the first step.

R: They are coordinated in overall transmission planning, mainly through a.c. load flow studies.

S: According to NORDEL recommendations generators are dimensioned cos♦ = 0.85.

T: Planning Depts of most authorities are small and reactive planning is included with transmission planning, but may be carried out as a secondary activity after the active power planning is finalised, except where the reactive installation is an alternative to transmission (eg deferring an augmentation).

3.2.2 <u>Which periods of the year are studied (peak load, light load, others).</u>

A: Three periods are studied (winter, summer, mid-season), each of them at peak load and light load.

B: a) Peak load.
b) Intermediate load (~85% of peak load) with a high level of generation in the 400 kV system (Nuclear Power) and a low level of generation in the 150 and 70 kV systems. In this case, some regions are very sensitive to any loss of generation.

C: 1) Peak load (of average of 3 days of maximum demand in summer time).
2) Night load in off peak seasons.

D: a) Peak load time (2 or 3 P.M. of weekday of August).
b) Bottom load time (5 or 6 A.M. of the 2nd of January).

E: Peak load.
Light load.

F: 1) Winter load peak
2) Winter night
3) Summer load peak
4) Summer night
5) Summer minimum load

G: 1) Summer Peak
2) Winter Peak
3) Minimum Load for Year
4) Minimum Load for Peak Day
5) Eighty Percent Summer Peak Load

H: Peak load (Wednesday, mid-February at 11 h 30 a.m.) Light load (Sunday, mid-August at 4 h 30 a.m.)

I: Both peak load and light load, but in addition also other situations with intermediary load. In the latter case the total load level is intermediary but protions of the network is heavily loaded, e.g. transmission from hydro resources during the spring flood.

J: Peak load.
Light load.

K: The peak load conditions studied are: winter evening peaks and summer morning peaks. The minimum loading condition is obtained for a red letter-day summer-night light load.

L: The periods studied include those corresponding to summer minimum, winter peak, and approximately 85% of winter peak demands. The latter case is that for which much oil fired generating plant is shut down for economc reasons, and since it is concentrated in the south of the country, gives rise to high north to south power flows and consequent low voltages.

M: Six different load conditions are considered:
- Peak and light load condition in the winter working day.
- The same for the summer working day.
- Yearly minimum load.
- Off-peak hours (12.00-14.00) in the summer working day. (This load condition is examined because all the shunt capacitors are in service while load is lower than peak.)

N: Maximum and minimum load conditions, energizing of system after breakdown.

O: Analysis is performed on various load conditions including summer peak, winter peak and summer light load.

P: Our reactive power studies look at both peak load conditions and system minimum load conditions.

Q: The peak and light load periods are mainly studied.

R: Two periods of the year are studies (winter and summer) each of them at the moment of peak load and of light load of the same day. The yearly minimum load of the system is not studied.

S: Both peak load and low load and any load between where the economic dispatch stresses the sytem most in relation to the reactive reserve.

T: (7/7) Study peak load
(6/7) Also study light load
(3/7) Also identify other critical load conditions
(1/7) Also studies representative loads for loss evaluation.

3.2.3 <u>How is the seasonal time load variations included.</u>

A: By the choice of the studied periods (see 3.2.2). Comparisons of the results between the different periods are done in order to optimize the tap changes of the transformers or the characteristics of the materials.

B: Not considered - See 3.2.2.

C: Check of the most heavy loaded time and night loaded time.

D: We do not consider it.

E: The seasonal load variations are within the range between peak load and light load above mentioned.

F: See cl. 3.2.2.

G: By projecting loads (real and reactive) based on recent historical trends.

H: -

I: Seasonal time load variations represent the maximum total loading (winter) and minimum total loading (winter) and minimum total loading (summer), but intermediary loading is also considered as mentioned in item 3.2.2.

J: Not included.

K: See item 3.2.2.

L: Minimum system demand occurs in July, winter peak demand occurs in January.

M: Different load conditions are considered (see 3.2.2).

N: Normally not included.

O: Due to the load diversity of our system, sensitivity analysis of the effect of seasonal load variatio has been performed using specific summer and winter peak load conditions.

P: Most of our capacitor installations are in small blocks and have both radio control and voltage control. This greatest need for capacitors is during a local area's system peak, this is the season's needs are covered by the automatic controls.

Reactors are planning for at the system minimum (except those required to control line energization voltage) and again controls are used to provide the needed amount of reactive power during other time periods.

Q: The seasonal time load variation is taken into account considering the peak and light load conditions in winter and summer.

R: The seasonal time load variation is taken into account with the two periods studies (winter and summer load).

S: See 3.2.2.

T: (Authorities interpreted this question in different ways.)
(4/7) Concentrate mainly on peak and light load extremes.
(2/7) Base intermadiate studies on the load-duration curve.

3.2.4 <u>If you have defined base load cases, how are they established.</u>

A: * The base load cases have been chosen to take into account daily and seasonal time load variations.
* For each period, different operation conditions are considered, each of them is defined by a set of unavailable 400 kV lines and power plants; they are selected in a random sample generated by a Monte-Carlo method with a criterion of active losses (computed with a DC load flow on the 400 kV network).

B: Not considered.

C: 1) Active Power: Forecast in base of demand forecasted by JAPAN electric power investigation committee.
2) Reactive Power: Forecast by past demand and growth rate in August.

D: In the peak load case, we use the active power planning of it. In the bottom load case, we estimate the state of the system by ones of a few past years.

E: -

F: The total active power of the system is distributed proportionally into consumption nodes according to their consumption in the 110 kV network (and at lower voltage levels). Thus, each consumption node of the transmission network has a certain established balance of active power. The reactive power balance is calculated for this active power balance according to the structure of sources and of consumption. The consumption in nodes is taken according to the reached values in the past reality and to the detailed future development plans.

G: Each individual model is updated each year by using new loads for each substation and new generation schedules based on economic loading. Network models are changed when there are changes in plans.

H: By measurement of active and reactive loads.

I: Maximum or minimum load during the time period of one hour.

J: Based on energy pronoses for the Norwegian System.

K: The base load cases were defined under 3.2.2. We further specify that in Romania the summer-morning peak includes high irrigation loads, while the peaking hydro-power plants are off.

L: Base load is determined from the trend of previous years. To ensure a pessimistic value of active power, approximately 500 MW is subtracted from the value indicated by the trend to give the amount used for the analysis. This assumes summer minimum demand is defined as base load.
The reactive power is calculated by multiplying active power by the Q/P ratio established in previous years.

M: Only one load growth scenario is considered.

N: Maximum power transmission based on historic evaluation.

O: The base load cases are retrieved from the Northeast Power Coordinating Council's Automated Data Bank (NPCC ADB). The NPCC ADB consists of load flow data supplied by the members of NPCC to represent the NPCC system conditions from 1985 to 2000.

P: In base load cases, all load serving buses have an assumed power factor based on the policies on distribution power factor used in that particular subsystem. Most of the subsystems require unity power factor on the distribution system.

Q: The base cases are established from the forecast demand, considering different situations of generation (wet or dry hydraulicity, etc.).

R: Base load cases are established from the daily duration curve with different situations of hydraulic generation (dry, wet) and taking into account the average forced outage rate of thermal units.

S: A base case is established every year from measurements near peak load.

T: (4/7) utilities have range of base cases, using load forecast estimates and planned augmentations. Forecasting of reactive loads is included to varying degrees of accuracy.

3.2.5 <u>How is the development of future network taken into account? For instance by analyzing</u>
* intermediate and horizon years,
* varying increase in demand,
* other alternatives.

A: * Only one horizon year is studied (n+5); however, reactive power planning studies are regularly made (each 2 years) and peculiar studies can be made for the intermediate years.
* Varying increase in demand can be considered if there are big uncertainties about it.

B: Intermediate and horizon years.

C: Consideration of system facilities construction planning based on demand forcast.

D: We plan reactive power only at peak and bottom load time in the two year future.

E: The reactive power planning is usually carried out for the next year. Therefore, the network development for the next year is naturally taken into account.

F: Horizon years (5 years planning horizons) and intermediate years in special cases.

G: Intermediate and horizon years are analyzed for the seasons and load levels described above.

H: Varying increase in demand.

I: The development of future network is taken into account by analyzing:
- certain stages (2-3) of intermediary and horizon years
- varying increase in demand (low load inreased after 1980).

J: Separate analyses for different future stages.

K: For a 5 year period we analyse the starting year, the horizon year (i.e. the fifth year) as well as the intermediate years when there occur important structure changes. The forecasted load increases are also considered.

L: Development of Future Network:
For reactive compensation at light load (considered at present to give most onerous high voltages) a horizon of four years is used, being the minimum time for commissioning of new equipment. For a given summer minimum demand alternative power factors are sometimes studied to reflect the uncertainty in our knowledge of supply point Q/P ratios.
For reactive compensation to remedy low voltages, an adopted winter peak demand is studied as a base case. The network is not studied in its entirety, but specific areas where known problems exist are often studied in considerable detail.
Sensitivity analysis is done for a high demand growth scenario and also negative growth.

M: The reference year usually considered in planning reactive power is 3-4 years forward the present one. In some cases an intermediate year is examined to verify the effect of the amount of reactive resources previously calculated. In other cases a projection is made forward the reference year, by examining the system studied in the course of the active power planning process.

N: Intermediate stages with major system changes and horizon stage.

O: See 3.2.4.

P: The future network is usually not an issue for those capacitors that are added to defer more expensive transmission because they are added for a specific immediate purpose, that of delaying major expenditures. The same is true for reactors added for line energization voltage control. Their location is dictaed by technical needs, and the future network won't impact them.
There is some analysis of the future network needs when adding capacitors or reactors for general system support. This is done by siting reactive sources where it appears that they will be most needed. However, since our reactive support is usually added in small increments and with short lead times, the potential long range problems due to under or over estimating load growth is not of great concern.

Q: The short term development of the network is studied analyzing the next years for a given forecast demand, and the long term development is studied considering a range of scenarios for high, medium and low increases of demand.

R: Intermediate and horizon years and sometimes varying increase in demand (duplication of load, for example).

S: Especially changes in the network structure due to new lines to the neighbouring areas is important to the long-term planning of reactive reserve.

T: (3/7) Base studies more on stages of development, than on specific years.

(1/7) Studies planning as an integrated problem are a 10 year period.

(1/7) Studies a representative range of load growth over a 7 year forecast period.

3.3 Modelling of system.

3.3.1 Is the system divided into subsystems, using geographical subdivisions or subdivisions in voltage levels? In each case, what criteria are used? (Organizational subdivisions, ownership and responsibility, technical reasons, others.)

A: A subdivision in voltage levels is used for organizational reasons.
- National studies on the EHV network lead to determine the amount of compensation devices.
- Regional studies on the HV network are made to locate these devices.

B: Due to the size of the Belgian System, we never subdivise the system.

C: Ownership.

D: It is not divided.

E: It is divided into subsystems using subdivisions in voltage levels. The criteria are to maintain the adequate voltage at the single contingency.

F: No. The transmission system (400 and 220 kV) is calculated completely as a whole and, moreover, its implementation into the Interconnected power system is considered.

G: The bulk transmission system is not subdivided. Subtransmission systems are studied as separate radial systems.

H: 7 subsystems (ownership) globally treated.

I: The system is divided in subdivisions based on the voltage level. The MVAr flow between the 220/400 kV systems and regional geographical areas is 0.

J: Subdivision in voltage levels, and geographical subdivisions.

K: First we apply subdivisions in voltage levels, then geographical and administrative subdivisions. The criteria used are: the classification of the network lines according to their function, i.e. transmission and distribution, and further on, the consideration of the administrative operational subsystems, for the distribution lines.

L: Generally the whole country is studied down to 132 kV, even though most 132 kV transmission assets are owned by the authority concerned with retail distribution (the Area Electricity Boards). The voltage levels studied are thus, 400/275/132/66 kV (66 kV is represented by only a relative few busbars). In special cases 33 kV is represented.

M: The HV network is divided for reactive power planning studies in:
- 380 and 220 kv national transmission network.
- Several 150-132 kV regional subtransmission networks.

N: Item of utility.

O: The system representation utilized by NYPP includes system data for the entire Northeast. The system data is organized according to company designation.

P: The system is divided into subsystems which are based on geographic areas. The geographic area subsystems are based on the company division boundaries in most instances.

Q: In the optimization reactive program, the full Iberduero network is modelled adding the interconnections with other utilities.
In other studies, the system is divided into independent geographical subsystems. The criteria used for the subdivision are mainly technical, and are based on considering areas connected through long transmission lines.

R: The system is divided into subsystems using geographical subdivisions. The criteria used within the system are organizational.

S: We try to subdivide on voltage level in order to obtain 0 MVAr exchange on the low voltage side of the 400/132 kV transformers. The whole NORDEL system is divided into 13 geographical subsystems.

T: Answers depend on size of system. Smaller ones are treated as a whole. Large ones are split up on basis of systems and subsystems which have little mutual interaction.

3.3.2 <u>For the calculation of each subsystem, how is the external system represented (loads, generation, network).</u>

A: For calculations on the EHV network:
- Plants on the HV network are modelled as P-Q injectors.
- Loads are modelled by their tgφ at EHV level, which includes losses on the HV networks.

B: Belgian network is a part of the European system. So we represent the 400 kV lines interconnecting the Belgian system and we use an external equivalent. The latter contains synchronous generators in order to simulate the reactive power behaviour of the foreign network in case of outage in Belgium (see 3.3.8).

C: Infinite bus.

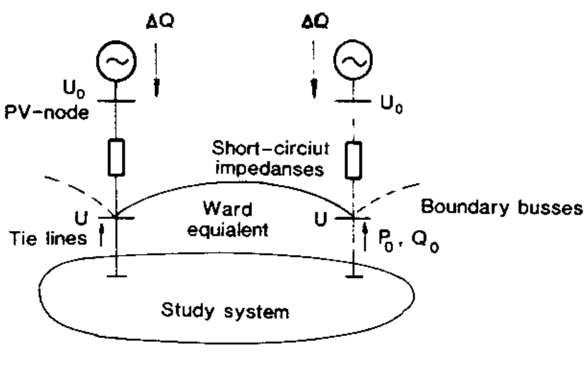
D: They represent loads and generations.

E: It is represented as loads.

F: The extend system (Interconnected power system) is represented exactly as a whole.

G: When a 69- or 46-kV substation is connected to more than one transmission substation, only the subtransmission system involved is added to the large base case for study of that local area.

H:



We represent external systems (20 interconnected lines with boundary contries) with Ward equivalent, and generators connected to the boundary busses (see figure above).

I: For the modelling of the 220/400 kV network all items above 70 kV are included. Other Nordic countries as detailed in stability studies.

J: By generations and loads at exchange buses.

K: For studying the distribution subsystem the external system is represented including the main nodes with enough power reserves. As an alternative, we use REI- DIMO equivalents for the whole external system.

L: Most loads are represented as fixed P and Q quantities on 132 and 66 kV busbars. Some loads are represented as "voltage sensitive" in especially difficult areas. Generation on the "external system" which is privately owned is usually not represnted because of its small size.
However, generation in Scotland is represented fully in winter peak studies (as is the Scottish network down to 132 kV).
At summer minimum demand it is assumed that interconnecting circuits between CEGB and Scotland have zero active transfer, but an allowance is made for the shunt susceptance of the interconnectors.
At all demand levels the whole network is represented down to 132 kV at 400/275 kV and 400/132 kV transformers. However, the interconnection between 132 kV busbars is often represented as an equivalent circuit. Losses in distribution transformers, and reactive power gains of l.v. circuits are represented. Series l.v. reactive power losses are estimated.

M: In 380-220 kV network equivalent loads are represented in the interconnections busses.
For the studies on the regional network a part of the external network (also at higher voltage level) is completely represented.

N: Only generation and resulting network if possible.

O: External system representation initially is developed by the North American Electric Reliability Council (NERC) Multi-Area Modeling Working Group (MMG) for the U.S. interconnected system. The resulting 9000 bus bar load flow model is reduced to approximately 2000 bus bars using networ equivalentizing programs which maintains the level of load and generation on the retained system network. The reduced representation is then merged to the NPCC ADB load flow representation.

P: The external system around the subsystem is modeled by its loads, generation, and transmission network. The system immediately surrounding the subsystem is not equivalized in any way. Northern States Power (NSP) develops virtually all its power flow models developed by the Mid-Continent Area Power Pool (MAPP) of the mid-western United States interconnected network. These models represent the MAPP transmission network in detail for 115 kV and above (depending on the type of study being done). NSP adds its particular subsystems to those models.

Q: The interconnections are modelled as fixed generations or loads.

R: In normal load flow studies, the full external system at the high voltage level is represented.
In O.P.F. studies a fixed equivalent for the external system (fixed impedances for the equivalent network between the boundary buses and a fixed load at these buses) is used.

S: For a typical calculation of a subsystem the neighbouring system is detailed represented, but it varies with type of investigation.

T: In subsystem studies the main system (source) is usually modelled as an infinite bus. In main system studies the subsystems are represented as a load, generator and/or impedance as appropriate.

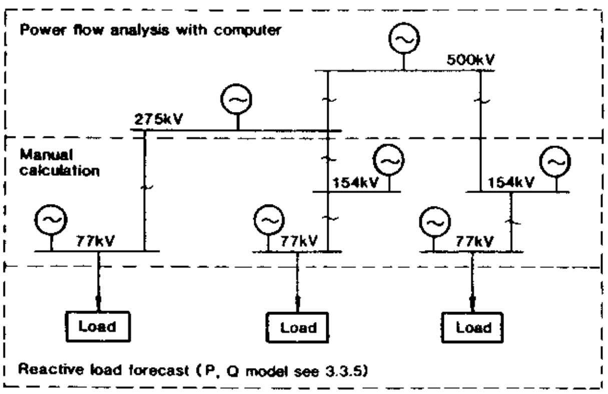
3.3.3 Describe the extent of representation of lower voltage level networks. What is the lowest voltage level network represented in the calculations?

A: For the national studies, only 400 kV and 225 kV networks are taken into account.

B: We represent the 70 kV system. Lower voltage level networks are not taken into account.

C: Represent extent : The voltage under 154 kV is not included.
Lowest level : 154 kV.

D:



E: 275 kV is the lowest voltage level network and 154 kV or 66 kV systems are represented as loads of 500/154 kV or 275/154 kV or 275/66 kV transformers.

F: The networks of lower voltage (110 kV) are represented by the load (consumption) in the node of the transmission system on primary or secondary side of 400/110 kV or 220/110 kV transformers.

G: The 161- and 115-kV networks are represented in detail. The 69- and 46-kV system are studied as radial systems.

H: Lower voltage levels modelled with fixed loads.

I: The lowest voltage level represented is 130 kV. A few nodes of 70 kV are included.

J: 132 kV. Lower voltages represented as loads.

K: The 5-year studies of the entire Romanian transmission network comprises all the grid nodes, including the 110 kV nodes. In the distribution sybsystem studies the medium voltages nodes (of 6, 10, 20 kV) are also considered.

L: See answer to 3.2.2.

M: See answer to questions 3.3.1 and 3.3.2.

N: Representation only by load MW/MVAr.

O: The lower voltage (115 kV and below) network is an usually equivalentized representation.

P: The extent of representation of lower voltage level network will depend on the study to be done (eg., a multi-utility EHV study, a single utility local area study, etc.) For large multi-utility planning studies where the focus of the study in on the high voltage or EHV system, the lowest voltage level represented is 115 kV. For local area studies, the lowest voltage level represented is the subtransmission voltage, which is generally 69 kV.

Q: The lowest voltage level represented is 146 kV. The network at lower voltage levels is represented as fixed loads at the buses where there are transformers to these lower levels.

R: The lowest voltage level represented is 66 kV for transmission planning studies.

S: For dimensioning of breaker switched capacitors : 50 kV
For reactors and SVC's : 132 kV

T: Modelling is generally included to the point where the responsibility of the authority ends. This varies from 66 kV down to 6.6 kV.

3.3.4 Describe the load models used (fixed impedance, fixed P&Q, etc.)

A: Fixed P and Q model.
B: Fixed P, Q.
C: Fixed P & Q.
D: They are fixed P, Q models.

E: We use the active and reactive load models as below:

$P = Po\ V^{\alpha}$ Po: active load at base voltage
V: voltage

$Q = Qo\ V^{\beta}$ Qo: reactive load at base voltage
α, β: load voltage characteristic factor

F: Fixed P & Q load models.

G: Load flow models use fixed P&Q loads. Transient stability studies normally use fixed impedance loads but sensitivity studies are made using fixed P&Q and/or fixed current.

H: Fixed P,Q and fixed impedances.

I: At load flow studies the loads are modelled as fixed active and reactive loads. For stability studies more sophisticated models are used with loads being dependent upon the voltage by an exponent.

J: Load models used are: Fixed impedances.
Fixed P&Q.

K: The loads are represented as fixed P & Q.

L: Most load models use fixed P and Q, but some are required to be sensitive to voltage change.

M: Normally fixed P and Q. The method applied also allows fixed P and $Q = Q_0 x (V/V_0)^2$.

N: Usually fixed P/Q representation, sometimes both P/Q and fixed Z alternating.

O: In general, the load model is a constant MVA representation for active and reactive power. Recently steady state load models as a function of voltage has been incorporated in reactive planning studies.

P: The local models used in power flow studies are constant MVA. However, in dynamic simulations, the local models are usually either 100% constant current or some percentage split of constant current and constant admittance. These representations are not base on any detailed load studies of NSP's system.

Q: The load model usesd is fixed p and q, although there is the possibility of representing these loads as a fixed impedance.

R: Fixed p and q.

S: For stability calculation: $P^{0.8} + Q^{1.8}$.
For static and quasi-static calculations: Fixed P and Q.

T: (7/7) use fixed P and Q for steady state calculations.
(3/7) sometimes study transient conditions, before and during tap change operation, and use various load/voltage indices for this.

3.3.5 How are the reactive load forecasted:

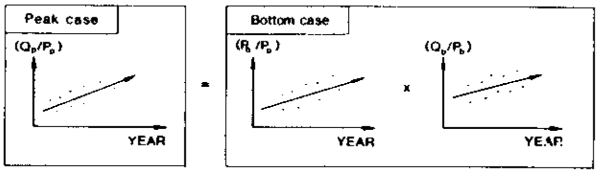
* by an analytical method? (e.g. by identification of special types of load groups or networks regarding reactive power demand)
* according to the active consumption forecasts?
* by extrapolation of the measurements?
* any others.

A: By extrapolation of measurements of the natural tgφ at the EHV level, one aasumes that the tgφ will remain constant, for a given period of the year, durinig the next years.

B: By extrapolation of measurements. The cos phi is measured in each node and taken constant along the time. No reactive load is forecasted according to the active consumption forecasts.

C: Extrapolation of the measurement of Q in August.

D:



'p' means peak time
'b' means bottom time
Only P_p is estimated by active power planning

E: -

F: According to the active power consumption forecasts. There is prescribed cosφ = 0.95 for consumption.

G: Load power factors are determined from metering and extrapolated according to active consumption forecasts.

H: According to the active consumption forecasts.

I: The reactive load is forecasted by relation to the active consumption.

J: According to active load forecasts and policies intended to limit the reactive power flow between each voltage level.

K: The reactive loads are forecasted starting from the forecasted active loads in correlation with the measurements as well.

L: Reactive loads are forecast according to the active consumption forecast. An assumed Q/P ratio is used, which is bases on surveys done many years ago. These surveys are no longer regarded as sufficiently accurate.

M: In agreement with active load growth forecast and by estrapolation of measurements of power factor.

N: According to increase of active power and measured ratios P/Q.

O: The characteristics of the steady state model were developed from actual field testing of special types of load groups. During the progress of the studies, the load types identified for each substation are assumed to be constant through time and for different load level.

P: Reactive power is generally forecasted according to estimate of the power factor based on the real power forecasts. Forecasts are prepared for each subsystem in addition to the total company forecast.
For a few very large loads on the system where the reactive power requirements are known, the reactive power is modeled exactly.

Q: The reactive load forecasts are made according to the active consumption forecasts and they are corrected by extrapolation of the reactive measurements.

R: According to the active consumption forecast. The q/p ratio used is modified in bases of periodic surveys.

S: According to active consumption forecasts and by extrapolation of the measurements.

T: All co-ordinate reactive forecast with active forecast, usually assuming constant power factor.

3.3.6 Are the reactive load forecasts made for any special period (high load, light load, others)? Please describe.

A: Measurements have been made at each studied period (winter, summer, mid-season at peak and low load).

B: See 3.2.2.

C: 1) Peak load of average of 3 days of maximum demand in summer time.
2) Night load in off peak seasons.

D: See 3.2.2.

E: They are made for peak load and light load.

F: The reactive power is forecasted separately for each of the 5 special periods - see cl. 3.2.2.

G: 1. Summer Peak
2. Winter Peak
3. Minimum Load for Year

H: High load and light load.

I: Reactive load forecasts are made for high load periods with approximative extrapolations to low load periods.

J: High load only.

K: The reactive load forecasts are made for the periods of the year and load conditions shown under item 3.2.2.

L: Reactive forecasts are made for:
Summer minimum demand
Winter peak demand
Sensitivities based on winter peak demand.

M: Different power factors are adopted for the different load conditions examined (see answer 3.2.2).

N: Forecast normally only for maximum load condition.

O: Both the active and reactive loads are established from individual company forecast methodology and entered individually for each bus bar in the NPCC ADB.

P: The reactive power forecasting we do is made for the peak load periods.

Q: The reactive load forecasts are made for the same situations of the active consumption forecast (peak and light load).

R: They are forecasted for the peak and light load (winter and summer periods).

S: Only high load and low load.

T: (4/6) Forecast for both high and light loads.
(1/6) Forecasts for high load only and takes light load in proportion.
(1/6) uses average load power factor, recognising that p.f. generally improves at the peak (if this is due to resistive heating i.e. winter peaking).

3.3.7 What is the experience so far of reactive load modelling adopted for your study purposes? Give comments on adequacy for study purposes. Are any modelling improvements in hand? If so please describe these improvements.

A: Modelling:
- Good adequacy for steady state analysis in normal case
- Variations of the loads with the voltage are not modelled (can be important in case of outage or for dynamic studies).

Data:
- Good knowledge of the reactive loads at a prease date.
- No forecasts possible, then no adaptation to the evalutions of the consumption structure.

B: P, Q loads seem to give satisfaction, due to the fact that all HV/MV transformers are equipped with automatic taps changers. The loads in load flow calculations correspond to these transformers.

C: Necessity of compensators plant's installation at most best locations.

D: We use only fixed P, Q models. I think the detailed modelling is useless.

E: The adopted load modelling can be said to be adequate from the record of actual operation.

F: -

G: Reactive modelling seems to be adequate. Recent improvements have been made in the analysis of metered data which has improved the accuracy of future studies.

H: No experience for the time being.

I: Sufficient for load flow studies.

J: -

K: Load modelling as fixed P & Q's is generally considered satisfactory. For the special conditions e.g. operation with high U & f deviations, we study load modelling with the steady state characteristics, $P,Q = F_{(V,f)}$

L: Experience so far:
1) The load model used is suitable for general purposes and tends to be pessimistic for voltage step changes, and also in so far as the need for reactive compensation is indicated.
2) Some load response data has been obtained for individual supply points but there is no overall programme of measurements. Data obtained from power system tests can be used in the analysis if required.
3) Installation of better metering and data logging over the next five years will give better assessment of reactive power demand, by using actual half-hourly averaged values, together with the active power. This improvement in data accuracy will probably be the greatest single improvement for the foreseeable future.

M: Fixed P,Q is considered an adequate model for the 380-220 kV network being the 150-132 kV voltage controlled by on load tap changers. In the studied on the regional (150-132 kV) networks a Q=Q(V) model might be used, but it requires the identification of the function Q(V).

N: Normally fixed P/Q, in special cases fixed Z (some industrial loads).

O: Presently there is insufficient reactive metering to ascertain the accuracy of the reactive load modeling, NYPP is presently considering the addition of state estimation to the system which would provide on-line monitoring of active and reactive load so that more accurate forecasts of loads can be extrapolated.

P: In general, NSP's reactive power modeling is in a very rudimentary stage because the company has only recently had to begin addressing the issue. Therefore, reactive load modeling is predominantly a power factor calculation from subsystem to subsystem. NSP is beginning to review the assumptions made for reactive load on its larger load areas, but there have been no specific modelling improvements made.

Q: Reactive optimization is a new activity in the planning process, therefore it is difficult to critizise the models used at this moment. Reactive compensation measures up to date have been based on operating criteria, using actual data and not models.

R: The load modelling (fixed P, Q model) is sufficient for the steady state reactive analysis. Efforts are under way to improve data collection methods for different types of loads through the use of magnetic tape recorders.

S: We expect there is a major uncertainty on the reactive load, and we try to adjust the tgϕ of the load by yearly measurements of the load under high and low load.

T: Constant P, Q models are adequate for steady state modelling. Those who model transient behaviour are aware of the need for better models.

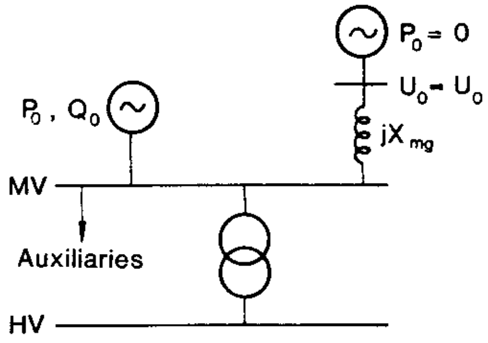
3.3.8 <u>Describe the modelling of controllable MVAr Supplying Devices for steady state analysis, such as:</u> synchronous generators
synchronous compensators
static var compensators.

* Please describe if they are modelled as P,V-nodes or P,Q-nodes at high voltage, low voltage, or behind a reactance, or modelled as pure impedances.
* Describe how limits and characterstics are handled in the models.

A:
* Nuclear power plants: They are considered as P.V nodes at low voltage (20 kV), behind the reactance of the plant transformer, which depends on the used tap. The loading limits are defined by the voltage limitations and the reactive possibilities of the alternator.
* Other plants and synchronous compensators are considered as PV nodes at high voltage (225 kV or 400 kV). The loading limits take into account the consumption of the plant transformer.

However, these P.V nodes become P-Q nodes int he calculation if the loading limits are reached.

B: Modelling of synchronous generators:
The post disturbance equilibrium state of a generator in a large system (neglecting ΔP) is given by the following figure.



Where Po, Qo are active and reactive power generated before disturbance and Uo the voltage (MV) before disturbance, Xmq is an equivalent reactance, function of the open loop gain of the AVR system. For more details, see "Quasi Steady State Synchronous Machine Linearization around an Operating Point and Applications". A.T. CALVAER, E. VAN GEERT - I.E.E.E. 84WM 019-6.

C: PV-nodes.
Especially none: Power factor within the limits of 95%.

D: Synchronous generators → P,V-nodes and P,Q-nodes.
Synchronous compensators → P,Q-nodes.
The constraints of generators
a) P,Q-nodes: bus and generator voltages constraints (about 15% of voltage levels, see 2.3.2.)
b) P,V-nodes: generator P.F. (about 95%).

E: They are modelled as P,Q-nodes.

F: Synchronous generators and synchronous compensators are modelled as P,V-nodes at a high voltage side. There are prescribed the limits of reactive power generation and consumption.

G:
1. Synchronous Generators - P, Q-nodes at high voltage.
2. Synchronous Compensators - P, Q-nodes at high voltage.
3. Static Var Compensators - None on the TVA system.

H: Synchronous generators and synchronous compensators: P,V and/or P,Q nodes; use of a simplified operating diagram of the synchronous machines.

I: Controllable MVAr supplying devices such as synchronous generators and compensators are for steady state analyses modelled to provide a acertain bus voltage with a MVAr range. Static var compensators are modelled to keep the voltage within a specific range.
At stability studies the detailed dynamic performance is included and nodes are modelled with series reactance included. The models are limited by maximum and minimum Q output.

J: Generators: P,V or P,Q nodes at high voltage.

Synchronous compensator: P,V or P,Q mainly at low voltage.
SVC: P,V or P,Q nodes at high voltage.
Limits handled as constraints.

K: The synchronous generators and compensators are represented as P, V at high voltage. In the subsystem studies the sysnchronous generators and compensators are modelled at their supply voltage. The limits considered are Q_{min}, Q_{max} and V_{fixed}

L: Controllable MVAr sources:
1) Synchronous generators
The machine terminals are represented as a constant voltage node (1 p.u. V). The active power is specified, but the reactive power is specified as a range of absorption and generation. Generator transformers are modelled as series R and X with a high voltage, manually adjustable tap changer.
2) Synchronous compensators (including declutched gas turbines). The model regulates the nodal reactive power generation or absorption in proportion to the difference between the study voltage and the voltage specified. The regulated node may be separated from the synchronous compensator node if required. The dQ/dV response is also specified and is currently 5%. A transformer impedance may be specified if required, in which case the reactive power at the l.v. is controlled with respect to the difference between HV study voltage and specified l.v. voltage.
3) Static Var compensators. The model is the same as 2) above.

M: Synchronous generators and synchronous compensators are as P,V nodes at medium voltage level (the step up transformer is directly represented). Moreover the limits of the capabilities curves are considered.

N: Modelling as P, V-nodes with limitation of Q-supply. Beyond limits fixed reactive or capacitive impedance.

O: Steady state modeling of controllable MVAR sources are basically P,V nodes with specific minimum and maximum reactive capability.

P: Static var compensators are modeled behind a reactance usually on a low voltage bus with a step-up to the transmission voltage. Until the last one-to-two years, synchronous generators were modeled on the high voltage bus. Recently, NSP has begun modeling its generators on the low-voltage bus through a generator step-up transformer.
NSP does not have any static var compensators on its system. When such devices are modeled for study purposes, the data and characteristics are patterned after similar devices in northern Minnesota or in Manitoba. The model characteristics (i.e. transfer functions) are taken from specific models contained in the Power Technologies, Incorporated Power System Simulation program.

Q: The only controllabale MVAr supplying devices used at this moment are synchronous generators and they are modelled as p, v nodes.

R: The controllable MVAr supplying devices, such as synchronous generators, synchronous compensators and static var compensators, are modelled as P, V nodes. If the limits are reached, these devices are modelled as P, Q nodes.

S: Synchronous generators are modelled as low voltage P,V nodes. Limitations are handled manually.

T: Synchronous machines are modelled on their terminal busbars (ie behind transformer reactance) as P, V nodes while within reactive lilmits (one also models reactive drop compensation characteristic). Most model as P, Q source after limits are reached - one allows limits to be a function of P. SVC's are modelled as zero P, constant V sources. (2/4) when modelling SVC, place this voltage source behind reactance corresponding to droop setting.

3.3.9 <u>Describe the modelling of uncontrollable MVAr Supplying Devices for steady state analysis, such as:</u> saturated reactors
normal reactors
shunt capacitors

A: Modelled like the generators (PV nodes or P-Q nodes).

B: Shunt capacitors are modelled as admittances if connected to 70 kV and 150 kV, but as fixed Q if connected in MV.

C: Q-constant nodes.

D: Normal reactors) fixed Q models.
Shunt capacitors)

E: They are modelled as fixed impedance.

F: Normal reactors and shunt capacitors are modelled as fixed impedance.

G: 1. Saturated Reactors - None on system
2. Normal Reactors - Constant Impedance
3. Shunt Capacitors - Constant Impedance

H: Normal reactors and shunt capacitors:
Fixed susceptance.

I: Uncontrollable MVAr supplies are modelled as follows:
No saturated reactors.
Normal shunt reactors and capacitors are modelled as impedances.

J: Normal reactors)
Shunt capacitors) represented as fixed impedances.

K: Normal reactors are modelled as impedance at their operation voltage. The shunt capacitors are considered fixed Q generators.

L: Uncontrollable MVAr sources:
1) Saturated Reactors: 3 x 150 MVAr saturated reactors will be installed (commissioning 1985/6) as part of the 2 GW Cross Channel HVDC Link scheme. These are harmonic compensated treble tripler type saturated reactors. 3 x 150 MVAr mechanically switched capacitors are also included as part of the compensators giving 150 MVAr rated capacity in both the inductive and capacitive range for each compensator (i.e. ± 150 MVAr). The steady-state model used to represent these compensators in load flow analysis is identical to that used for synchronous compensators (see Section 3.3.8). The compensator V-I characteristic is re-

presented by a slope (say 5%) from rated generation to absorption capability. The coupling transformer is normally omitted from the studies since the full capability of the compensators can be represented at the HV terminals.
2) Normal reactors. Represented as a shunt susceptance on a 100 MVA base (entered as a -ve number).
3) Shunt capacitors. Represented as a shunt susceptance on a 100 MVA base (entered as a +ve number).
2) and 3) therefore represent a shunt loss, and shunt gain respectively, which varies with the study voltage.

M: The normal reactor is represented as constant admittance. The shunt capacitors are always represented as constant Q, since:
- Those installed at 132 kV, are supplied at a nearly constant voltage.
- Those installed on MV network are not directly represented.

N: Fixed impedance for load flow studies. Actual characteristic for saturation phenomenas.

O: Steady state modeling uncontrollable MVA sources are entered with specific MVAR capability at nominal voltage. The program then converts the source to a constant impedance load at the bus bar. The shunt reactive compensation could be modeled switched shunt devices which could switch specified discrete amounts of capacitors or reactors to maintain the bus bar voltage.

P: Shunt capacitors (and reactors) are modeled by giving their G and B characteristics. If they are switchable, the blocks of capacitors to be switched and a voltage schedule are provided.

Q: The shunt reactors and capacitors are modelled as a fixed impedance, connected directly to the buses or through the tertiary of three-winding transformers, if they are so connected

R: They are modelled as fixed impedances.

S: Normal reactors and capacitors can be switched on and off by the load-flow routine in order to obtain desired voltages in the nodes in which they are located.

T: Saturated reactors (only one authority needs to model them) - constant voltage behind slope reactance. Reactors and Capacitors: Constant impedance (if voltage at busbar is controlled this results in P and Q remaining unchanged). If busbar is not specifically modelled but it is voltagecontrolled would model equivalent as constant Q.

4. ANALYTICAL SOLUTION TECHNIQUES UTILIZED IN REACTIVE POWER PLANNING

4.1 <u>In planning reactive power which of the following analytical techniques is utilized:</u>
* successive ordinary load flow studies.
* optimal load flow studies.
* other optimization techniques.

A: Optimal load flow.

B: - Successive ordinary load flow (with special representation of generators - see 3.3.8.).
- Optimal load flow.

C: Ordinary load flow studies.

D: We only use successive ordinary load flow studies. But we aim at limiting the reactive flow on 500 kV backbone lines. (See 3.1.2).

E: Optimal load flow.

F: Successive ordinary load flow studies are usually sufficient. Optimisation is being made only in special cases.

G: Successive ordinary load flow studies.

H: Optimal load flow studies.

I: In planning for the reactive power the following analytical techniques are used.
- Successive ordinary load flow studies.
- Optimal load flow studies is under development and is to be finished.

J: Successive ordinary load flow studies.

K: For reactive planning, the following calculations are performed:
- ordinary load flows
- optimal load flows

L: In planning reactive compensation, successive ordinary load flow studies are used.

M: Optimal load flow.

N: Normally successive load flow studies, sometimes optimal load flow.

O: Reactive power planning includes optimal load flow VAR Plan analysis and conventional load flow analysis to confirm the results of optimization techniques.

P: In planning reactive power, the following analytical techniques are used:
- Successive ordinary load flow studies
- Surveys of actual system flows

Q: Successive ordinary load flow studies have been used up till now. At present an optimal power flow program is being implemented.

R: Sucessive ordinary load flow studies, and now we are starting to use optimal load flow studies.

S: Successive ordinary load-flow studies.

T: (7/7) use successive ordinary loadflows.
(2/7) have access to optimal load flow program but rarely use it.
(2/7) also use supplementary simplified studies or manual calculations.

4.2. <u>If successive load flow studies are used, please indicate if there are any additional features included in the load flow technique towards reactive optimization?</u>

A: -
B: Nihil.
C: Particulary no.
D: There are not the feature of that kind.
E: -
F: -
G: There are none.
H: -
I: No.
J: -

K: The computer program for ordinary load flow (FAST) indicates that the required voltage limits are exceeded, that at the power plants the control reserves of Q are used up and that some circuits are overloaded.

L: No additional features.

M: -

N: Tendency to constant voltage profile at main busses.

O: -

P: There are no reactive optimization features included in the load flow techniques.

Q: None.

R: None.

S: By using the feature in 3.3.9 the program itself can give a hint on, where to place static MVAr-devices. SVC's are treated as generators in load-flow studies.

T: (5/7) have no additional features.
(1/7) calculates V versus Q sensitivity.
(1/7) summates total losses.

4.3. <u>If optimal load flow is used, give information about which method. (Reduced gradient, conjugate methods, linear programming, Hessian methods, quadratic programming, mixed techniques, etc.)</u>

A: The optimization method proceeds by linearization of the network equations around successive operating points. The linear programme obtained at each step is solved with a relaxation technique.

B: Generalized Reduced Gradient.

C: -

D: -

E: Reduced gradient method.

F: Penalty function method.

G: Optimal load flows are not presently used.

H: Successive linear programming with dual-relaxation method.

I: Generalized reduced gradient especially designed to handle the problem of reactive power optimization, for example new bus types are introduced in the load flow problem in order to model the reactive control problem.

J: -

K: The optimal load flows are a gradient method (the NEWOPT program).

L: Use of optimal load flow techniques are being investigated.

M: Step 1: Linear programming.
Step 2: Quasi Newton (Han Powel).

N: Evaluation strategy with basic Newton-Raphson load flow.

O: The optimal load flow utilizes sequential quadratic programming to achieve its optimization.

P: Not available.

Q: Linear programming.

R: The method used in the optimal load flow is the reduced gradient. Penalty factors are included in the objective function.

S: -

T: (2/7) who have optimal load flow use conjugate methods.

4.4. <u>If other optimization techniques are used, please describe the technique. (Dynamic methods, others)</u>

A: -

B: Nihil.

C: -

D: -

E: -

F: Penalty function method.

G: We use an optimization program to help customers locate capacitors on their distribution systems (13-kV radial feeders).

H: -

I: Other optimization techniques are considered but not decied upon. The extention of the technique encompassed then considerations to more transfer cases and contingencies.

J: -

K: -

L: Not applicable.

M: -

N: -

O: -

P: The only optimization techniques used are manual rule of thumb techniques such as placing reactive sources as close as economically reasible to the reactive load.

Q: None.

R: None.

S: Dynamic studies of network separation with stability program. The objective is (over)voltage control in connection with load shedding and also frequency activated load shedding.

T: No response.

4.5. <u>How large are the systems solved in your optimization? Please indicate number of busbars with generation, reactive compensation, etc.?</u>

A: 1000 nodes, all of them possible with generation or reactive.

B: Maximum number of busbars with generation or compensation : 50
Maximum number of regulated tap changers : 120

C: Total system node: 320
Generator node : 67
Compensator node : 154

D: -

E: Generation : 40
Reactive compensation: 60
Another node : 200

F: 20 busbars with generation.
10 busbars with compensation.

G: NA

H: 172 busses
301 branches
71 generators and synchronous compensators.

I: In ordinary load flows about 300 buses. 50-75 controllable reactive sources.

J: System size : 100 buses
Generators : 40 generators
Compensation: 10-15 buses

K: The NEWOPT program permits calculating a 600 node network, of which 225 may have synchronous generators and compensators.

L: Not applicable.

M: The maximum number of components are:
- 50 generators
- 50 busses candidates for the installation of new reactive resources
- 50 on load tap changer.
Moreover an overall limit of 100 control variable is to be respected.

N: Theoretically no limitation.

O: 4000 bus bar Total System Size Constraint
1000 generations
1000 transformers
100 phase shifters
All 4000 bus bars can be considered as potential locations for reactive compensation.

P: We don not use any computerized optimization techniques.

Q: 155 busses, 34 of which are generators.

R: In ordinary load flow studies about 300 buses are used, 50 of which are generators.

S:

Typical study	Bus	Bus with generation	Bus with MVAr-device
Own network	90	25	20
Neighbouring network	160	35	50
Total	250	60	70

T: Can be up to 140 busbars - most would be less than 100, with some as low as 10 or 20. Typically about 15% with generation, 30% with compensation.

4.6. <u>If implemented in your optimization, please describe in order of importance how the following factors are included:</u>
* investment costs
* transmission losses
* reactive power reserves
* transmission capacities
* effect of contingencies and/or multiple contingencies

Describe further how these factors are combined in your decision process (manually, by defining an overall criterion of optimization, other methods).

A:
* Effect of contengencies: Successive optimizations are made with various network situations (see 3.2.4). New shunt capacitors or reactors are added up from a situation to the other in order to determine the amount of compensation necessary to meet the technical constraints in all the studied situations.
* Investment costs: They are included in the criterion, the objective is to minimize them.
* Transmission losses: They are taken into acount in establishing the highest voltage profile.
* Reactive power reserves: More restrictive limits on voltage or reactive possibilities of the plants can be introduced in order to prevent outages (see 4.10).
* Transmission capacities: They are not introduced as constraintes, but only pointed out.

B: Investment costs and transmission losses are included together with voltaage constraints in the optimal power flow process. The decision process can be summarized as follows:
- Respect of voltage constraints (possibly with the aid of the optimum flow),
- In case of incident, the post-disturbance equilibrium state of the generators (see model in 3.3.8) must be inside their capability curves otherwise, we invest shunt capacitors or we reinforce the structure.

C: 1) Manually
3) "
4) "
2) "
Multiple contingencies

D: -

E: 1) investment costs
2) transmission losses
3) effect of contingencies and/or multiple contingencies
4) reactive power reserves
The investment costs and transmission losses are included in the optimal load flow study. Reactive power reserves and effect of contingencies are handled manually.

F: 1) Investment costs
2) Transmission capacities
3) Transmission losses.

G: Once the system need is identified, alternatives are evaluated considering all pertinent life-cycle costs.

H: 1) Investment costs
2) Transmissioin losses
3) Transmission capacities
4) Effect of contingencies and/or multiple contingencies
1), 2) are included in objective function. 3) is included in constraints.

I: Minimum life cycle cost is desired. Investment, operation and maintenance, reactive reserve, network and equipment losses are taken into account. The calculation is performed manually.

J: Decision process based on manual judgement regarding investment costs and effect of contingencies.

K: For the reactive power sources alloted in steps, the NEWOPT program determines how the amounts of reactive source should be distributed to the nodes, so as to have minimum losses in the studied network.
The reactive power rserves for the power plants are maintained and the overloading of the transmission lines are signalled. The results obtained with this program are then used for manually calculating the total updated expenses, considering the investment in the reactive compensation devices as well as the value of the network losses reduction. In addition to the compensating devices established as shown before, from the analyses of the contingencies (see it. 3.1.5.) there result supplementary reactive compensation devices necessary for maintaining the voltages within the specified limits.

L: Not applicable.

M: A. investment costs
B. transmission losses
C. reactive power reserves
D. transmission capacities
E. effect of contingencies and/or multiple contingencies
In step 1, "A" is minimized respecting "C" and "E" constraints. In step 2, "B" is minimized respecting "C" and "E" constraints. No transmission capacities constraints are applied. Then a comparison performed between the higher capital changes due to additional reactive

installations (over the amount required by technical constraints) and the corresponding savings in cost of losses.

N: Transmission losses and voltage deviations are the objective functions in the optimal load flow studies.
For overall optimization, however, the order of priority is:
- technical constraints (voltage limits, reactive power flow and reserves under normal and contingency conditions)
- investment costs
- transmission losses

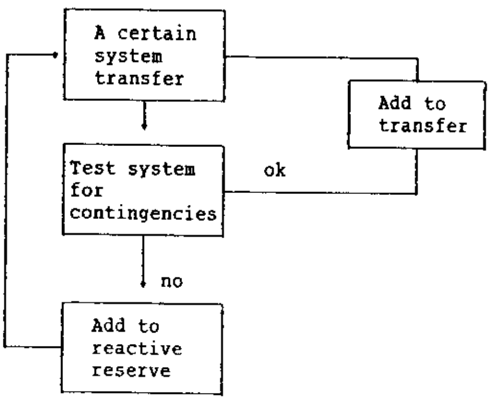
O: The factors considered in the optimization include:
1. effect of contingencies and multiple contingencies
2. investment costs
3. transmission losses
The first two factors are simultaneously optimized in the VAR Plan program. In this case the investment costs are reflected as minimum reactive compensation additions. The transmission losses are optimized utilizing the optimal load flow program. The procedure to optimize all three factors are accomplished by an interactive process where the OPF results are used for input data to the VAR PLAN analysis and vise versa.

P: We combine the described optimization factors manually in our reactive power planning. Adding reactive power sources are considered as just one option along with other facility for solving contingency caused problems and reducing losses. Whatever the most economical way of solving the system problems is the alternative that is followed.

Q: Generation costs are optimized.

R: Transmission losses are included in the optimal power flow. Investment costs, reactive power reserves and the effect of contingencies are handled manually at present.

S:



The result of this process is a curve, which relates system transfer to reactive resources. This result is combined with investment costs the value of system transfers (incl. losses) to an optimal solution.

T: Responses to this question reflect the replies to Questions 3.1.1 to 3.1.3.

4.7. <u>Are primary and secondary voltage control as well as reactive power control included in the calculations? If not, how is the coordination carried out?</u>

A: Secondary voltage is included in the calculations.

B: Primary control : see 3.3.8.
Secondary control: nihil.

C: Included.

D: Tap of transformer is included. But it is not change automatically.

E: They are included in the calculations.

F: Primary and secondary voltage controls are not included in the calculations of load flow, but they could result from optimisation calculations.

G: NA

H: Yes, possibility of secondary voltage control (not realized for the time being).

I: The division of reactive power between generators is decided upon the basis of minimum losses for the sum of all generators. A loss function is specified for each generator.

J: Manually coordinated.

K: The primary voltage control is taken into consideration in the calculation by modelling the generators as P, V nodes. The coordination is carried out by analyses of successive power flows and by distributing as required the necessary reactive power compensating devices. (See it. 4.6.)

L: In our ordinary load flow studies, the CEBG on-load tap changers are generally the only ones represented. Although in practice they are non-automatic, the program carries out automatic tap changing so that 132 kV and 66 kV voltages can be maintained at 1 p.u. in the steady state. In general 400/275 kV transformers do not have tap changers on the CEGB system.
Since 132/33 kV transformers are often not represented, it is usually considered sufficient to maintain 132 kV voltages at the required value. It is assumed, except where specific information indicates otherwise, that no voltage control problems exist on the Area Boards' systems. When Area Board problems are known to exist it is sometimes necessary to model 132/33 kV transformers, which have automatic on-load tap changers.

M: Only primary voltage control is taken into account.

N: Voltage regulation in included by automatic tap changing of transformers.

O: Yes, the program attempts to optimize all control parametes simultaneously.

P: Voltage control is included on the generators and on the LTC transformers in the load flow calculations, which are used for optimization.

Q: Only primary voltage control is included, through the automatic voltage regulators of the generators and the transformer tap-changers.

R: The secondary voltage control is not included in the calculations, but it is an important factor to consider in the future.

S: The primary voltage control is included. We have not agreed on how the secondary voltage control is included, except for the subdivition mentioned in 3.3.1.

T: (2/7) include primary and secondary voltage control.
(1/7) includes manual control of generator voltage.
(1/7) includes co-ordination of tap changer timing using model studies.

4.8. <u>Are the optimization methods developed for operation planning or for medium/long term expansion planning?</u>

A: Optimization methods have been developed for medium/long term expansion planning, with applications to operation planning.

B: Optimum power flow is not used for operation planning (only for expansion planning).

C: Optimization methods is not developped.

D: We didn't use such methods.

E: They are developed for medium term expansion planning.

F: Medium term expansion planning.
G: NA
H: Operation planning.
I: The optimization model is developed for opration planning purposes. It may be used for expansion planning as well. One version of the program can handle multiple contingencies.
J: Both.

K: The optimization methods are developed only for medium term planning (5 years).
L: Not applicable.
M: Both for operation and medium term expansion planning.
N: For operation and expansion planning.

O: The optimization methods are basically a medium/long term expansion planning. Significant improvements to decrease the solution time are necessary before it could be an effective online operating tool for the NYPP system.

P: The optimization techniques developed are used both operational and long-range planning.

Q: These methods are used both for operation planning and for medium/long term expansion planning.

R: For both of them.

S: For medium-/long-term expansion planning.

T: (2/7) cover medium/long term planning.
(3/7) cover operational and medium-term planning. (Remainder do not apply these methods.)

4.9. <u>How are the future network stages taken into account in the planning of reactive power installation?</u>

* by separate studies of network stages
* by one study covering the whole period
* by other methods

A: Studies at horizon n+5 made each 2 years.
B: By separate studies of network stages.
C: By separate studies of network stages.
D: By separate studies of network stages, see 3.2.2 and 3.2.5.
E: By one study covering the whole period.
F: By separate studies of network stages.
G: Ongoing studies are made of future network development.
H: By separate studies of network stages.
I: By separate studies of network stages.
J: By separate studies of network stages.
K: The network development studies are considered in the studies drawn up repeatedly every 5 years; within the 5 year period they are considered according to it. 3.2.5.

L: The future network is specified up to six years ahead as part of the Transmission Plan. For summer minimum demand the system four years ahead is chosen and is the only system studied (e.g. in 1985 the 1989 system is being studied). For peak and off-peak demands the situation is less rigid regarding time scale, in the sense that developments from four years onward are studied, but concentrating on particular areas rather than surveying the whole system. This is because some specific areas can be depleted of generation as the demand falls to around 85% of peak, thus causing that generation to be "out of merit".

M: By separate studies of network stages.

N: Separate studies of stages.

O: The optimization techniques are valid for only one network configuration. Analysis must be repeated for each network scenario considered in the study.

P: Future network stages are analyzed by sub-area in separate studies. However, one study may include several steps in which optimization of reactive power may be done.

Q: By separate studies of network stages.
R: By separate studies of network stages.
S: By separate studies of network stages.
T: (7/7) use separate studies of network stages.

4.10. <u>Describe the analytical techniques used to study the voltage stability and reactive power reserve condition of the network? (Sensitivity techniques, other techniques.)</u>

A: * After optimization, a security criterion is computed, it is based on the calculation of sensitivity coefficients which indicate the variation of the reactive power supplied by all the generation units if the reactive power demand at a system node is increased by 1 MVAr.
* Effects of the tripping of a system element (400 kV line, generation plant) on the voltage profile, after the action of the secondary voltage control, are computed by a load flow, in order to simulate the secondary voltage control, the network is divided in areas, in each of them a P.V node is defined, whose voltage is held by the plants of the area. Results of these calculations are used to define the necessary reactive power reserves.

Iterations with the optimal load flow can be done, to determine the additional amount of compensation devices necessary in case of outage of network elements.

B: Voltage stability is studied only for operation planning. We mainly use a criterium based on the value of:

$$\left| \frac{U_i}{E_i} \right|$$

Where U_i are the actual voltages at each node of the network and E_i the voltages of the same network, putting loads and active generation equal to zero and taking into account the behaviour of the AVR of the generators.
We have also studied other criteria. For further information, see "Voltage Stability - Fundamental Concepts and Comparison of Practical Criteria" by P. BORREMANS and All - CIGRE 1984.

C: Voltage stability : Not considerated
Reactive power reserve: Not considerated

D: We didn't use such techniques.

E: Sensitivity techniques ($\partial V/\partial Q$).

F: Analytical techniques for the voltage stability analysis are now under study.

G: Conventional load flow studies are made considering the possible locations of reactive power generation.

H: -

I: A number of load flows with successively increased transfers is studies to provide the base for the analysis. The dynamic behaviour of the system is studied in the neighbourhood of the stability limit.

J: By load flow studies.

K: The resulting reactive compensating solution is checked with respect to the steady state stability by using the SAMY program based on the method of changing the sign of the characteristic equation describing the system operation.

L: Voltage stability is assessed by simulating credible fault outages.
These are set out in 3.1.5. After the fault, transformer tap changing is inhibited to give the voltage step change (normally without any load/voltage response data). Reactive absorption/generation reserves are automatically calculated for very zone of the system, and for the whole system.

M: Not considered.

N: Increase of reactive load caused by loss of important lines.

O: Dynamic voltage response is performed with the transient stability program. Presently sensitivity analysis is performed by a trial-and-error process.

P: Power flow studies are the primary analytical tool used to study voltage conditions and reactive power requirements of the network. The power flow studies may simulate different load levels or different reactive power conditions to analyze changing system conditions.

Q: No analytic techniques are used at present.

R: At present, only conventional load flow studies are used, considering the possible locations and amounts of reactive power generation. Sensitivity analysis are now under study.

S: Successive load-flow studies with all automatic and no manual controls in action.

T: (4/7) use contingency analysis.
(5/7) mention various forms of sensitivity analysis including V v's Q curves (2/5) and E v's P (1/5).

4.11. <u>Are transient stability analysis or other kind of dynamic simulations carried out to decide the amount of reactive power reserves?</u>

A: Dynamic simulations are carried out to choose between the different devices (capacitors, reactors or static compensators) or to define the control law.

B: No.

C: Transient stability analysis: Not considerated.

D: We didn't use such techniques.

E: Special dynamic simulation is carried out for determining the necessary amount of shunt compensation when necessary to ensure the regular operation of Power Load Unbalance Relay at a nuclear power plant in the wake of a load rejection at the receiving end of a transmission line.

F: Yes, the transient stability is analysed in special cases when making decisions on the underexcitation limits (Q-limits) at power plants.

G: Stability studies are made to evaluate the ability of units to absorb reactive power during light load periods. In addition, studies are made to evaluate voltage collapse and the effect of reactive supply during these contingencies.

H: No.

I: a) Dynamic simulations are performed in order to study the necessary reactive reserves during the dynamic sequence caused by a network fault.
b) Steady state calculations are performed on a post fault situation in the network. In this case a more detailed model is used for the generators than the one used in ordinary load flow. The improved model gives a better pricture of the post fault voltage condition in the network.

J: No.

K: We do not carry out dynamic stability studies in connection with the reactive power source program.

L: Routine generator dynamic and transient stability studies are carried out. If a need is identified, then proposals may be made to switch in shunt capacitors post-fault, to provide generators with voltage support.
For voltage stability, double circuit fault outages are simulated with transformer taps fixed to give an indication of the reactive power reserves required to preserve voltage stability.

M: No, in the usual planning process.

N: Transient analysis is important for layout of reactive power components in HV-projects.

O: NYPP does not assess reactive power reserves for dynamic voltage response.

P: Transient system analysis is used to analyze the effects of reactive power on the high voltage or EHV network, particularly in determining what type of reactive power device should be installed (eg., static var compensator, switched shunts, fastswitching, etc.).

Q: No.

R: No.

S: Both transient stability analysis and (over)voltage calculations

T: (4/7) consider transient stability, but not necessarily within the cost optimization. Stability usually defines a requirement above that for voltage control.

4.12. Please describe your overall experience of the analytical techniques used in your planning process including your possible criticisms of such techniques.

A: Linear programming allows to study great size networks (1000 nodes). However, the criterion isn't well suitable to the minimization of losses.

B: Methods give satisfaction.

C: Particularly no.

D: -

E: -

F: -

G: Our conventional study techniques are time consuming. However, since we must study large systems (2000 bus) to accurately simulate the bulk network, we are not aware of an optimization program that is available for production work.

H: Difficulties in modelling external systems.

I: On a critical note our experience with the present analytical methods is that it is important to identify the most relevant transfer conditions and contingencies. Optimal load flow is only part of the problem. Further, the manual process used for evaluation of minimum life cycle cost is time-consuming and an automated technique would permit more alternatives to be investigated.

J: Satisfactory in the past, but gradually becoming inadequate.

K: Our experience in reactive power planning covers 15 years of applying the analytical techniques mentioned. We study modalities for improving load modelling and for extending the automatic calculations to all the optimizing process. For the actual studies the existing techniques are satisfactory.

L: The methods used are adequate for most system conditions. However, difficult conditions of voltage sensitivity sometimes lead to problems of pin-pointing the exact area(s) concerned. This leads us to believe that an automatic diagnostic feature would be desirable, which relied say, on the rate of change of reactive power during the study process. A more accurate load model may also give greater understanding of voltage sensitivity phenomena.

M: The methods applied are considered adequate in term of computing time, of constraints and of models if compared with the purpose to plan the medium term expansion of ENEL network. (There is necessity of improvements in coordinating the result obtained on the national 380-220 kV network witht the studied performed on the regional 150-132 kV.

N: Analytical tools are improved according requirements.

O: Utilization of optimization techniques for reactive power compensation studies have been improved to conventional loadflow analysis. However, further developments are required to improve loadflow solution with severe low voltage solutions and simultaneous optimization of extreme low and high voltage violations.

P: Both power flow and transient system analysis are powerful tools to make initial judgements in the performance of existing reactive supplies and determination of additional reactive requirements. They are also useful in doing some sensitivity analysis. However, they are limited in reactive power optimization because only one scenario can be analyzed at a time. It would be more precise and faster to optimize on a range of conditions which some newer programs can do.

Q: At present the critical point in the development is the inversion of big matrices greater than 300 x 300.

R: We have not experience enough with optimization methods (O.P.F.), but the results thus far are not quite satisfactory.

S: Our technique with successive load-flow calculations is a very cumbersome technique, but guarantees that false (unstable) loadflow solutions are detected.

T: (2/7) recognise that the repeated load flow technique is cumbersome and (1/2) doubts that optimal load flow is the answer.
(1/7) states that a robust, easy to use, optimal load flow is required.
(1/7) notes difficulty in treating varying power factor of loads and notes that improved load/voltage modelling is needed.

4.13. What kind of computer is used for running the analytical techniques utilized in the reactive planning process. (Micro, mini, big)?

A: Big computer: IBM 3081.

B: Big.

C: Big (UNIVAC 1100/90)

D: We use big computer (IBM 3081) through TSS terminals with TV display and printer.

E: A big computer is used. (HITAC M-280D, 32 MBITE, 9.6 MIPS; MIPS: Million Instruction Per Second)

F: Medium-size computer.

G: Two Prime 400 mini computers.

H: VAX 11/780

I: Big computer and minicomputer are used.

J: Mini-computer.

K: At present we use a computation system with

89

512 kbytes memory (FELIX CE 512).

L: An IBM 370 mainframe is used exclusively.

M: The method is normally used on big computers, but it may run also on mini computers.

N: Siemens Systems 7500.

O: The NYPP computer is a National Advanced System 9000 which is a big mainframe computer.

P: Prime 750 mini-computer.

Q: Big mainframe computer.

R: Big mainframe computer, accessed through a RJE terminal.

S: A Prime 450.

T: (3/7) have access to a mainframe (one of these is considering going to a dedicated mini).
(3/7) use a large mini (VAX 11/780 or 11/750).
(1/7) uses a mini (HP3000).

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21, rue d'Artois
FR-75 008 PARIS
Tél. : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99

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Tel : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99