

**PLANNING AGAINST VOLTAGE COLLAPSE
(Extensive version with all appendices)**

**Task Force 38-01-03
of Study Committee 38
(Power System Analysis and Techniques)**

October 1986



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Report on

Planning Against Voltage Collapse

(extensive version with all appendixes)

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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 use 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.

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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.

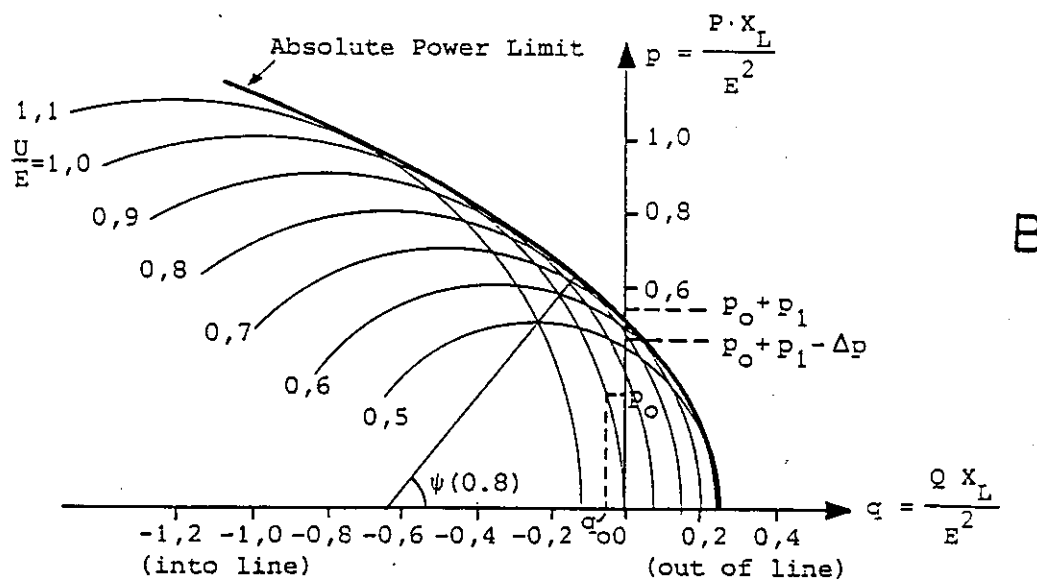
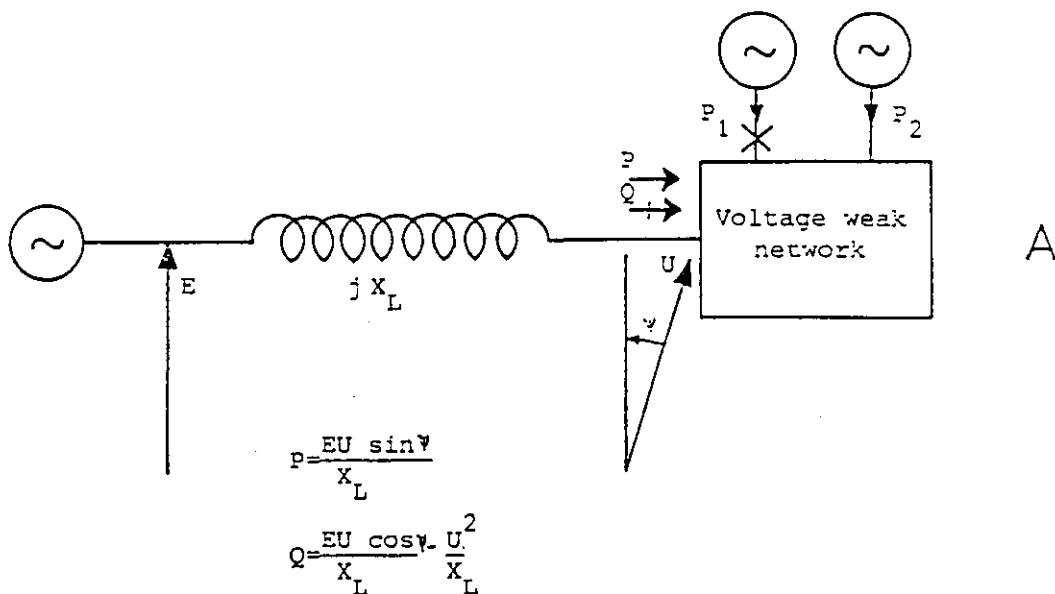
The most well-known steady state limitation to power transmission on a system occurs when the electrical angle between the voltage sources at the two ends reaches 90 degrees.

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 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



Note: Centres of circles are at $P = 0$
 $Q = -U^2/X_L$
 Radii are at $R = EU/X_L$

Figure 1. Receiving end line performance chart.

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.

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 when the reactive power generating capacity of P_1 is lost), equilibrium will be established at a lower voltage and with a lower transmission $P_0 + \Delta P_1 - \Delta P$, where P 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° . For instance, the transmission angle for $U/E = 0.8$ is shown by the designation $\psi (0.8)$ in figure 13.

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.

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 (appendix 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 $\text{tg}\phi$, 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 $\text{tg}\phi$ has a strong influence on the receiving-end voltage. For voltages in operating range 0.9 to 1.0 p.u. loads with positive $\text{tg}\phi$, with zero, or with low negative $\text{tg}\phi$ tend to reduce U as the load P increases. With large negative $\text{tg}\phi$ U increases until P reaches a much higher value. This represents an unstable operation condition for the assumed constant $\text{tg}\phi$ 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 examples SVC's) means that load $\text{tg}\phi$ is not constant.

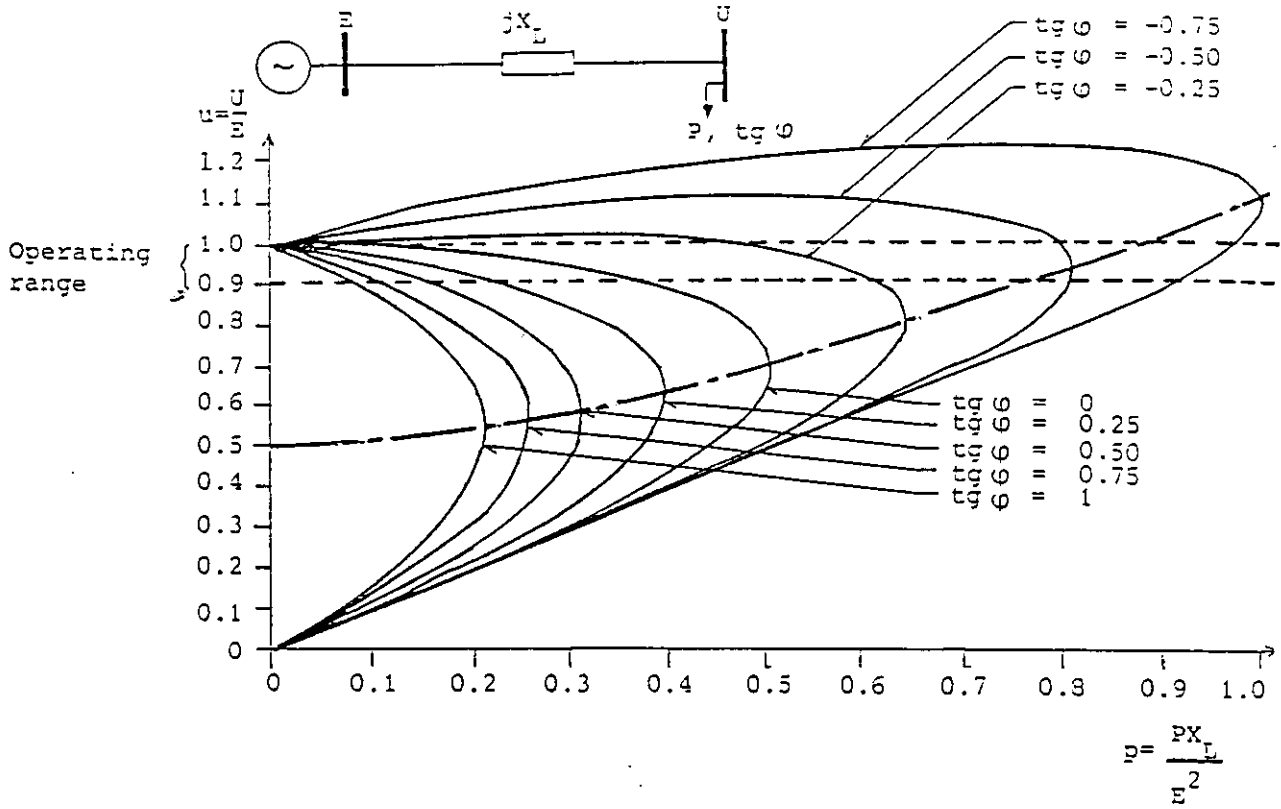


Figure 2.

U-P curves illustrating the relationship between the voltage and the load with $\text{tg}\phi$ as parameter.
 --- Curve connecting points with maximum power.

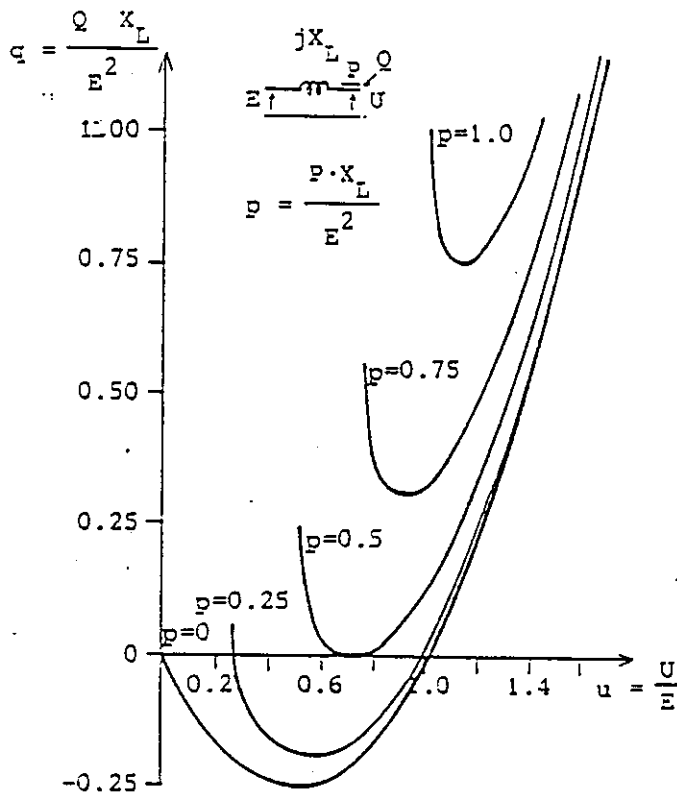


Figure 3.

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

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 several lines and the load plus compensation. General Q-U curves are derived in appendix 3. 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 (appendix 3) 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 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 pure 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 first 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 second 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.

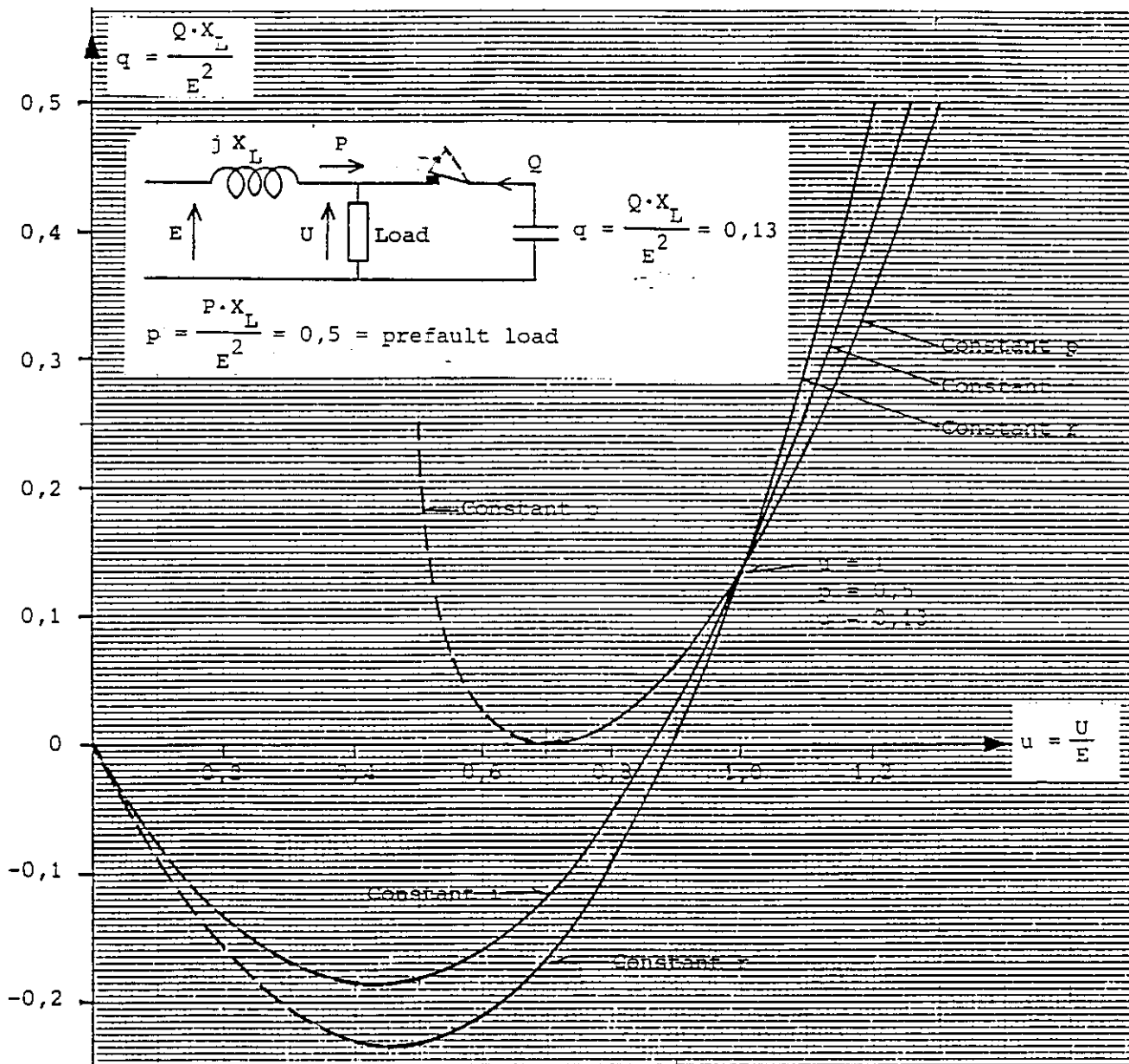


Figure 4 Q-U curves showing the influence of the load VS voltage characteristic on voltage stability.

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 SC38-02 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 subtransmission 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 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 use this measure 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 occurrence. There might not be sufficient justification to install transmission plant to prevent voltage collapse in such cases. However, it might be consistent for those utilities who use underfrequency load shedding to cover severe generating capacity loss to also 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 occurring 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 Stigsræs 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.

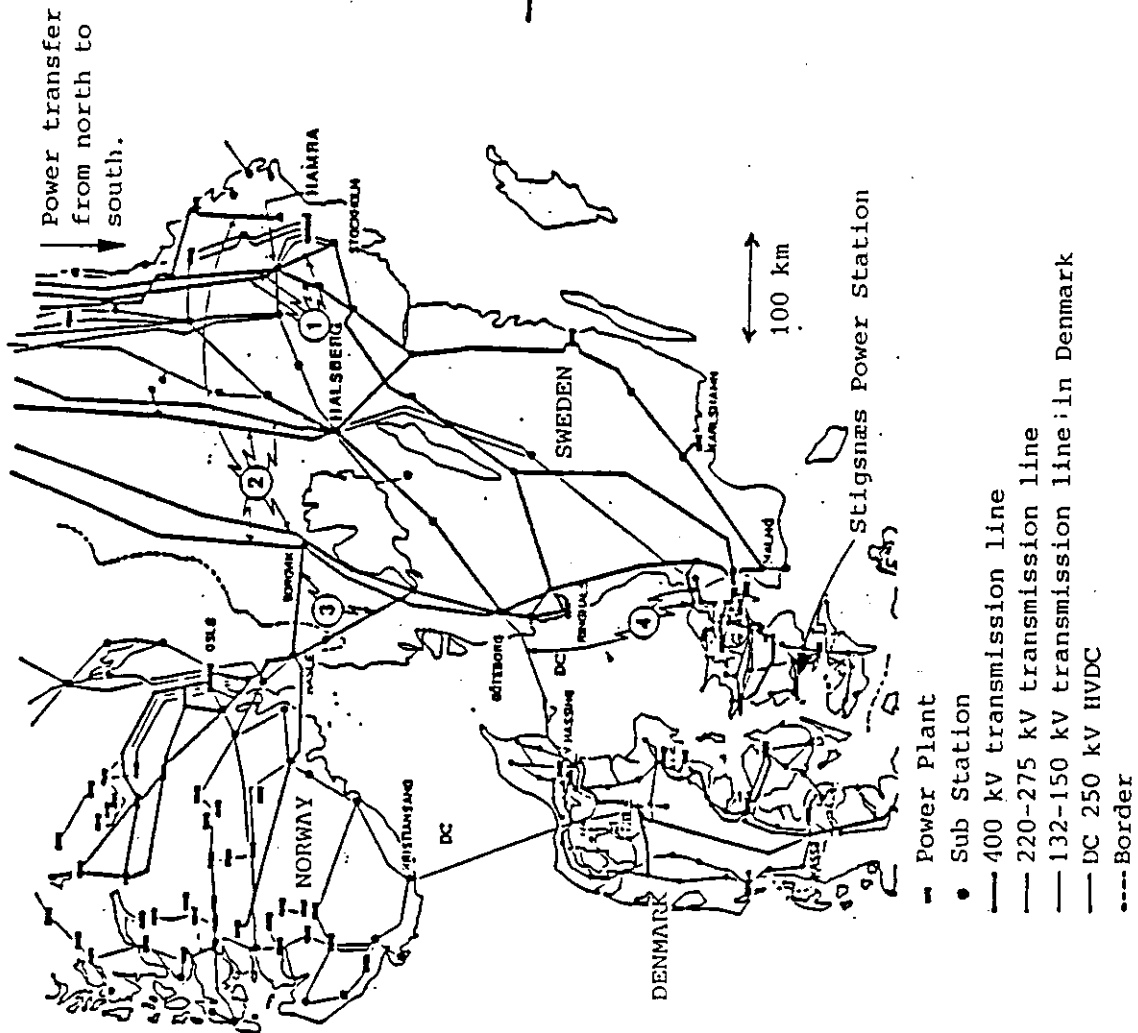


Figure 5

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 9.

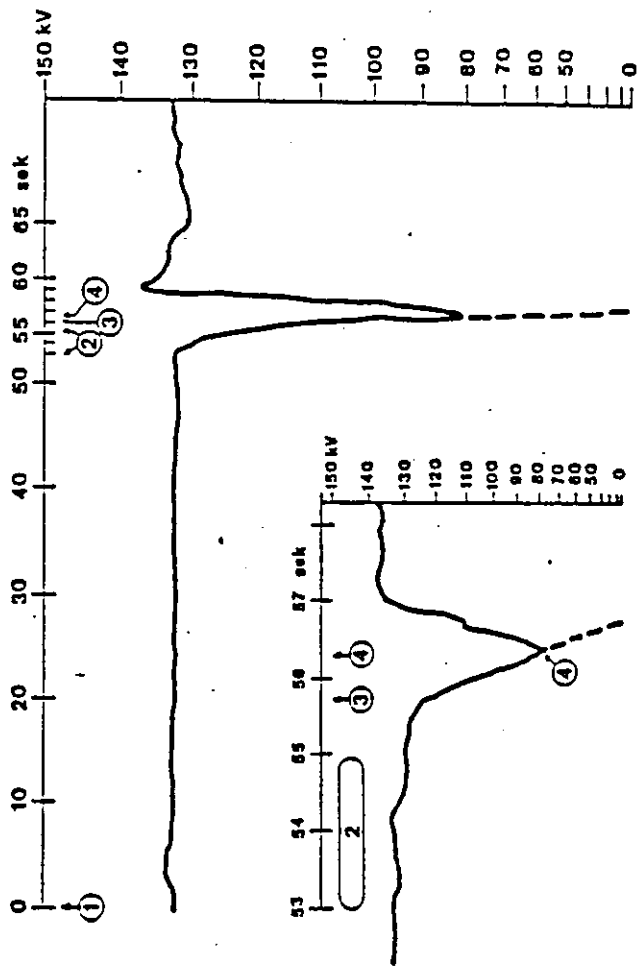


Figure 6

132 kv voltage measured at Stignäs 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 Sweden are tripped. About this time the Kontiskan line HVDC is tripped.

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

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 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 sta-

bility 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.

Reconnection 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 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 (appendix 4) use n-2 security criterion in reactive power planning (i.e. gene-

rator + 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 an $n-1$ 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 number of in-service breaker-switched capacitors in the pre-fault conditions. It is always an advantage to run 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 reduce the risk of voltage collapse after the contingency. Other than high system voltage the only limitation is due to the under-excitation 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 appendix 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 appendix 5. A description of the 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

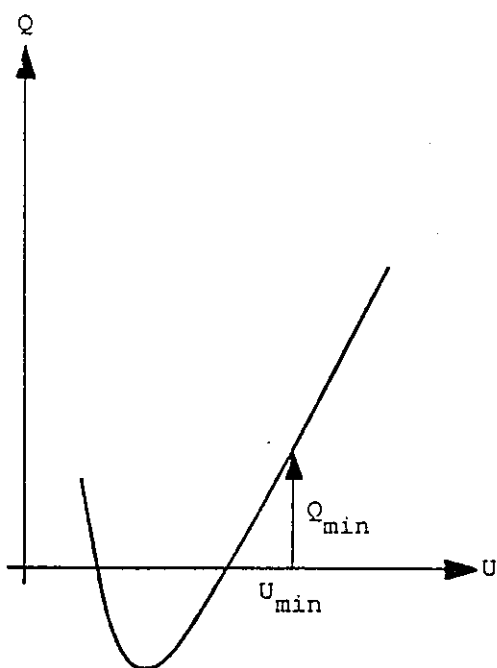


Figure 7. Post-fault constant power Q-U curve with intersections of the U-axis.

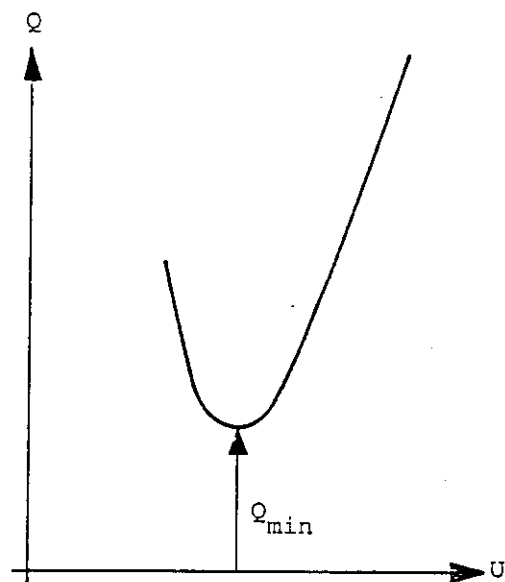


Figure 8. Post-fault constant power Q-U curve without intersections of the U-axis.

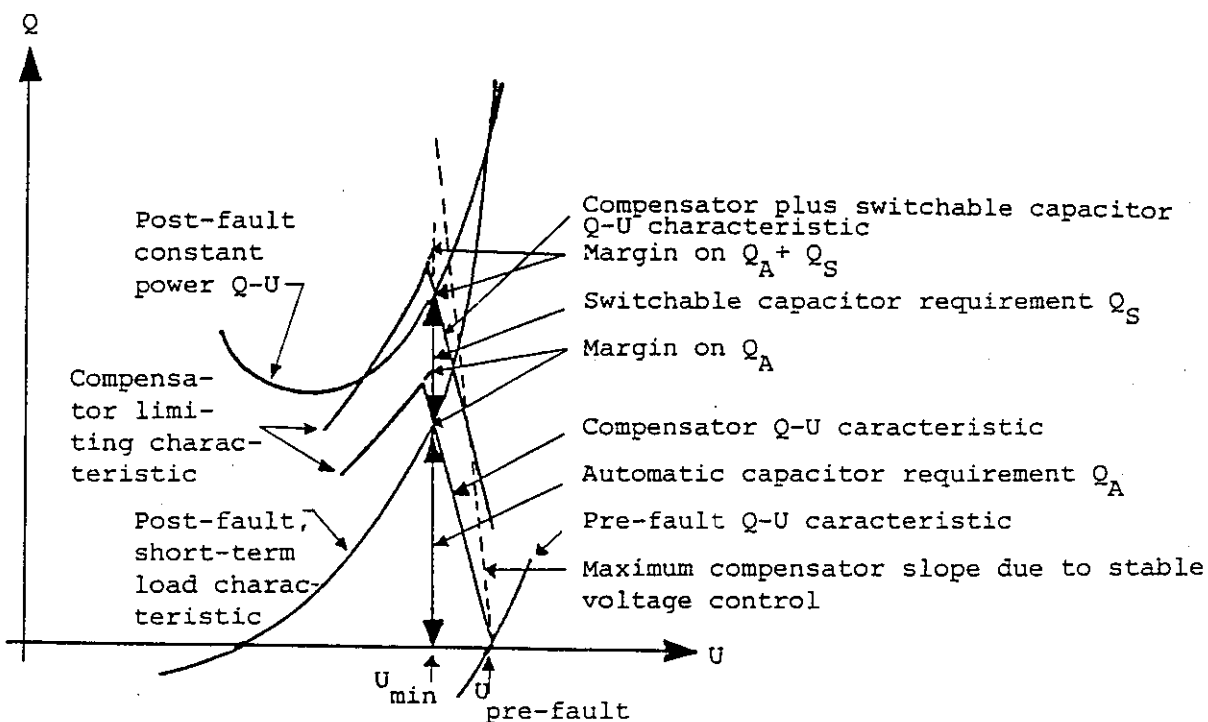


Figure 9. Procedure to determine the total need and the proportion of automatic and switchable reactive power injection at a certain busbar.

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

$$P = P_0 \left(\frac{U}{U_0}\right)^a \quad Q = Q_0 \left(\frac{U}{U_0}\right)^b$$

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 (appendix 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 of the response of generators to an over-excitation 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 correct representation of capacitors (and the network shunt capacitances) connected between the load and the main system.
10. Maintain practical margins from Q-U limits.

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An example to illustrate the use of the Q-U method is given in appendix 6.

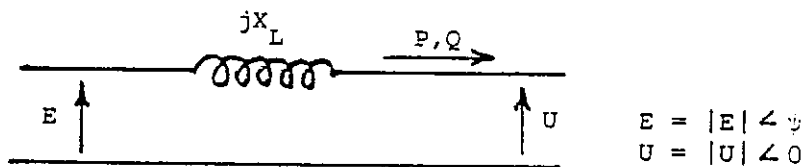
6. References

- [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. Fælck Christensen, J.S. Christiansen, T. Østrup,
1985. IEE Conference Publication, 255, 51-56.

General Expressions and PQ-curves for Lines

The electric power transmission on a line depends on its characteristics. For comparing different cases, it is easier to have a general expression for the system. In this appendix these general expressions and PQ-curves are given by substituting the per unit values for the quantities.

At first, the line will be represented in the following way:



with the equations:

$$P = \frac{E U}{X_L} \sin \psi$$

$$Q = \frac{E U}{X_L} \cos \psi - \frac{U^2}{X_L}$$

By isolating $\sin \psi$ and $\cos \psi$, squaring each and adding them, you will get an expression which is equal to one. Isolating P gives the following expression:

$$P^2 = \frac{E^2 U^2}{X_L^2} - \left(\frac{U^2}{X_L} + Q \right)^2$$

When this expression is rewritten, it is possible to change over to per unit values:

$$\left(\frac{P}{E^2/X_L} \right)^2 = \left(\frac{U}{E} \right)^2 - \left(\left(\frac{U}{E} \right)^2 + \frac{Q}{E^2/X_L} \right)^2$$

By substituting the following per unit values, you will get an expression without the reactance X_L and the voltage source E :

$$p = \frac{P}{E^2/X_L}, \quad q = \frac{Q}{E^2/X_L}, \quad \text{and } u = \frac{U}{E}$$

The per unit value equation is as follows:

$$p^2 = u^2 - (u^2 + q)^2$$

pq-curves

$$p^2 + (q + u^2)^2 = u^2: \text{ circles with centre } \left. \begin{array}{l} (p, q) = (0, -u^2) \\ \text{and radius} = u \end{array} \right\} \Rightarrow$$

$$\text{max. } q = -u^2 + u \text{ with a given } u$$

$$\frac{d(\text{max. } q)}{du} = -2u + 1 = 0 \text{ for } u = 1/2 \Rightarrow q = 1/4$$

Greatest value of $q = 1/4$ is obtained for $u = 1/2$ and $p = 0$

Envelope curve

$$p^2 = u^2 - (u^2 + q)^2$$

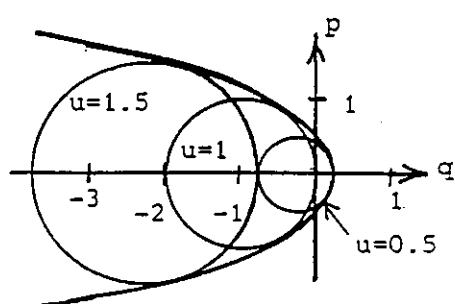
max. p . with given q for $\frac{dp}{du} = 0$

$$2p \frac{dp}{du} = 2u - 2(u^2 + q)2u = 0 \Rightarrow$$

$$q = 1/2 - u^2 \Rightarrow p^2 = u^2 - 1/4$$

$$p^2 = 1/4 - q$$

This is a parabola with focus in (0.0)



$$p^2 = 1/4 - q$$

u	(p, q) on envelope curve
0.5	(0, 0.25)
1	(0.87, -0.5)
1.5	(1.41, -1.75)

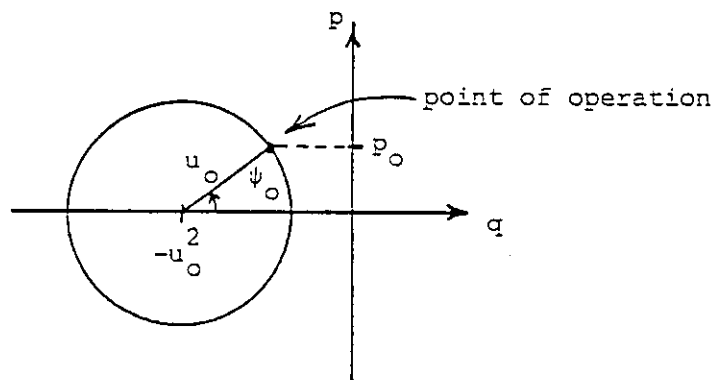
Power transmission

$$P = \frac{UE}{X_L} \sin \psi \quad (\psi \text{ transmission angle})$$

$$p = u \sin \psi$$

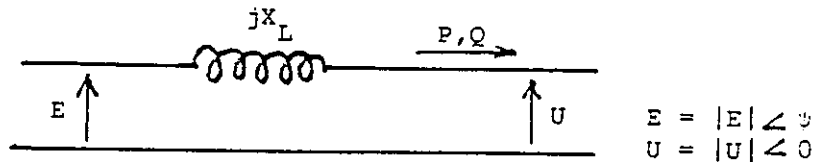
Transmission angle ψ

The expression above shows that this angle can be found in the pq-diagram as the angle between the q-axis and a line connecting the point of operation with the centre of the actual constant u-circle.



General Expressions and UP-curves for Lines

The line will be represented in the following way:



$$E = |E| \angle \psi$$

$$U = |U| \angle \theta$$

$$p = \frac{P}{\frac{E^2}{X}}$$

$$q = \frac{Q}{\frac{E^2}{X}}$$

$$u = \frac{U}{E}$$

As will appear from Appendix 1, page 2, the following equation is valid for a line represented as shown in the figure:

$$p^2 = u^2 - (u^2 + q)^2$$

Graph 1 presents the up-curve for q equal to zero.

The slope of this curve is given by the following expression:

$$\frac{du}{dp} = \frac{\sqrt{1 - u^2}}{1 - 2u^2}$$

The value of the slope at the beginning and at the end of the curve is stated in the graph.

The point p_{\max} is found with $\frac{dp}{du} = 0$ and gives:

$$p_{\max} = 0.5 \text{ and } u = \sqrt{0.5}$$

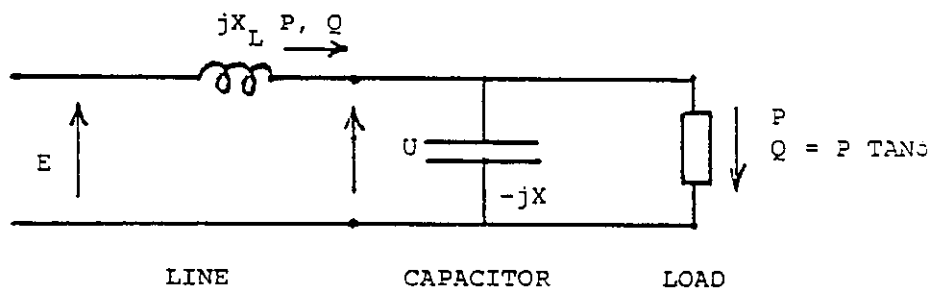
for a resistance load $R = X_L$.

Professor A.J. Calvaer has generalized this procedure for linear electric multiports in [1].

Instead of being constant the quantity Q can be made up of two parts.

- 1) The reactive power produced by a capacitor X with the size of U^2/X .
- 2) A consumption of reactive power with the size of $P \text{ TAN} \phi$.

This is represented by the following figure:



So the following expressions for Q and q can be written:

$$Q = -\frac{U^2}{X} + P \text{ TAN} \phi$$

$$q = -\frac{u^2}{x} + p \text{ TAN} \phi \text{ with } x = \frac{X}{X_L}$$

By substituting this last expression for q in the equation for p^2 a more detailed expression is obtained.

$$p^2 = u^2 - \left(u^2 - \frac{u^2}{x} + p \text{ TAN} \phi \right)^2$$

For a line with a capacitor X at the receiving end and $\text{TAN} \phi = 0$ the slope of the up-curve is given by the following expression:

$$\frac{du}{dp} = \frac{\sqrt{1 - u^2 \left(1 - \frac{1}{x}\right)^2}}{1 - 2u^2 \left(1 - \frac{1}{x}\right)}$$

The slope for $u = 0$ is $\left(\frac{du}{dp}\right)_{u=0} = 1$

The slope is 0 for $p = 0$, $u = \frac{1}{1 - \frac{1}{x}}$

p_{\max} is found by $\frac{dp}{du} = 0$:

$$p_{\max} = \frac{1}{2\left(1 - \frac{1}{x}\right)}, \quad u = \frac{1}{\sqrt{2}\left(1 - \frac{1}{x}\right)}$$

The curve connecting the points with p_{\max} for different $\text{tg}\phi$ (and no capacitor X) is found by:

$$p^2 = u^2 - (u^2 + p \text{tg}\phi)^2 \Rightarrow \text{(by implicit differentiation)}$$

$$\frac{du}{dp} = \frac{p(1 + \text{tg}^2\phi) + u^2 \text{tg}\phi}{u(1 - 2u^2 - 2p \text{tg}\phi)}$$

At p_{\max} $\frac{dp}{du} = 0$ and therefore $1 - 2u^2 - 2p \text{tg}\phi = 0$ giving

$$u^2 + p \text{tg}\phi = 1/2$$

This inserted in the basic expression gives $p^2 = u^2 - 1/4$.

This is a hyperbola with asymptote $u = p$ and intersecting the u -axis at $(u, p) = (0.5; 0)$ with a slope = 0.

The curve is shown on graph 1.

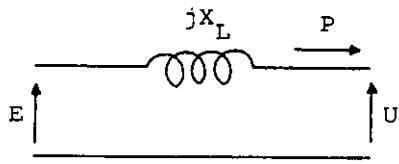
References

[1] A.J. Calvaer

On the Maximum Loading of Active Linear Electric Multi-ports

Proceedings of the IEEE, Vol 71, n^o2, February 1983, pp. 282-283.

Graph 1.



$$U = \frac{U}{E}$$

$$\left(\frac{\partial U}{\partial P}\right) = 0$$

$$U = 1$$

1,00

0,75

0,50

$$U^2 - P^2 = \frac{1}{4}$$

$$P_{max} = 0,5, U = \sqrt{0,5}$$

$$U = P$$



Nr. 249

1 x 1 mm

$$\left(\frac{\partial U}{\partial P}\right) = 1$$

$$U = 0$$

0

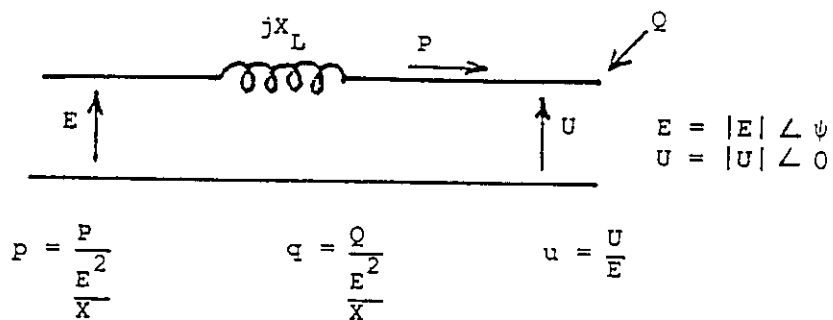
0,25

0,50

$$P = \frac{P \cdot X_L}{E^2}$$

General Expressions and QU-curves for Lines

The necessary amount of reactive power to get a given voltage at the receiving end of the line which transmits a fixed amount of active power can be read from a QU-curve. The characteristics of these curves will be examined. The line will be represented in the following way:



As will appear from Appendix 1, page 2, the next equation is valid for a line represented as shown in the figure (sign has been changed for Q):

$$p^2 = u^2 - (u^2 - q)^2$$

By rewriting this equation, you will get the next expression for q:

$$q = u^2 - \sqrt{u^2 - p^2}$$

The general qu-curves for several values of p have been drawn in graph 2.

End-points

The amount of active power, which can be transmitted along a reactance X_L at a voltage E at the sending end and a voltage U at the receiving end, is

$$P = \frac{E U}{X_L} \sin \psi$$

where ψ is the angle between U and E . The maximum of P is reached when

$$\psi = 90^\circ, P_{\max} = \frac{E U}{X_L}$$

By rewriting this equation it is possible to change over to per unit values:

$$\frac{P}{E^2/X_L} = \frac{U}{E} \Rightarrow p = u$$

The qu -curve ends on its left side in the point where $p = u$. All the qu -curves lie in the area between the curve $q = u^2$ (where $p = u$) and the curve $q = u^2 - u$ (where $p = 0$).

The slope of the curves with $p = \text{constant}$ is as follows:

$$\frac{dq}{du} = 2u - \frac{u}{\sqrt{u^2 - p^2}}$$

$$\frac{dq}{du} \Big|_{p=u \neq 0} = -\infty$$

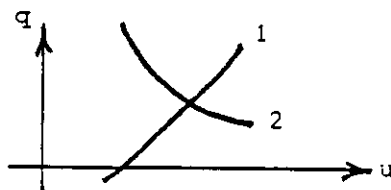
$$\frac{dq}{du} \Big|_{p=u=0} = -1$$

Minimum of the qu -curve

The qu -curves are made up of two parts which both depend on the voltage:

- 1) $Q_{\text{transmitted}}$
- 2) Q_{losses}

These are shown in the next figure:



The local minimum can be found by $\frac{dq}{du} = 0$:

$$u = \sqrt{p^2 + 1/4}$$

$$q_{\min} = p^2 - 1/4$$

It is seen that this minimum always exists.

The curve $q = u^2 - 1/2$ in graph 2B contains all the minimum points of the q -curves.

Steady-state stability

We can examine the steady-state equilibrium in a certain point of the curve by using the following methods with constant P :

- a) To make a small change of the voltage E and to keep Q constant.
- b) To make a small change of the voltage E and to suppose that Q is produced by a capacitor (or consumed by a reactance).

The curves for different values of the sending end voltage can be found by using the next expression:

$$q = u^2 - \sqrt{(E'/E)^2 u^2 - p^2}$$

where

E = the per unit voltage

E' = the new voltage at the sending end

re point a)

E.g. point A in graph 2A. A small decrease of E to E' ($E'/E = 0.98$) at the sending end of the line causes a decrease of the voltage U at the load at the receiving end. A new equilibrium is found in point B. Also a new equilibrium is found when a small increase of E to E' ($E'/E = 1.02$) takes

place, but then in point C. When we choose a point on the left side of the minimum of the curve, point D, a small decrease of the voltage E to E' ($E'/E = 0.98$) causes a decrease of U . Following the line $q = \text{constant}$ there is no intersection with the curve with the same p and at the new voltage at the sending end $E' < E$. When the voltage E increases a little, we follow the line $q = \text{constant}$ in the opposite direction. The qu -curve with $E' > E$ ($E'/E = 1.02$) is not intersected in the neighbourhood of the starting point, and the first equilibrium will be point C. Therefore, the part of the curve on the left of the minimum point has no steady-state stability for constant Q .

In graph 2B the curve $q = u^2 - 1/2$ between the area without and with steady-state stability for constant Q is drawn. This is the same curve as the one which contains all the minimum points of the qu -curves.

re point b)

E.g. point A in graph 2C. A decrease of E causes a decrease of U . An equilibrium is found, when we assume that the reactive power is produced by a capacitor at the intersection of the curve with the same p and the new voltage E' with the curve $q = 0.15 u^2$, point B. Also a new equilibrium is found when the voltage E increases, but then in point C. When we choose e.g. point D, a small voltage drop causes a voltage drop at the receiving end at the load. The qu -curve for E' smaller than E is not intersected any more, and there is no equilibrium. There is no equilibrium in the neighbourhood of the starting point when the voltage increases a little. The limit case is when the curve $q = ku^2$ touches a qu -curve which happens for $k = 1 - 1/(2p)$. This is shown in graph 2D for the qu -curve $p = 0.75$ which touches the curve $q = 0.33 u^2$. The area on the left of the curve $q = u^2 - u/\sqrt{2}$ has no steady-state stability when Q is produced by a condensator (or reactor). On the right side it has.

In graph 3 the qu -curves are drawn for different values of the current per unit value i . The value of i can only vary between 0 and 1. The curves for these two values also give the two limit curves.

The expression for the qu -curves for constant i is as follows:

$$q = u^2 - u \sqrt{1 - i^2}$$

The curve which goes through all the minimum points has the next equation:

$$q = -u^2$$

The points of the qu -curves above this curve have steady-state stability for constant i and constant q . The explanation is similar to the one of the qu -curves for constant p . The whole qu -curve has steady-state stability when q is produced by a capacitor or consumed by a reactance.

In graph 4 the qu -curves are drawn for different values of the load resistance per unit value, r . The qu -curve for $r = \infty$ is one of the limit curves, the other one is formed by the parabola $q = u^2$. The expression for the qu -curves for constant r is as follows:

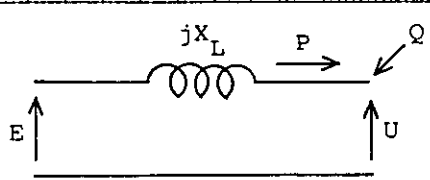
$$q = u^2 - u \sqrt{1 - u^2/r^2}$$

The curve which contains all the minimum points of the qu -curves for constant r has the following equation:

$$q = \frac{1}{2} u^2 - \frac{1}{2} u \sqrt{u^2 + 2}$$

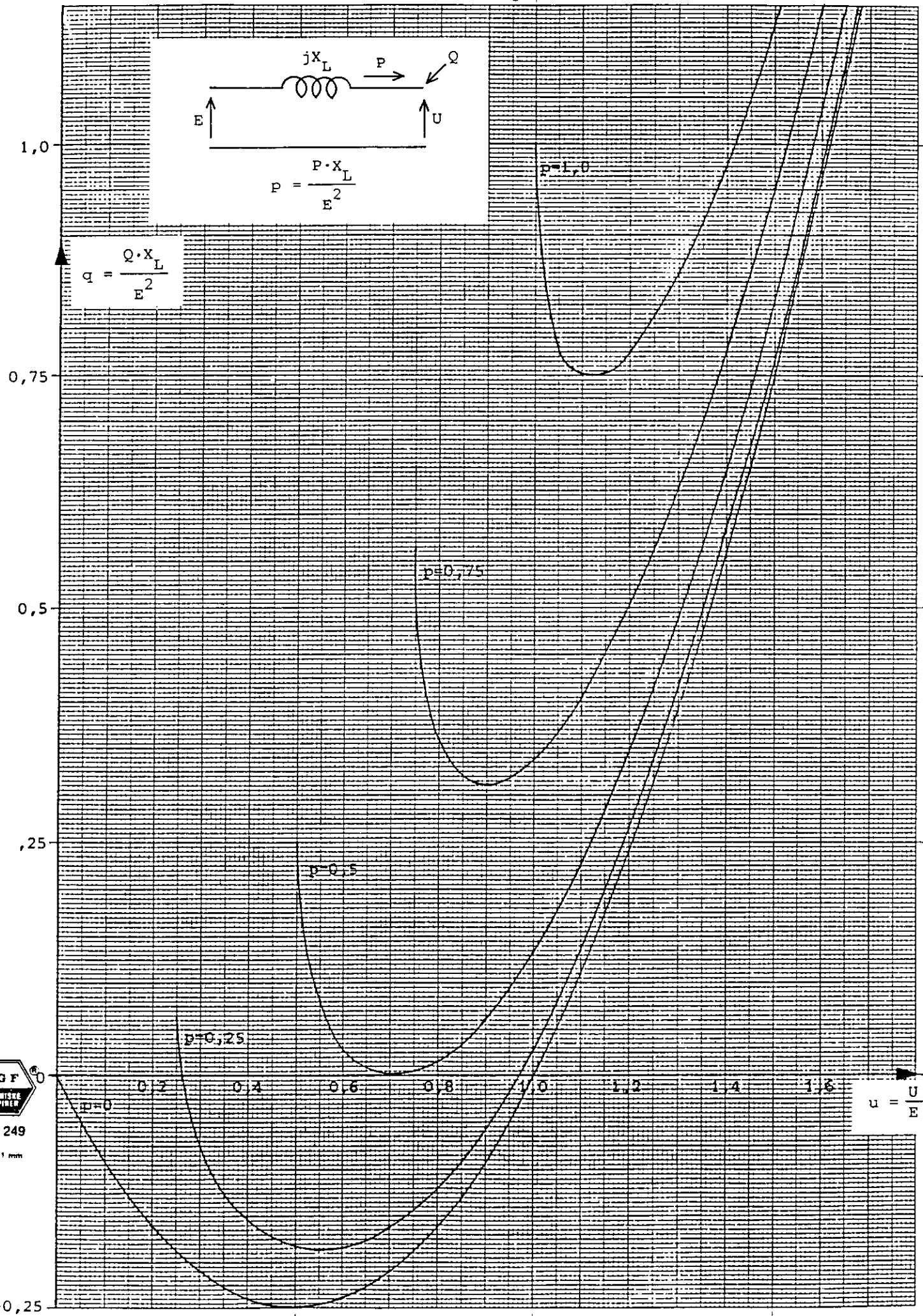
This curve gives the boundary for steady-state equilibrium with $q = \text{constant}$. All parts of the qu -curves has steady-state stability when q is produced by a capacitor or consumed by a reactance.

Graph 2.



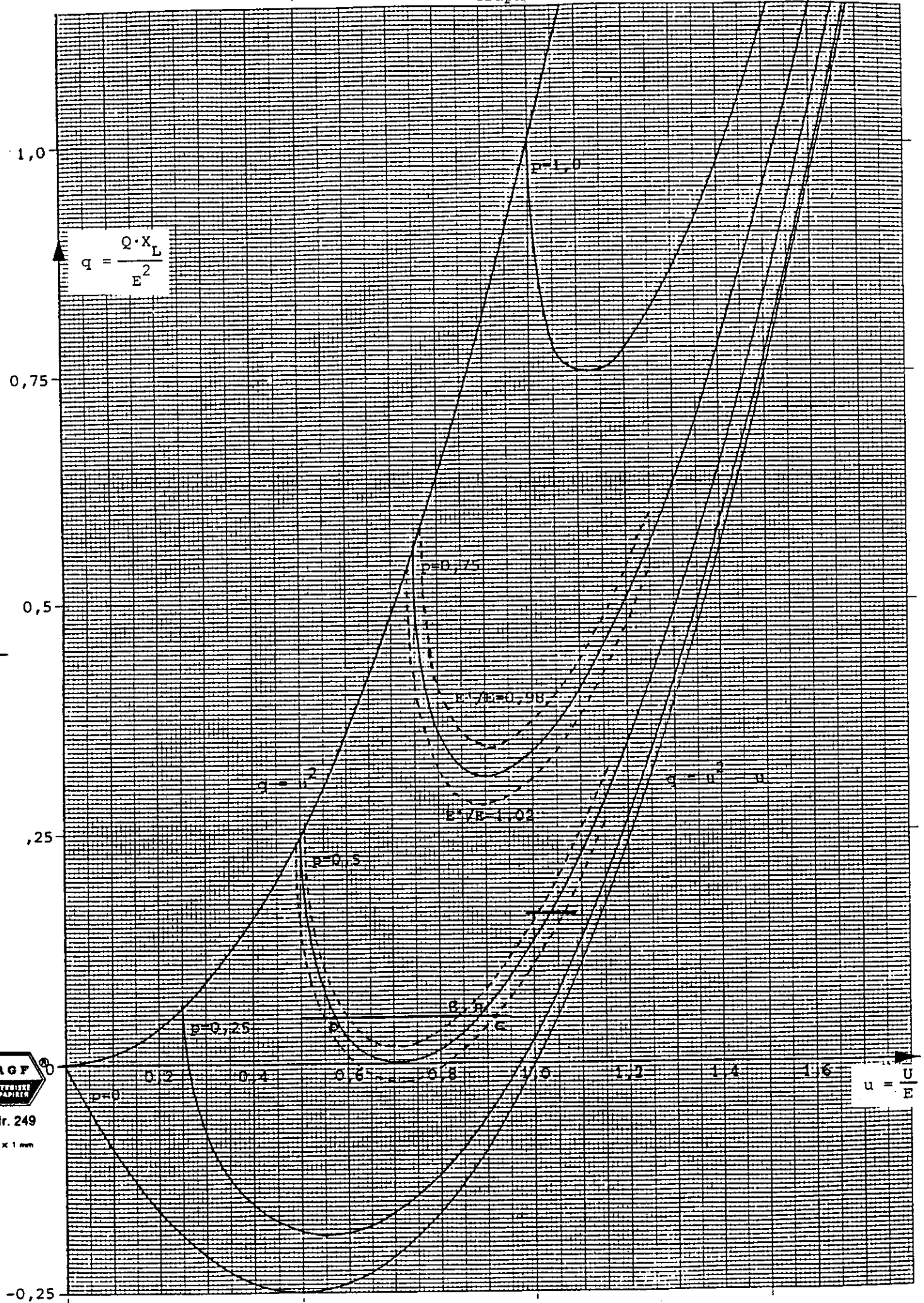
$$p = \frac{P \cdot X_L}{E^2}$$

$$q = \frac{Q \cdot X_L}{E^2}$$



Nr. 249
1 x 1 mm

Graph 2A.



Nr. 249
1 x 1 mm

$$u = \frac{C}{E}$$

Graph 2B.

$$q = \frac{Q \cdot X_L}{E^2}$$

1,0

0,75

0,5

,25

-0,25

$p=1,0$

$q = u^2$

$p=0,75$

$q = u^2$

$p=0,5$

$q = u^2$

$p=0,25$

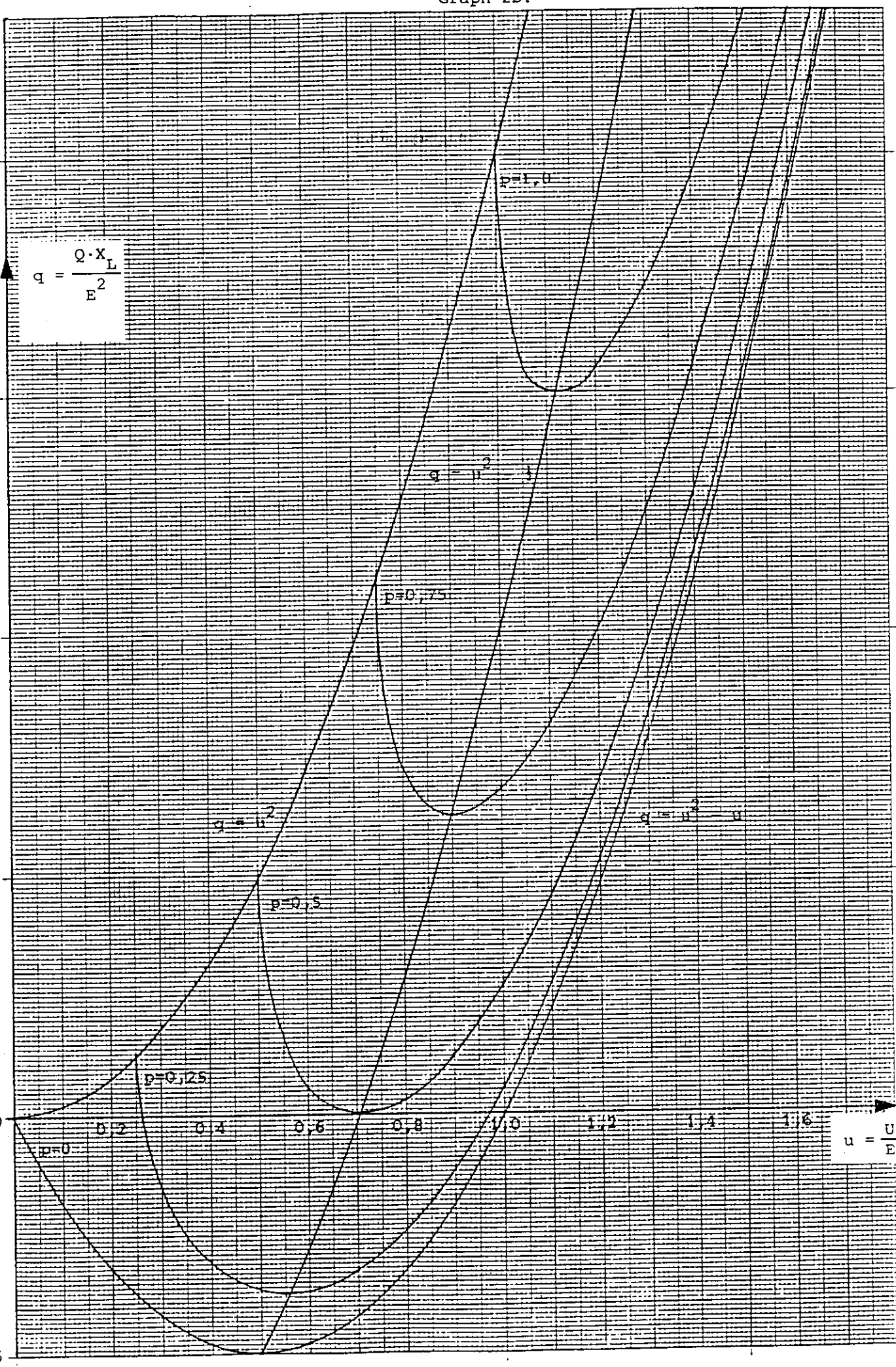
$p=0$

$u = \frac{U}{E}$

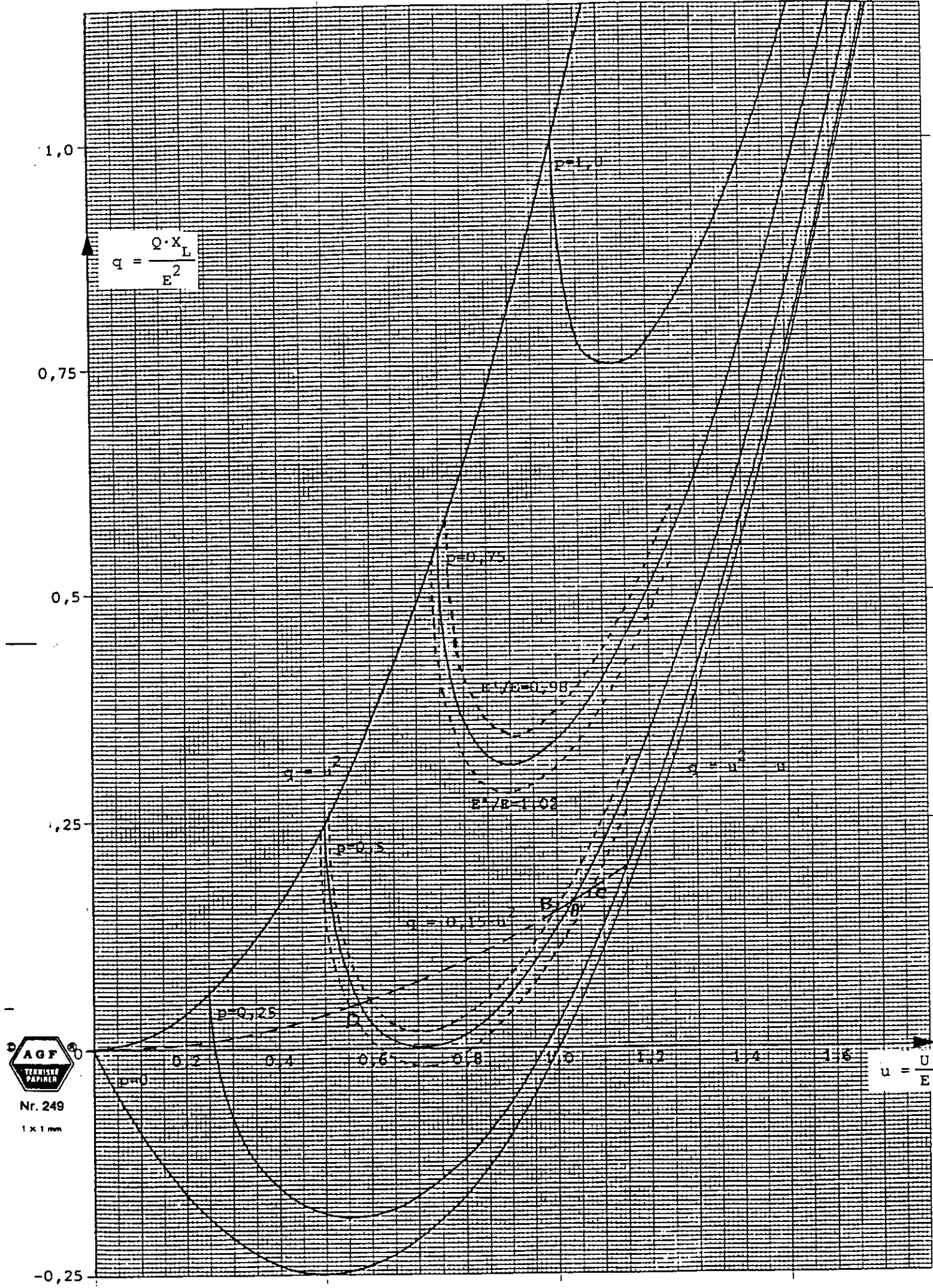


Nr. 249

1 x 1 mm

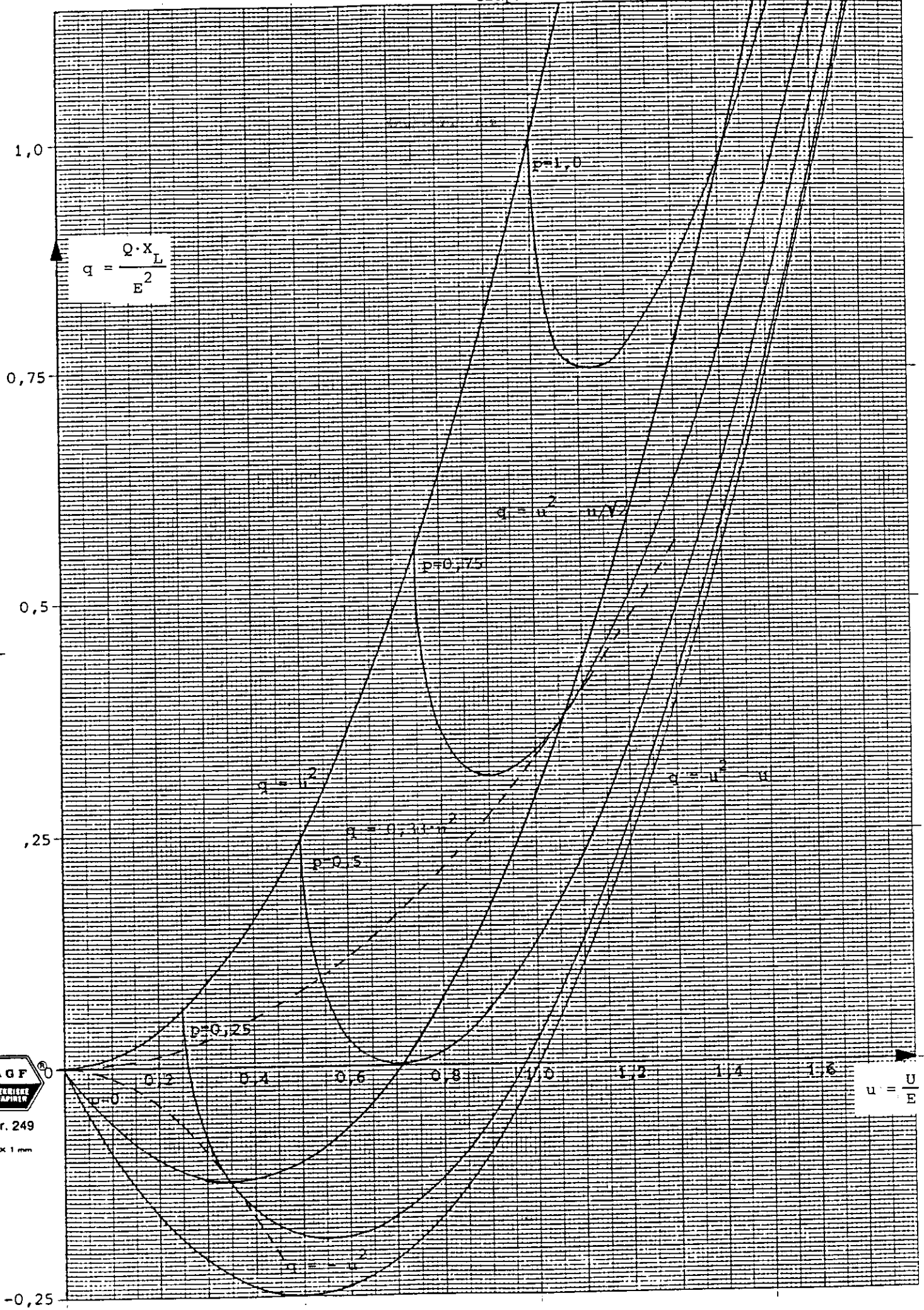


Graph 2C.



Nr. 249
1 x 1 mm

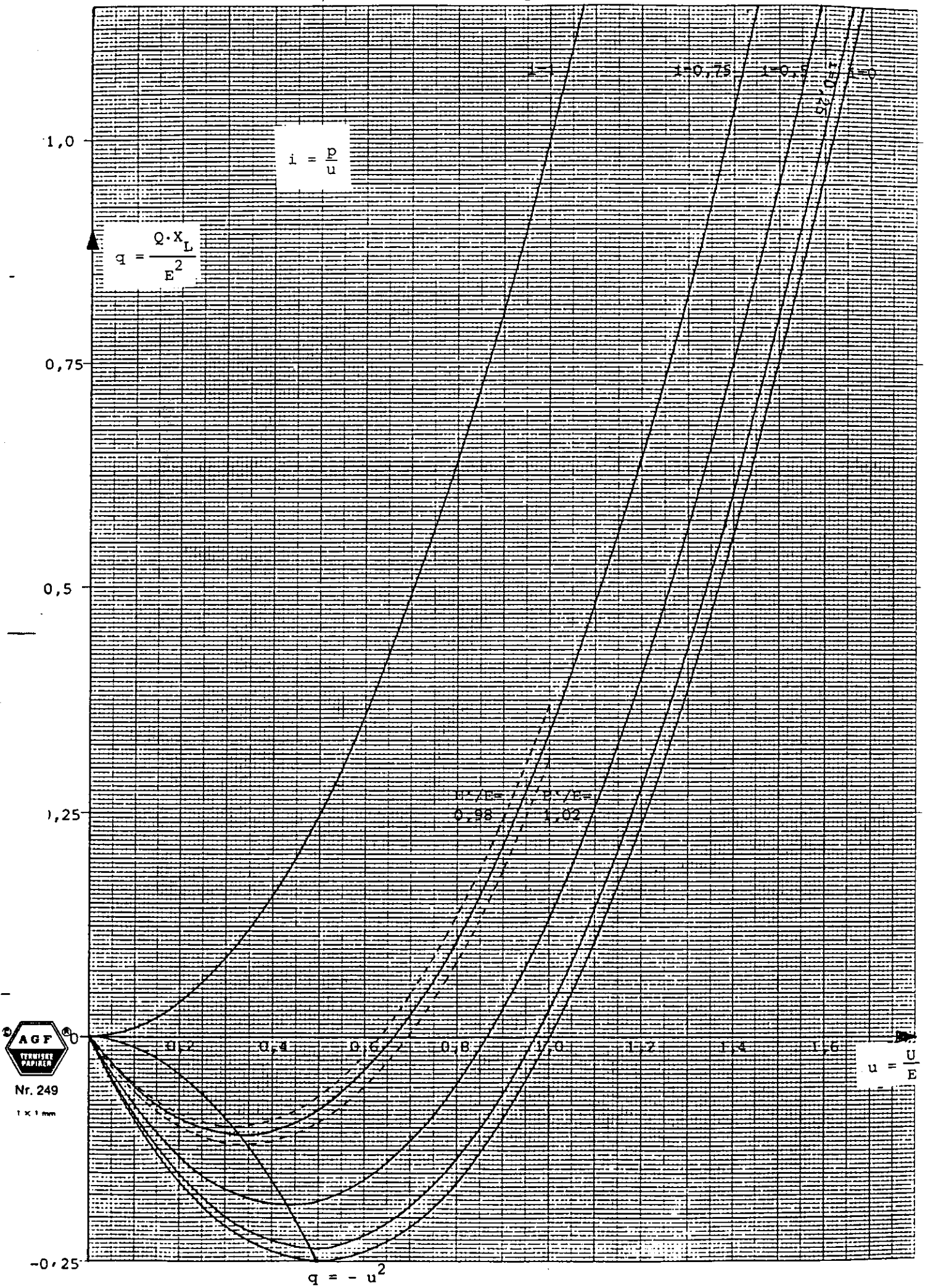
Graph 2D.



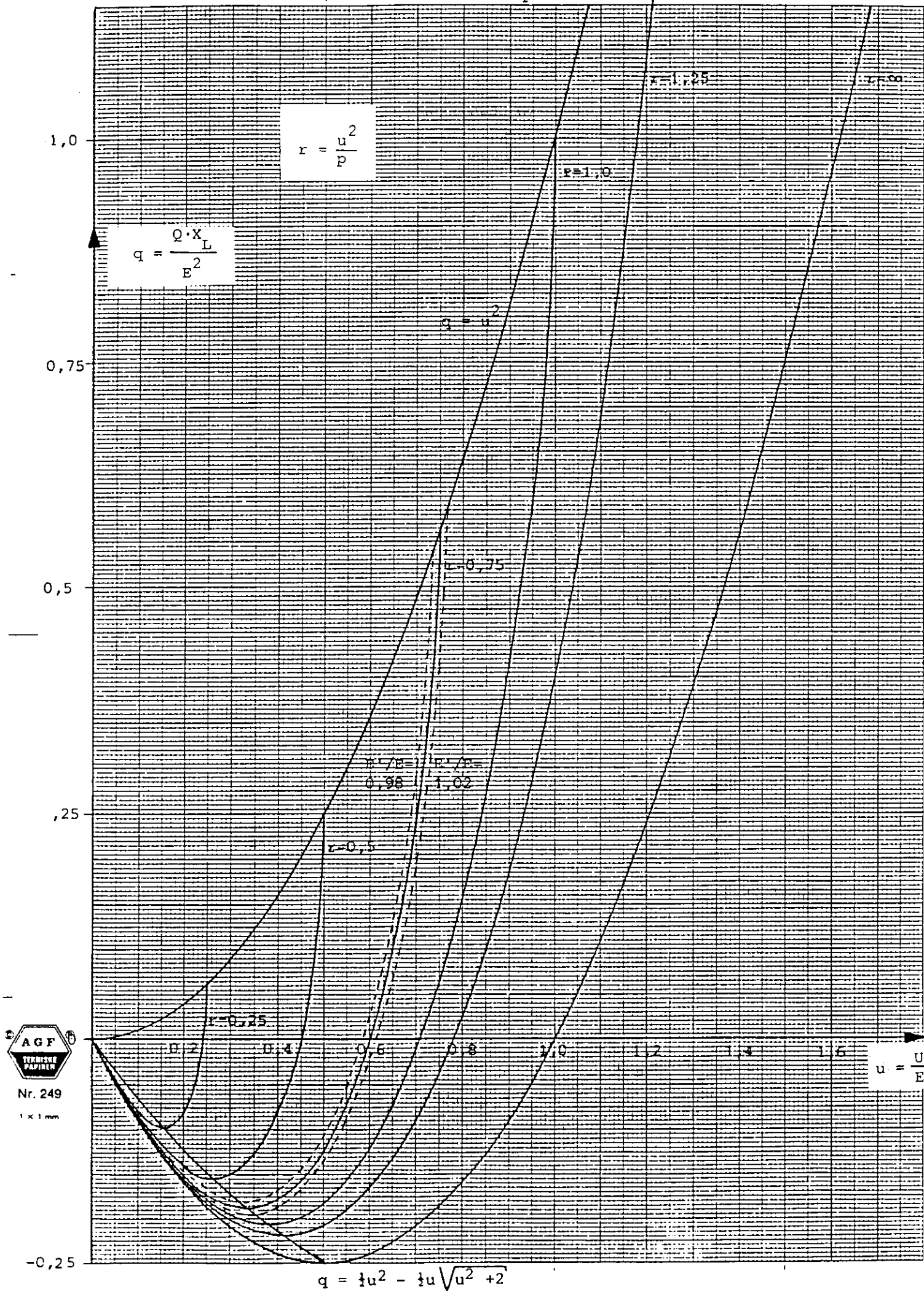
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Graph 3.



Graph 4.



Extract of:

Answers to the Questionnaire on Use of Reactive Power
Optimization Techniques in System Planning

CIGRE SC 38 WG 01 TF03

August 1985

Extract based on a going-through the questionnaire in
relation to planning against voltage collapse.

Country/ Company	Objectives	Security Criterion	Implementation in the planning process of:	Analytical techniques for studying:	Transient stability or other dynamic simulations
E.D.F. (France)	Observance of technical constraints in normal and emergency cases in many different operation conditions	- n-1 security: tripping of one line or one generator	- contingencies: successive optimizations with various network conditions: new shunt capacitors or reactors added up from one situation to the other - reactive power reserves: more restrictive limits on voltage or reactive possibilities are introduced	- security criterion: $\frac{\delta Q_p}{\delta Q_L} = \frac{\text{reactive power supp.}}{\text{reactive load incr.}}$ - simulation of post-fault conditions	- to choose between the different devices or defining the control laws
Belgium (combined)	- to get a sufficient reactive power reserve on generators in order to avoid their overloading in case of tripping	- n-1: one line (or transformer), one generator - n-2: generator + line (or transformer) - tripping of 400 kV busbar	- study of post-disturbance equilibrium state of the generators	- voltage stability criterion: $\frac{U_i}{E_i}$ -> actual voltage -> voltage with load and active generation equal to 0	
Chubu (Japan)	- adjustment of voltage level in electric power system - supply of reactive power consumption - loss minimization	- n-1 security	- multiple contingencies	not considered	
Tokio (Japan)	- to maintain adequate voltage - to reduce transmission losses	- n-1 security	- reactive power reserves and effects of contingencies are handled manually	- sensitivity techniques ($\Delta V/\Delta Q$)	- to study effects of load rejection on nuclear plants

Country/ Company	Objectives	Security Criterion	Implementation in the planning process of:	Analytical techniques for studying:	Transient stability or other dynamic simulations
Czechoslovakia	- preservation of voltage in technical limits	- n-1 security - n-2 in special cases	- reactive power reserves - effects of contingencies and/or multiple contingencies	- voltage stability - reactive power reserves conditions	- to make decisions on the underexcitation limits (Q-limits) at power plants
T.V.A. (U.S.A.)	- voltage control • steady-state • control of voltage during switching - reduction of real losses - limit reactive power absorbed by generators	- n-1 security - probability of occurrence - stability considerations - limit reactive output of nuclear generating sets		- conventional load flow considering the possible locations of reactive power generation	- to evaluate ability of units to absorb reactive power during light load periods - to evaluate voltage collapse and effect of reactive supply during the contingencies
Switzerland (combined)	- constraints of voltage - minimum cost investments and minimum MW losses	- n-1 security - n-2 security for some particular cases			
Swedish State Power Board (Sweden)	- technical and security constraints	- safety margin in planning for shunt capacitors and reactors (one unit out of generation) - busbar faults shall not cause load shedding	- reactive reserves handled manually	- load flows with successively increased transfers	- to study necessary reactive reserves during the dynamic sequence caused by a network fault - steady-state calculations on a post-fault situation in the network
Norway (combined)	- satisfactory voltage levels during normal and (n-1) outage conditions	- n-1 security - n-2 security is under consideration	- effect of contingencies handled manually	- load flow studies	

Country/ Company	Objectives	Security Criterion	Implementation in the planning process of:	Analytical techniques for studying:	Transient stability or other dynamic simulations
Romania	<ul style="list-style-type: none"> - to achieve safe operation for transmission system - to minimize power transmission and distribution costs 	<ul style="list-style-type: none"> - loss of largest generator unit and of the most important transmission line 	<ul style="list-style-type: none"> - calculation of supplementary reactive compensation devices for maintaining the voltage within the specified limits during the contingencies 	<ul style="list-style-type: none"> - changing the sign of the characteristic equation describing the system operation 	
CEGB (England)	<ul style="list-style-type: none"> - steady state voltage limitation of voltage step changes following double circuit fault outages - sufficient reactive power reserves 	<ul style="list-style-type: none"> - single, two circuit or double circuit overhead line outage - supergrid transformers outage - reactive compensator outage 	<ul style="list-style-type: none"> - both reactive compensation and reserves are considered and evaluated, both under the above planning criteria and other critical multiple outage contingency conditions 	<ul style="list-style-type: none"> - simulating credible fault outages with inhibition of transformer tap-changers and calculation of reactive absorption/generation reserves (especially in case of double circuit fault outages) 	<ul style="list-style-type: none"> - transient stability studies define mainly the amount and type of reactive power compensation that should be installed to provide not only transient but also the necessary post outage voltage support. The switching in of shunt capacitors is a special case within this process
ENEL (Italy)	<ul style="list-style-type: none"> - to meet technical and security requirements - to improve system economy 	<ul style="list-style-type: none"> - n-1 security applied in implicit form: suitable reserve margin on generators, limiting the permitted variation range of voltage 	<ul style="list-style-type: none"> - included 		
Siemens (Germany)	<ul style="list-style-type: none"> - voltage regulation in all load conditions of system including contingency economic load flow 	<ul style="list-style-type: none"> - n-1 security under various operating conditions 	<ul style="list-style-type: none"> - included 	<ul style="list-style-type: none"> - increase of reactive load caused by loss of important lines 	<ul style="list-style-type: none"> - to lay out reactive power components in HV-projects

Country/ Company	Objectives	Security Criterion	Implementation in the planning process of:	Analytical techniques for studying:	Transient stability or other dynamic simulations
New York Power Pool (U.S.A.)	<ul style="list-style-type: none"> - to provide acceptable voltage response for pre- and post-disturbance conditions and to maximize economic transfer capability 	<ul style="list-style-type: none"> - respect of voltage limits in pre- and post-contingency conditions 	<ul style="list-style-type: none"> - contingencies: interactive process with optimal load flow 	<ul style="list-style-type: none"> - sensitivity analysis by a trial-and-error process 	
Northern State Power (U.S.A.)	<ul style="list-style-type: none"> - to maintain the system voltage during normal operation and severe disturbances - using capacitors to defer expensive transmission facilities - reducing losses and capital expenses 	<ul style="list-style-type: none"> - to keep the system operation within established criteria 	<ul style="list-style-type: none"> - adding reactive power sources is considered for solving contingency-caused problem 	<ul style="list-style-type: none"> - power flow with different load levels or different reactive power conditions 	<ul style="list-style-type: none"> - to determine what type of reactive power device should be installed
Hidroeléctrica Española (Spain)	<ul style="list-style-type: none"> - voltage limitation during normal and (n-1) outage conditions - to minimize active power losses - to maintain the stability 	<ul style="list-style-type: none"> - n-1 security 	<ul style="list-style-type: none"> - reactive reserves and effect of contingencies handled manually 		
ELKRAFT (Denmark)	<ul style="list-style-type: none"> - to withstand certain contingencies - optimum between installation of reactive power and the matching limitation on the economic dispatch 	<ul style="list-style-type: none"> - Nordel dimension criteria (n-1 security) 	<ul style="list-style-type: none"> - curve with system transfer related to reactive resources, including contingencies 	<ul style="list-style-type: none"> - successive load flow with all automatic controls in action (QV-curves on post-fault operating conditions) 	<ul style="list-style-type: none"> - Transient stability studies - Studies of overvoltages in connection with load rejection and load shedding

Modelling of the Response of Generators to an Overexcitation
Demand From the System

1. Introduction

Synchronous generators are the main source of reactive power in most power systems. A good knowledge of their behaviour and of their voltage control system is necessary for the study of the network voltage stability and for the sizing of reactive sources and reserves at the planning stage.

Here we do not want to develop the transient stability modelling but only a quasi steady-state model, which allows the calculation of the post-disturbance equilibrium state with a load flow computer program

2. Generator under the control of its voltage regulator

In order to calculate the post-disturbance equilibrium point of the generators after the tripping of a generation unit or a line, A.J. Calvaer ([1] to [4]) has developed a linearized model of the generator and its auxiliaries. The main advantage of the model is the efficient choice of the independent variables, mainly the reactive current I_Q . This choice allows a linear behaviour, as far as possible, and a fair simplicity of mathematical equations.

Hereafter we will go through the model in a very shortened way.

Let us consider a synchronous generator at a given operating point described by the injected real power P_0 and reactive power Q_0 , the terminal voltage being U_0 .

Around this (stable) operating point, the terminal voltage U may be written as follows (limiting the Taylor's expansion formula to the first order), neglecting the frequency deviation:

$$U = U_o + \frac{\partial U}{\partial I_P} dI_P + \frac{\partial U}{\partial I_Q} dI_Q + \frac{\partial U}{\partial U_C} dU_C$$

where: dI_P is the active current variation
 dI_Q is the reactive current variation
 dU_C is the control voltage variation

Using the following notation:

$$U = U_o - X_{mP} dI_P - X_{mQ} dI_Q + K_C dU_C$$

one can prove (see [4]) that, in most common cases:

$$X_{mP} \approx \frac{X \sin \theta}{G} \quad X_{mQ} \approx \frac{X \cos \theta}{G} \quad K_C \approx 1$$

where: X is the generator synchronous reactance
 θ is the generator internal angle
 G is the open loop static gain of the AVR.

The magnitudes of X_{mQ} and X_{mP} are about a few percent (for normal value of $G = 20, \dots, 200$). Their values depend on the machine operating point.

Now we derive an equivalent circuit for the generator around its operating point, as shown in figure 1.

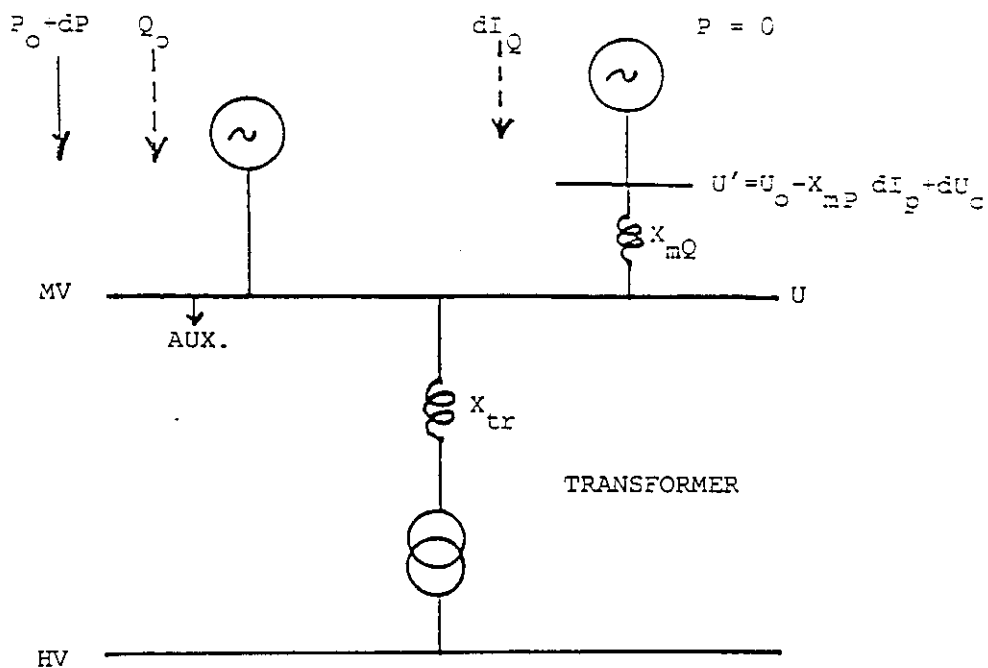


Figure 1: The "Two-generators" equivalent circuit of a synchronous machine around a given operating point (P_0 , Q_0 , U_0).

In the case of a pure network voltage disturbance (without permanent frequency deviation, one assumes $dP \approx dI_p \approx 0$, and the model consists of adding one P.V. node behind the X_{mQ} reactance at each generation bus of the load flow calculation process.

3. Excitation limitation

To the increase of the reactive power, as a result of a network disturbance for example, corresponds an increase of the field current if_d . If the latter goes beyond a preset value, the rotor protection is activated, and the field current limiter is put into service, maintaining the field current at a fixed value if_{dm} (below the permanent maximum field current).

Figure 2 shows the above linear model characteristic (straight line a) and the boundary lines (1) and (2) corresponding to the working of the field current limiter for two values of the active power.

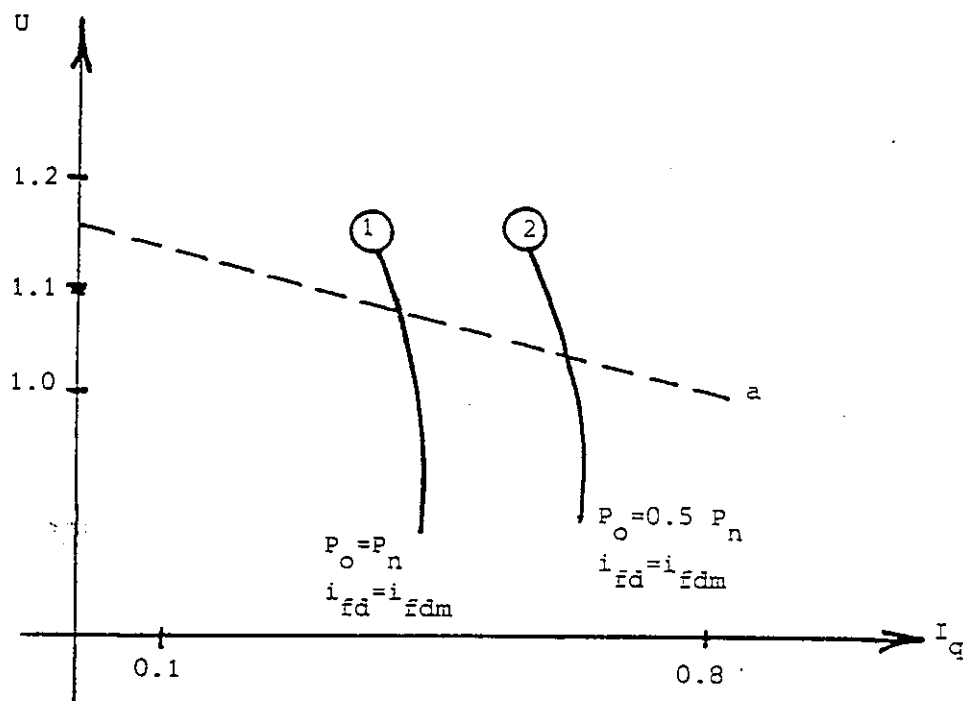


Figure 2: U - I_Q characteristics and boundary lines corresponding to the field current limiter.

The boundary lines are calculated by the Potier's method in order to take into account the magnetic saturation effect of the generators. To process a classical load flow calculation on a network including generators working with field current limiters, it is necessary to convert the (U, I_Q) curves into (U, Q) tables and to use PV nodes with a special iteration scheme.

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- [2] A.J. Calvaer, B. Lemal, "A Straightforward Determination of the Post-Disturbance Equilibrium State of an A.C. Power System", Proceedings of the Sixth Power Systems Computation Conference (PSCC), Darmstadt (FRG), published by IPC Science and Technology Press (England), Vol. 2, pp. 688-691, August 21-25, 1978.
- [3] A.J. Calvaer, E. van Geert, "Quasi Steady State Synchronous Machine Linearization Around an Operating Point and Applications" - IEEE/PES 1984 Winter Meeting, Dallas, Texas, January 29 - February 3, 1984.
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29 août - 6 septembre - Rapport n° 38-11.

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 on 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. The worst contingency is a busbar fault indicated by "fault 1" on 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 on 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.

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

From figure 10C it appears that there is no need for thyristor-switched capacitors at all, but with the alternative load response on 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 on 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 on 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.

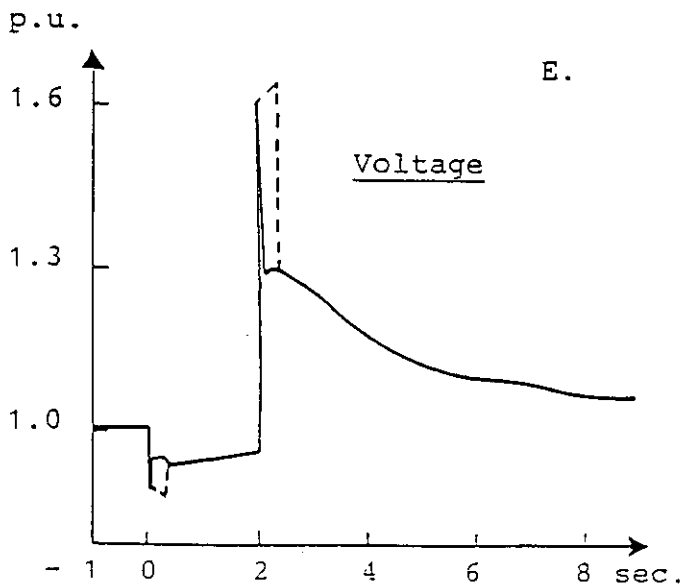
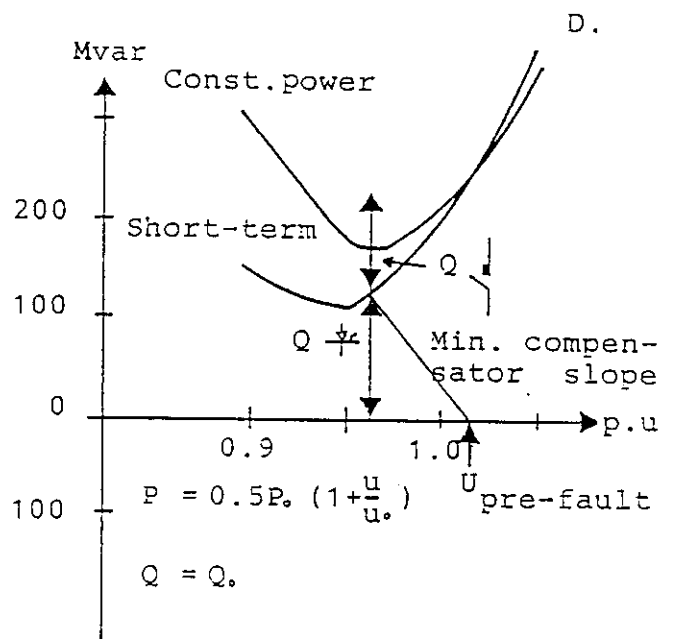
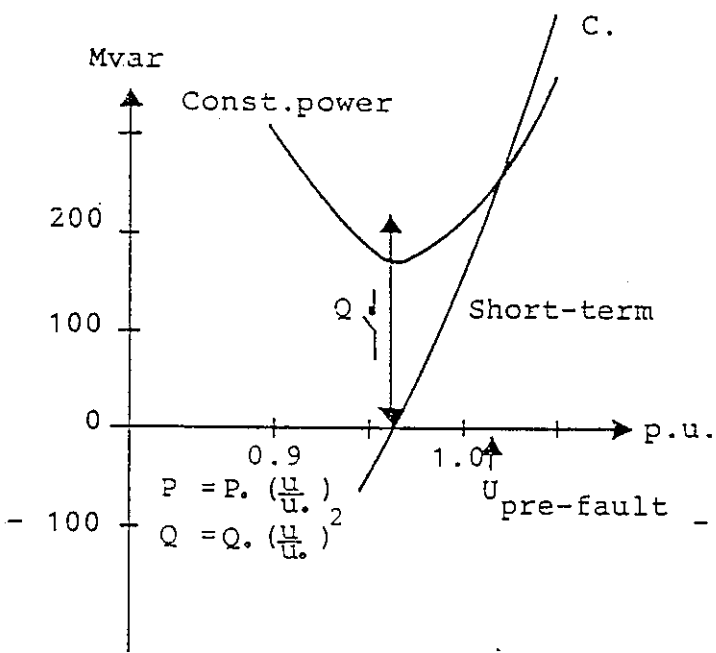
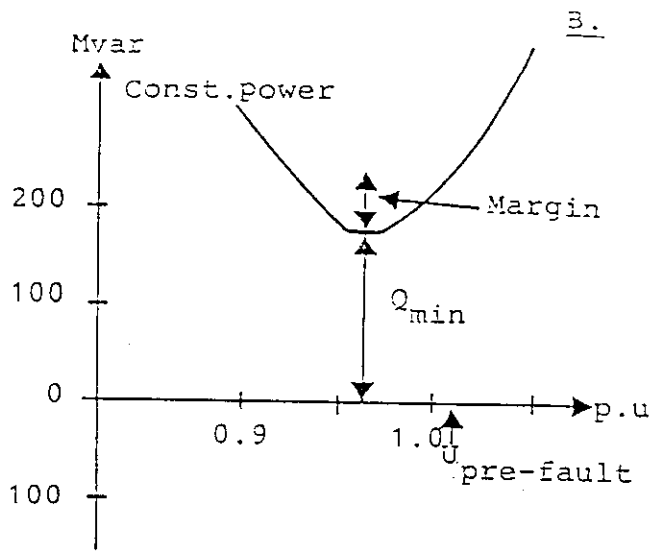
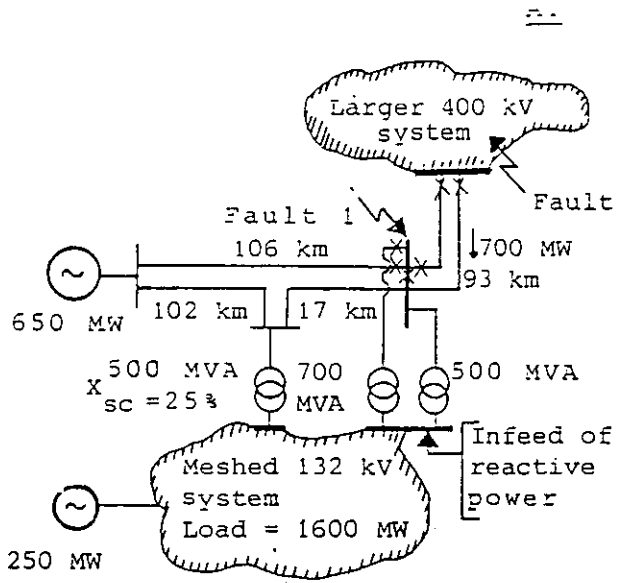


Figure 10
Example showing how the thyristor-switched and the mechanically switched parts of a SVC are determined.

- 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

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