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# METHODS FOR REACTIVE POWER OPTIMIZATION

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# METHODS FOR REACTIVE POWER OPTIMIZATION

by

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## 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

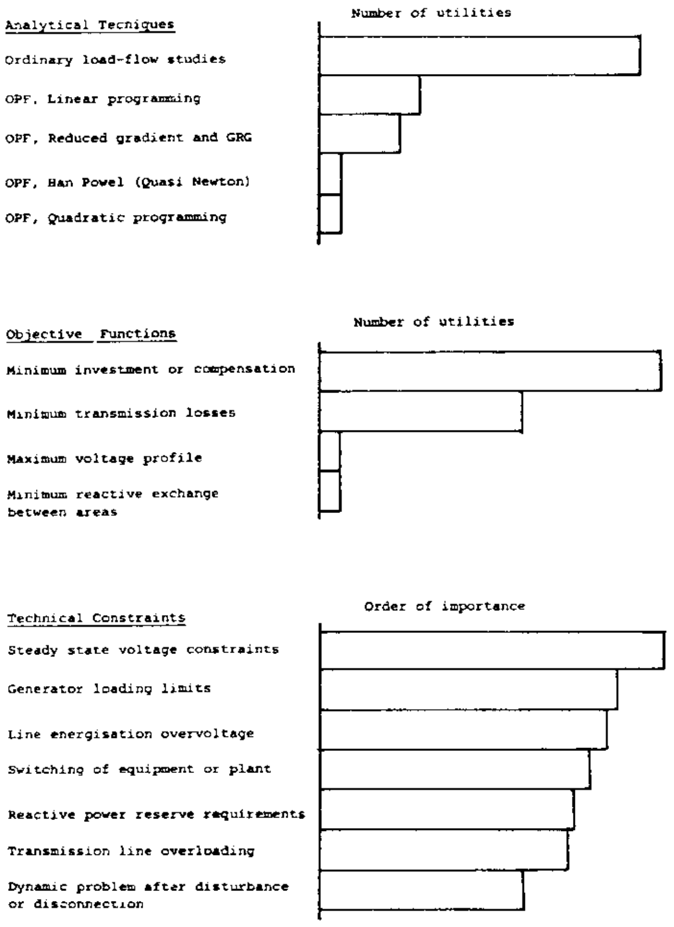

Fig.2 - Answers to Questionnaire - Appendix 5

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