OPTIMAL REACTIVE POWER FLOW METHODOLOGY IN POWER SYSTEMS WITH SECONDARY VOLTAGE CONTROL

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The voltage - reactive power control in the transmission networks has become a major problem in recent years. The Hierarchical Voltage Control System (HVCS) represents one of the best alternatives to the traditional voltage control.

The paper focuses on the implementation of an Optimal Reactive Power Flow (ORPF) methodology in power systems with Secondary Voltage Control (SVC). To achieve this, the mathematical model of the optimization problem was studied considering two major aspects: establishing the constraints of the objective function in order to fulfill the actual operating condition of the SVC system and to avoid the power system equipments reaching their technical limits and, on the other hand, finding the proper objective function. The mathematical model was implemented in AMPL and simulations were performed on a power system with SVC.

Keywords: hierarchical voltage control, optimal reactive power flow, security and economy.

1. Introduction

The control of grid voltages and reactive power has become more critical in recent years due to access to networks, to electricity market and to the general trend by system operators and electrical utilities to operate the transmission networks as close as possible to their maximum capacity [1]. The need for suitable control solutions capable of dealing with increased power loads and losses, possible grid contingencies and the risk of voltage collapse in ever more tightly meshed networks has therefore grown. To improve voltage control in transmission grids, many projects have been developed around the world. One of the best solutions proved to be the Hierarchical Voltage Control System (HVCS), a solution based on network area and resources subdivision.

The purpose of this paper was to adapt the Optimal Reactive Power Flow (ORPF) problem to power systems with Secondary Voltage Control (SVC), in order to improve the operation and security of such networks. Thus, the HVCS,

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the proposed mathematical model (MM) of the ORPF and the case study together with the conclusions will be further extended.

2. The structure of HVCS

Generally the HVCS is made by a primary level (primary voltage control-PVC) given by the generators AVRs (Automatic Voltage Regulator), a secondary voltage control level (SVC) and a tertiary voltage control level (TVC) [2] (Fig. 1).

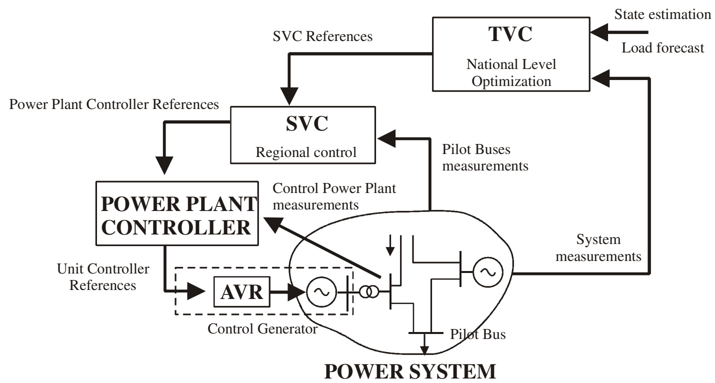


Fig. 1. The structure of the hierarchical voltage – reactive power control system.

The SVC exploits a network subdivision into electric areas around the so-called pilot buses, representative for the voltage profile of the area's load buses. Each pilot bus voltage is regulated by the most effective area's generators - the control generators - by changing their reactive output in accordance with the area reactive level q (the ratio between the supplied and the maximum reactive power at a control generator from the respective area). Thus, an equal reactive loading of all the control generators from each area is achieved. The adjustment of each generator is locally accomplished by acting on the set-points of the AVRs, action performed, for each control area, by a secondary voltage regulator (SVR).

The TVC closes the control loop and coordinates the actions of the SVRs by computing the values of the set-points of the pilot bus voltages on the bases of load forecast and the data given by the state estimator.

3. The mathematical model of the ORPF

The purpose of the ORPF is to improve the reactive power flow in an electric grid, minimizing thus the active power losses and assuring the network security. In the presence of SVC the objective of the ORPF is to compute the optimal values of the set-points of the pilot bus voltages, which is equivalent to finding the optimal profile of the area reactive levels [3].

Mathematically, solving an optimization problem means minimizing (or maximizing) an objective function (OF):

$$\min f(\mathbf{P,Q,U,\theta}) \tag{1}$$

where:

f is the objective function;

$\mathbf{P}$ and $\mathbf{Q}$ – the vectors of the active and reactive nodal powers, respectively;

$\mathbf{U}$ – the vector of bus voltage magnitudes;

$\boldsymbol{\theta}$ – the vector of bus voltage angles;

The OF being subjected to equality (2) and inequality constraints (3):

$$g(\mathbf{P,Q,U,\theta}) = 0 \tag{2}$$

$$h(\mathbf{P,Q,U,\theta}) \le 0 \tag{3}$$

For our ORPF the equality constraints are given by the equations that describe the mathematical model of the power flow (PF) in the presence of SVC [1], [4]:

$$P_i - \sum_{k=1}^{N} U_i U_k \left[G_{ik}\cos(\theta_i - \theta_k) + B_{ik}\sin(\theta_i - \theta_k)\right] = 0,\ i=1...N \tag{4,a}$$

$$Q_i - \sum_{k=1}^{N} U_i U_k \left[G_{ik}\sin(\theta_i - \theta_k) - B_{ik}\cos(\theta_i - \theta_k)\right] = 0,\ i=1...N \tag{4,b}$$

$$\frac{Q_1^j}{Q_{1,\max}^j} = \mathrm{K} = \frac{Q_k^j}{Q_{k,\max}^j} = \mathrm{K} = \frac{Q_{n_c^j}^j}{Q_{n_c^j,\max}^j} = \frac{\sum_{k=1}^{n_c^j} Q_k^j}{\sum_{k=1}^{n_c^j} Q_{k,\max}^j} = q_j,\ k=1\ldots n_c^j\ ,j=1\ldots n_a \tag{5}$$

where:

$P_i = P_{g,i} - P_{l,i}$ is the active nodal power at bus i;

$P_{g/l,i}$ – the active power generated/absorbed in the bus i;

$Q_i = Q_{g,i} - Q_{l,i}$ – the reactive nodal power at bus i;

$Q_{g,l,i}$ – the reactive power generated/absorbed in the bus i;

n_a – the number of areas;

k – the index of the control generators from area j;

n_c^j – the number of control generators from area j;

q_j – the reactive level of area j;

and the subscript *max* denotes the upper capability limit.

The expressions (4,*a* and *b*) represent the power flow equations while equations (5) express the condition of the SVC (5), i.e. the reactive loading of the control generators from each area must be in accordance with the area reactive level. In order to solve this PF model five bus types are defined: the three known bus types from the basic power flow problem [3] (load bus-PQ, generator bus-PV and slack bus-SL) and two new bus types given by the presence of the SVC: the pilot bus-PVQ and the control generator bus-P (see Table 1).

Table 1

Bus types for solving the Power Flow in the presence of SVC

Bus type	Given variables	Variables to be determined	Number of buses
PQ	P, Q	V, θ	n_l
PV	P, V	Q, θ	n_g
PVQ	P, Q, V	θ	n_p
P	P	Q, V, θ	n_c
SL	V, θ	P, Q	1

The pilot bus is a load bus but with the voltage magnitude is fixed (PVQ), due to the control action of the SVR. Moreover, the control generator is modeled as a generator bus without a specified voltage magnitude (P) since its reactive output changes according to the area reactive level. However, considering the goal of the ORPF, the voltage magnitudes of the pilot buses will be considered unknown variables and will be determined by solving the optimization problem.

The inequality constraints are the lower and upper bounds of the bus voltage magnitudes and the capability limits of the generators (SL, PV and P):

$$V_i^{\min} \le V_i \le V_i^{\max}, \ i=1...N \tag{6,a}$$

$$Q_j^{\min} \le Q_j \le Q_j^{\max}, \ j \in \boldsymbol{G} \tag{6,b}$$

where:

CV is the set of the voltage controlled buses;
G – the set of SL, PV and P buses;
$V_i^{\min}, V_i^{\max}$ – the lower/upper bounds of the bus voltage magnitude, V_i ;
$Q_j^{\min}, Q_j^{\max}$ – the lower/upper bounds of the supplied reactive power, Q_j .

As regards the objective functions, the following ones were proposed:

a) *Minimizing active power losses*: consists in minimizing the sum of the active power losses in the branches of the network. This is equivalent with minimizing the active power produced by the slack generator:

$$\min P_{SL} \tag{7}$$

where P_{SL} is the active power produced at the slack bus.

b) *Minimizing the reactive power produced/absorbed by the control generators*: the objective is to determine an optimal point in which the considered generators have a wide regulation margin, assuring the power system with a consistent reserve of reactive resources. Thus, the sum of the absolute values of the control generators reactive outputs will be minimized:

$$\min \sum_{i \in \boldsymbol{P}} \left| Q_{g,i} \right| \tag{8}$$

where $\boldsymbol{P}$ is the set of the controlling generators.

Taking into consideration the difficulty of deriving such a function the following alternative OF was used:

$$\min \sum_{i \in \boldsymbol{P}} Q_{g,i}^2 \tag{9}$$

c) *Multi-objective function (MOF)*: consists in the combined effect of the two previous described OFs. The goal is to solve both problems, each of them having its ratio in the MOF:

$$\min \alpha P_{SL} + (1-\alpha) \sum_{i \in \boldsymbol{P}} Q_{g,i}^2 \tag{10}$$

where $\alpha \in [0,1]$ is a parameter expressing the weight of the two OFs.

4. Simulations and results

The MM of the ROPF was implemented in AMPL [5], a modeling language specially designed for optimization problems. A *primal-dual infeasible interior point method* was used to find the solution. For validation a test power system of national grid size was used in two configurations – "Network 1" and "Network 2". The two networks are identically divided into 13 control areas but they are loaded different, one having a low load ("Network 1" ≈23500 MW) while the other is more stressed (≈27500MW).

Figure 2 illustrates the voltage profiles obtained by minimizing the losses (7) and the reactive power (9) for each grid's configuration. It can be seen that minimizing the active losses gives high voltages while minimizing the supplied reactive power gives lower voltages. Moreover, the difference between the voltage profiles is more obvious for "Network 1" because the grid is less loaded and hence the voltages have a wider regulation range, while for "Network 2" the voltages almost coincide because the grid is higher loaded and the control possibility is reduced.

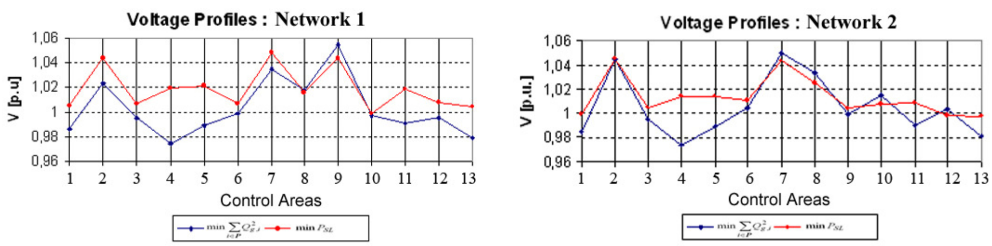


Fig. 2. Voltage profiles: *a*. "Network 1"; *b*. "Network 2".

The results are natural since minimum active losses requires high voltages in the network and, thus, a high production of reactive power from the control generators, while lowering the generated reactive power causes low voltages.

The difference between the supplied reactive power for the two OF is around 600 MVAr (see Table 2). This important reduction is obtained with an increase of the active power losses of about 0.04 % of the total load of the network (~10 MW).

Table 2

OF values for the two networks

$\sum_{i\in P}\lvert Q_{g,i}\rvert[MVAr]/\Delta P[MW]$	"Network 1"	"Network 2"
min P_{SL}	4371,4/327	5595,2/430,130
$\min \sum_{i\in P} Q_{g,i}^2$	3702,6/337,63	5054,3/439,053

Comparing the results for the two networks (Fig. 3) one can notice that minimizing the losses leads to a lower profile for "Network 2". This because "Network 2" is higher loaded. However, the voltages of some pilot buses have nearly equal values for both systems due the high reactive power generation capability available at the corresponding areas control generators (see also Fig. 4). Further, in the case of reactive power minimization the voltage profile for "Network 2" is major than for "Network 1". This because minimizing the reactive power gives a low voltage profile and because for "Network 1" the voltage control range is reduced.

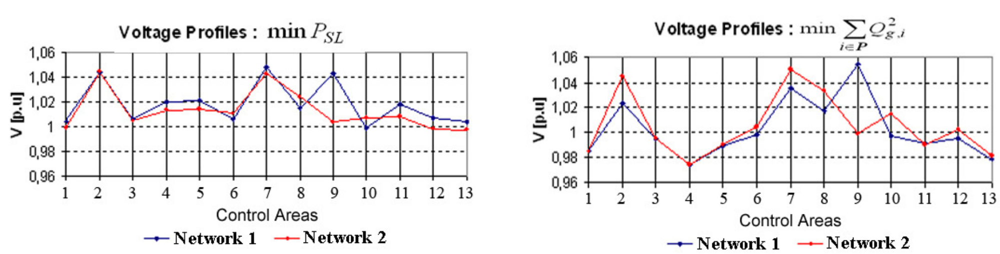
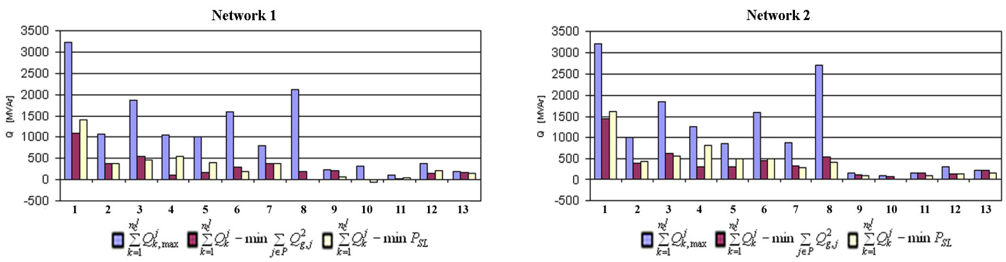


Fig. 3. Voltage profiles: *a*. for min P_{SL} ; *b*. for $\min \sum_{i\in P} Q_{g,i}^2$.

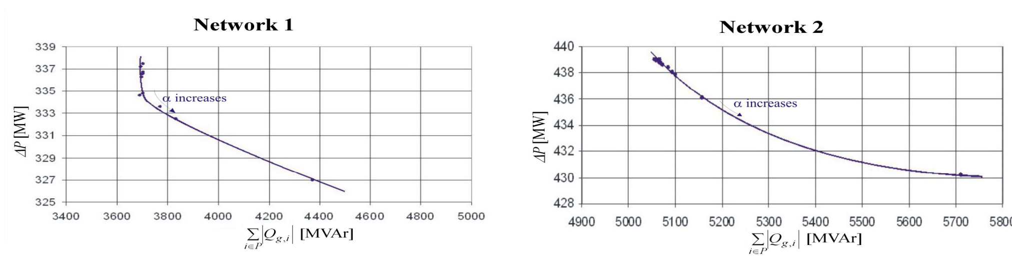
Figures 4 shows that, whatever the OF or the load level of the network, an important quantity of reactive power is available from the control generators in the areas with a high reactive capability. In this areas the reactive levels don't exceed 0.5-0.6 so an important reserve of reactive power is available in order to assure the reliability of the power system.



a. *b.*

Fig. 4. Reactive power production: *a*. "Network 1"; *b*. "Network 2".

Figure 5 shows the behavior of the MOF (10) for the entire spectrum of α. The curves illustrate the "evolution" from one component of MOF (9) to the other one (7) with the increase of α. One can see that for $\alpha \le 0.8$ a small reduction of the active losses ($\approx$2 MW) is obtained without a significant increase of the reactive production (<100 MVAr). On the contrary, for $\alpha \in [0.8 \div 1]$, an important augmentation of the reactive production of about 600-700 MVAr occurs with a diminution of the active power losses of about 8 MW. The behavior shows that for $\alpha \le 0.8$ minimizing the reactive production is dominant in the MOF, while for $\alpha > 0.8$ minimizing the active losses is dominant.



a. *b.*

Fig. 5. MOF for different values of α: *a*. "Network 1"; *b*. "Network 2".

Finally, computations of the loadability margin (LM) for the voltage profiles of "Network 2" were performed with VOSTA [6] in order to have an indicator for the voltage stability (see Table 3). For $\alpha \in [0 \div 0.8]$ the LM is low (respect to $\alpha = 1$) and increases slowly, then, for $\alpha > 0.8$, it increases fast. This due to the characteristics of the MOF discussed above. Moreover, the LM values are high enough (≥4500 MW) to say that the voltage stability of the system is assured.

Table 3

Loadability margins for “Network 2”

α	0	…	0,6	0,7	0,8	0,9	1
Loadability Margin [MW]	4497,2	…	4553,6	4581,7	4590,1	4823,4	5117

5. Conclusions

Preliminary results concerning the optimization of the pilot bus voltage set points were obtained. The results come to support the system operator in choosing the appropriate OF to be implemented. This reduces to the choice of a proper value for α considering three major factors: the security level wanted (the LM, the reactive power reserves), the cost reduction of the active power losses with the increase of α and the reactive power market policy. Thus, we’ll opt for a low if the control generators are paid for the reactive power produced or for a high α if they are paid for the reserve available.

Further development of the subject will focus on the Romanian power transmission network were the SVC system implementation is under study.

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