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Optimal Power Flow procedure for real-time security and economic re-dispatching in a market structure

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***Abstract*--This paper investigates the possibility of utilizing Optimal Active Power Flow (OAPF) and Optimal Reactive Power Flow (ORPF) algorithms for on-line safety and economic re-dispatching in an Ancillary Services Market (MSD) structure. It is described a procedure that the Italian Transmission System Operator (TERNA) has implemented recently for real-time operation.**

Starting from a real-time snapshot, the procedure ranks all the possible contingencies and re-dispatches the active (through OAPF) and reactive (through ORPF) power productions in order to prevent the effects of the most dangerous ones. The re-dispatching is achieved by minimizing the economic effort, according to the offer/bids on the MSD. The fulfilled constraints are: nodal balance, maximum flow limit for the transmission lines (under N and N-1 security conditions), nodal voltage limits, minimum and maximum power offered in the MSD, gradient limitations. Examples are provided about the application of the procedure to the Italian main transmission system (1700 buses).

***Index Terms* — Dispatching procedures, optimization methods, security analysis.**

I. INTRODUCTION

GEnerally, market structures are essentially related to active power scheduling: the current practice, in the day-ahead energy market, is to define the Unit Commitment (UC) of the generators and the relevant dispatching complying with transmission constraints, adopting a simplified model (zonal representation, as for the Italian system) for calculating the real power flows among the zones. In this way, every information related to the network voltage regulation is lost, whereas it would be extremely useful to have more accurate information on the security of the grid as a whole, i.e. including the aspects related to the reactive power and the voltage pattern in the nodes of the grid.

The Italian electricity market ([1]) basically consists of three separate and subsequent markets: the Day-Ahead Market (MGP), the Adjustment Market (MA) and the Ancillary Services Market (MSD). MGP and MA, managed by the Italian Market Operator (GME) are zonal markets for wholesale trading of energy between market participants, where prices, traded quantities, injection and withdrawal schedules for the following day are at first defined (MGP) and then eventually revised (MA) by producers themselves in order to correct unfeasible schedules generated by MGP output. MSD is the market managed by the Italian System Operator (TERNA) for getting the resources required for its dispatching services: the accepted offers/bids are used to revise the injection and withdrawal schedules resulting from the MA market output, so as to relieve any residual congestion not managed in such markets and to create the reserve margins needed to guarantee the system adequacy and security.

Fig. 1 shows a typical example of an offer presented for MSD by the producers. The same economical offers are used both for day-ahead operational planning ([2]) and for real time operation at the command system for balancing reasons, which is the aspect investigated in this paper. The reasons for the need of a real time re-dispatching may be several, such as consumer demand different from load forecast, real injection different from scheduled power production, generation units' tripping etc. The proposed procedure is able to manage the real time re-dispatching at the minimum economic effort, considering all the safety constraints.

II. PROCEDURE DESCRIPTION

The procedure, defined by TERNA and developed by CESI, is performed off-line starting from a snapshot of the real-time status of the electrical system. The starting snapshot is taken every 15 minutes (in the future 5 minutes) from the output of the state estimation of the real-time system. The automatic procedure consists of the following steps: N-1

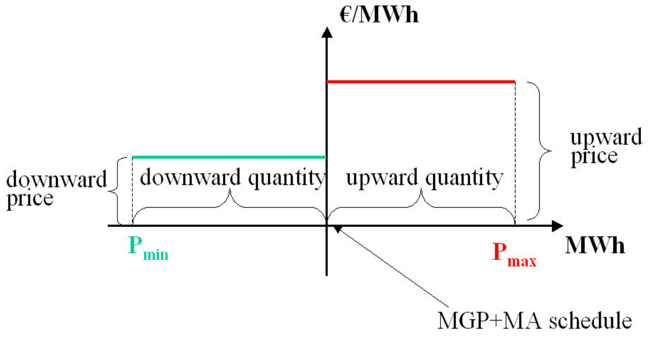

Fig. 1. Typical offer for the MSD market

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security analysis, ranking of the most dangerous contingencies and selection of the critical ones, Optimal Active Power Flow (OAPF) calculation, Optimal Reactive Power Flow (ORPF) calculation.

The N-1 security analysis consists in the simulation of credible contingencies in the transmission grid, such as the tripping of transmission connections (lines, transformers and parallel lines), of power units and of power stations or bus-bars of the electrical system. For each contingency, the steady-state behavior of the system is found and analyzed, considering all the automatic regulations of the electrical system, also including Automatic Voltage Regulation, Load Frequency Control, load shedding, differential bus-bar protections, control of critical grid sections with automatic load curtailment ([3]) and intervention of the automatic tripping devices ([4]).

The contingencies ranking consists in the evaluation of the severity of every contingency on the basis of the violations that the contingency causes in the transmission grid. For the ranking calculation of the contingency severity each kind of violation is weighted with suitable coefficients, in order to allow a comparison among voltage or current violations. At the end of the ranking step, the most dangerous contingencies are given as an input to the OAPF and ORPF calculations, which are performed considering as N-1 constraints the most critical contingencies selected by the ranking analysis. The OAPF and ORPF calculations are performed by two different and subsequent algorithms; although from a theoretical point of view it would be better to have a joint optimal problem with both active and reactive constraints, because of the substantial de-coupling of active and reactive system behavior there is a negligible loss of precision in utilizing the output of the active optimization as the starting point of the reactive optimization. This decoupling reduces in a significant way the complexity of algorithm. It must be noticed that reactive limits of the power units are modeled with a very precise capability curve, able to consider that the reactive limits depend on both the active production and the voltage value. For this reason, it is necessary to perform at first the OAPF calculation, in order to find the active power schedule which must be used to evaluate the reactive power limits to be considered in the following ORPF calculation.

The OAPF and ORPF calculations are characterized by robustness in the possibility of finding a suitable solution even if there are inadequate resources to fulfill all the required constraints: this is due to the implementation of “elastic constraints”, which is a mathematical strategy introducing penalty factors in the objective functions. Both OAPF and ORPF have been solved implementing a primal-dual interior point algorithm ([5], [6], [7]); since they are the bulk of the procedure, they are described in detail in the following paragraphs. The entire procedure is implemented in the CRESO tool ([8]), which is the software environment that TERNA daily uses for the secure and economic operation planning of the Italian transmission grid, and that is under continuous development. The realization of balancing orders suggested by algorithm requires some minutes for dispatchers’ validation and for producers’ acknowledgment.

III. OAPF ALGORITHM

A. *Initial settings*

Since the offers, as shown in Fig. 1, are referred to the market schedule, while the active power production is that derived from the real-time system, the first step performed by the OAPF algorithm is to arrange the offers in order to refer them to the real time production and not to the market scheduled one. As shown in Fig. 2, if the real time production $P_{real\text{-}time}$ is greater than the market schedule power P_{market}, there is the arise of one upward step and of two downward steps, where the first downward step presents the same price of the upward step. In order to assure the convexity of the optimal problem, the first downward price is put to the 98% of the upward price. Dual considerations may be done if $P_{real\text{-}time}$ is lower than P_{market}.

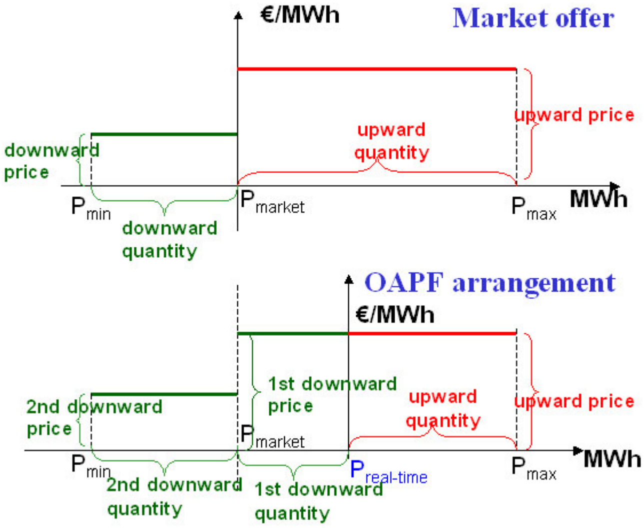

Fig. 2. Arrangement of offers to real time power

The gradient limits are simulated by shortening the maximum allowed change in production, both upward and downward, according to a defined ramp time, i.e. 15 min.

The realization of balancing orders suggested by algorithm requires some minutes for dispatchers’ validation and for producers’ acknowledgment. For this reason the system snapshot used as input is corrected by an external procedure that considers the load and the generation forecasted for the next few minutes. The same external procedure also calculates the optimal final net unbalance for each regulation area that OAPF has to provide as a result of the optimization. Using all these inputs OAPF guarantees the most economical and security compliant dispatching schedule.

B. *Objective function*

The OAPF algorithm has the objective of minimizing the total cost of the deviation of the production of the generators from the real-time power injection.

The objective function is then:

$$\min \sum_{i=1}^{NAUp} c_i \left(P_i - P_{i\_real-time}\right) \qquad (1)$$

where:

$NAUp$: number of units available for active rescheduling;

c_i : appropriate cost (upward or downward) of unit i;

P_i: optimal power, which is obtained by the OAPF solution for unit i;

$P_{i\_real-time}$: initial power of unit i which is taken from the real time system.

C. Constraints

The constraints of the OAPF problem are the following:

- Active power flow equations:

$$f_i(x) = 0 \qquad (2)$$

where $f_i(x)$ is the expression of the active power balance at node i

- Constraints on maximum flow limits for each transmission line under N security conditions:

$$I_j \leq I_{j\max} \qquad (3)$$

where I_j is the current flowing in line j and I_{jmax} is the maximum acceptable current under N security condition. I_j depends, as a first approximation, on the angles of the nodal voltages, since the modules can be considered constant.

- Maximum flow limits constraints for each transmission line under N-1 security conditions:

$$I'_i = I_i + \beta_{ji} I_j \qquad (4)$$

$$I'_i \leq I'_{i\max} \qquad (5)$$

where I'_i is the current flowing in line i under N-1 conditions (after the tripping of line j which was carrying a current I_j) and I'_{imax} is the maximum acceptable current under N-1 security condition (overload capability depends on element characteristics). β_{ji} is a transfer coefficient considered constant during all the OAPF calculation to reduce computational efforts: it is calculated at the beginning of the calculation and it represents the amount of the active power which shifts from line j to line i after line j tripping. Lines j are those found by the ranking analysis.

- Constraints on the single production units:

$$P_i + s_i \leq P_i^{MAX} \qquad (6)$$

$$P_i - s_i \geq P_i^{MIN} \qquad (7)$$

$$0 \leq s_i \leq s_{MAX\,i} \qquad (8)$$

where:

P_i^{MAX}, P_i^{MIN} are respectively the maximum and the minimum power limit declared for the time frame of optimization for unit i (the variation for each unit must not exceed neither the offer nor the technical limits of the unit);

s_i is the secondary semi-band calculated by the OAPF for unit i;

$s_{MAX\,i}$ is the maximum semi-band allocable for unit i.

Equations (6) to (8) on the one hand represent the fulfillment of the minimum and maximum amounts of energy offered by each unit in the MSD market, and on the other show that the secondary reserve semi-bands are symmetrical in the respect of the optimal power. The values used as upper and lower power limits in (6) and (7) are curtailed using the maximum variation possible with declared gradient in the ramp period considered. Ramp time is also a parameter.

- Fulfillment of the secondary reserve requirements:

$$\sum_{i\in AZ} s_i \geq S_{MIN}^{AZ} \qquad (9)$$

where S_{MIN}^{AZ} is the need for secondary reserve of zone cluster AZ. The clusters considered in the Italian network, corresponding to load-frequency regulation areas are peninsular Italy, Sicily and Sardinia islands.

- Transit limit between zone clusters:

$$\sum_{z\in ZC} \sigma_{Z'Z''}^{z} \cdot \left[\sum_{i\in z} P_i - C_z\right] \leq VT_{Z'Z''} \qquad (10)$$

where:

ZC is the number of zone clusters

$VT_{Z\,Z''}$ is the maximum limit between zone cluster Z' and zone cluster Z";

$\sigma_{Z'Z''}^{z}$ is the sensitivity of the units belonging to zone cluster z in the evaluation of the transit between zone cluster Z' and Z" depending on connection matrix;

C_z is the load (including network losses) of zone cluster z.

The zone clusters considered in (10) are the same of (9) in order to represent in a correct way constraints not linked directly with a N-1 violation: Sicily and Sardinia at the moment are both connected to Italian mainland only through one cable, so the tripping of this link can provoke frequency deviation not compatible with their primary regulation capability. Dynamic considerations give the limitation to the power transit between zone clusters.

Zone clusters are anyway configurable in order to enhance flexibility of the algorithm also for future needs.

IV. ORPF ALGORITHM

A. Starting point

The ORPF calculation starts from the set-point of the active power established by the previous OAPF calculation, while the information related to the voltage regulation is directly derived from the on-line system.

B. Objective Function

In vertically integrated utilities, the common practice was to minimize network real losses ([9], [10], [11]), in order to reduce operational costs; on the contrary, the security was implicitly guaranteed by the respect of operational limits. The minimizing of network real losses guarantees the fulfillment of the operational limits and, at the same time, allows keeping costs low. It is well-known that the losses of the transmission network have a quadratic dependence from the currents flowing in lines and generators. These currents represent a function of node voltage. Therefore, the minimization of losses can be achieved through the increasing of the set point values of generator voltages; generators are thus bound to operate with voltage values near to the maximum values admitted. As a consequence, a working condition of this kind is generally required for all units whose voltage belongs to the control variables of the problem. However, it has to be underlined that such general increase in the network voltage is not always compatible with the operational procedures adopted for some specific generation units in the transmission network.

In a liberalized context, new possible objective functions for reactive dispatching, containing new formulations of the objective function tailored for the operation of power systems in a deregulated framework, have been investigated ([12], [13], [14]). In the ORPF three different objective functions are implemented: the first is the classical minimization of the real losses (achieved by minimizing the power to be injected at the slack-bus to guarantee the active power balance), while the other two are the following:

- $$\min \sum_{i=1}^{N\_BUS} (V_i - V_{nom\_i})^2 \qquad (11)$$

where:

N_BUS: number of buses;
V_i : optimal voltage for bus *i*;
V_{nom_i}: rated (or assigned) voltage for bus *i*.

- $$\min \sum_{i=1}^{NRUp} Q_{gi}^{\ 2} \qquad (12)$$

where:

NRUp: number of units available for reactive rescheduling;
Q_{gi}: optimal reactive power for generator *i*.

Equation (11) expresses the possibility of finding a voltage profile for the electrical system not too far from the rated or assigned one, while eq. (12) allows the possibility of maximizing the reactive margins available after the ORPF calculation. The three different objective functions may be mixed by the use of proper weighting factors; no price is associated to the change of the reactive profile in none of the possible objective functions.

C. Constraints

The constraints of the ORPF problem are the following:

- Reactive power flow equations:
  $$h_i(x) = 0 \qquad (13)$$
  where $h_i(x)$ is the expression of the reactive power balance at node *i*

- Active power flow equations, with the same formulation as in (2) for the OAPF algorithm.

- Constraints on the single production units:
  $$Q_{gi\min}(V_i, P_i) \le Q_{gi} \le Q_{gi\max}(V_i, P_i) \qquad (14)$$
  where Q_{gimax} and Q_{gimin} are respectively the maximum and the minimum reactive power limit for the hour for unit *i* (and they depend on the voltage and active production of the generator).

- Constraints on the nodal voltage limits:
  $$V_{i\min} \le V_i \le V_{i\max} \qquad (15)$$
  where V_{imax} and V_{imin} are respectively the maximum and the minimum voltage allowed for bus *i*;

- Constraints on the nodal voltage limits in N-1 condition, after the trip of the line *L* that connects bus *h* and bus *k*:
  $$V^L{}_i = V_i + \alpha_{iL} Ta_h(V, \vartheta) + \beta_{iL} Tr_h(V, \vartheta) +$$
  $$+ \gamma_{iL} Ta_k(V, \vartheta) + \delta_{iL} Tr_k(V, \vartheta)$$
  $$V_{i\min} \le V_i^{\ L} \le V_{i\max} \qquad (16)$$
  where:
  $V^L{}_i$: voltage of bus *i* after the trip of line *L*;
  Ta_h, α_{iL} : respectively active transit of line *L* from bus *h* to bus *k* and sensitivity of the voltage of bus *i* to that transit
  Tr_h, β_{iL}: respectively reactive transit of line *L* from bus *h* to bus *k* and sensitivity of the voltage of bus *i* to that transit
  Ta_k, γ_{iL}: respectively active transit of line *L* from bus *k* to bus *h* and sensitivity of the voltage of bus *i* to that transit
  Tr_k, δ_{iL}: respectively reactive transit of line *L* from bus *k* to bus *h* and sensitivity of the voltage of bus *i* to that transit.
  Equation (16) expresses the variation of the nodal voltage at bus *i* after the trip of line L in a linear way, using sensitivity coefficients that are kept constant during the iterative calculation. Lines *L* are those found by the ranking analysis

- Secondary voltage regulation constraints, for which every generator produces the same percentage q_R of reactive power:
  $$q_R = \frac{Q_{gi}}{Q_{gi\max}(V_i, P_i)} \qquad (17)$$
  $$-1 \le q_R \le 1 \qquad (18)$$

V. ELASTIC CONSTRAINTS

The constraints expressed in (3), (5), (9), (10), (15) and (16) may become ‘elastic’ constraints: this means that some of them may be relaxed in order to obtain a solution of the mathematical problem even if there are no enough resources to meet all the constraints. For sake of simplicity, let us consider only constraint (9) referred to the respect of the need of secondary reserve in the OAPF algorithm. It is possible to re-write its expression in this new way:

$$\sum_{i\in AZ} s_i + \Psi_{AZ} \geq S_{MIN}^{AZ} \qquad (19)$$

where Ψ_{AZ} is a penalty variable which also enters in the expression of the objective function.

The new expression of the objective function so becomes:

$$\min \sum_{i=1}^{NUp} c_i \left(P_i - P_{i\_real-time}\right) + \alpha \sum_{AZ} \Psi_{AZ}^2 \qquad (20)$$

where α is a weight constant higher (at least 1.5 times) than the maximum cost c_i of the single units. If there are enough resources to meet all the constraints, the OAPF algorithm makes Ψ_{AZ} naturally tend to zero, and so (19) becomes equal to (9) and the secondary reserve constraint is respected. Instead, if there are no enough resources, the OAPF algorithm will compute a Ψ_{AZ} different from zero which enables to find a problem solution even if constraint (9) is not respected. Each elastic constraint has its own weight constant, which is possible to tune before the OAPF or ORPF calculation: in this way, it is possible to choose in which order constraints can be relaxed whenever there are no enough resources.

VI. SIMULATIONS

A. *OAPF simulations*

Some examples are provided about the application of the procedure. For confidentiality reasons all economical information is set in an arbitrary but realistic way and the names of the units and network elements involved in the examples are modified. The starting point of the examples is a realistic evening peak hour of a typical winter day. The whole Italian 380-220 kV transmission network with an appropriate foreign equivalent (more than 1700 nodes) is considered. No voltage violations are present, and for this reason the ORPF results are not reported for this test. For sake of simplicity in this case the net unbalance requested is set to zero. No N security violations are present; the goal is to reestablish the N-1 security at the minimum cost effort. After the trip of a generation unit in North East Italy the network section between North and Center Italy is no more in N-1 security condition.

TABLE I lists the N-1 constraints resulted as the most dangerous during the initial ranking analysis; I_T represents the value of current in Ampere in the tripping line, I_C the current in the overloaded one before the tripping, I_C' the current in the overloaded one after the tripping, and I_{maxC} the maximum permanent thermal limit of the overloaded line. The trip of lines between North West and North East part (which becomes a deficit area) causes a loop flow that overloads the 380 kV descending line SP-VI.

TABLE I – RANKING OF THE MOST DANGEROUS CONTINGENCIES

Trip	**Overload**	**I_T[A]**	**I_C [A]**	**I'_C[A]**	**I_{maxC} [A]**
PA-SR	SP-VI	1244	1523	1795 100.1 %	1790
BA-PI	SP-VI	1386	1523	1867 104.3 %	1790

Starting from this base case some different uses of constraints and optimization parameters are shown in TABLE II:

a) Limit I_C' accepted 105%, all constraints active except zone cluster transit limit between Sicily and Italian peninsula
b) Limit I_C' accepted 100%, all constraints active except zone cluster transit limit between Sicily and Italian peninsula
c) Limit I_C' accepted 100%, all constraints active
d) Limit I_C' accepted 95%, all constraints active

TABLE II – OAPF RESULTS

	Limit $_{N-1}$ [%]	**Trip**	**Overl.**	**I'_{OAPF} [A]**	**ZC**	**O.F. [€]**
a)	105%	PA-SR	SP-VI	1798 100.4%	No	-24359
		BA-PI	SP-VI	1867 104.3%		
b)	100%	PA-SR	SP-VI	1693 94.6%	No	-5910
		BA-PI	SP-VI	1790 100.0%		
c)	100%	PA-SR	SP-VI	1694 94.6%	Yes	-1336
		BA-PI	SP-VI	1790 100.0%		
d)	95%	PA-SR	SP-VI	1654 92.4%	Yes	7128
		BA-PI	SP-VI	1764 98.5%		

Some important aspects can be highlighted from these few cases:

- In case a) with 105% limit there are no network constraints to cope with, so there is a lot of room in optimization of generation units of Italian mainland and Sicily.
- In case b) with 100% limit there is the need to redispatch in order to solve network constraints: this decreases the income of optimization
- In case c) objective function value grows because of the consideration of limit between Italian peninsula and Sicily. The increase of cheap generation in Sicily is limited by this constraint.
- In case d) with a more strict current limit, objective function value becomes positive, so that the system has to pay some thousand euros. There are no enough resources to respect all constraints together so one of the N-1 and the limit between Sicily and Italian peninsula are slightly violated. The convergence of algorithm is guaranteed by elastic constraints. The entity of the violation of

constraints depends on the relative values of weight constants used in objective function.

B. *ORPF simulations*

In order to show the ORPF procedure validity, the results of two study cases are reported: the first one is a off peak load case holiday day and the chosen objective function is the minimization of active losses together with the minimum distortion of the assigned voltage profile (11), while the second one is a peak load case working day and the chosen objective function is the minimization of active losses together with the minimum reactive power production (12).

For the off peak load case, Fig. 3 and Fig. 4 compare the voltage profiles before and after the ORPF calculation respectively for the 400 kV and the 220 kV transmission system, while Fig. 5 shows the voltages of the power units before and after the optimization. Before the optimization, about 300 maximum voltage limit violations were present for the whole 400-220 kV transmission system: the application of the ORPF function reduces the number of the voltage violations to about 80, since one of the constraints of the optimization process is the respect of the voltage limits in all nodes.

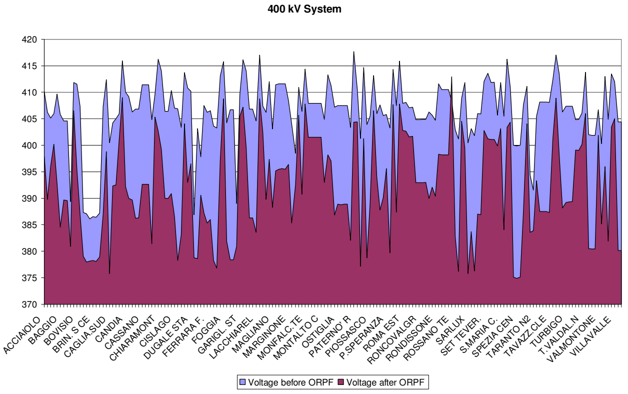

Fig. 3. Off peak load case: 400 kV system – voltages before and after optimization

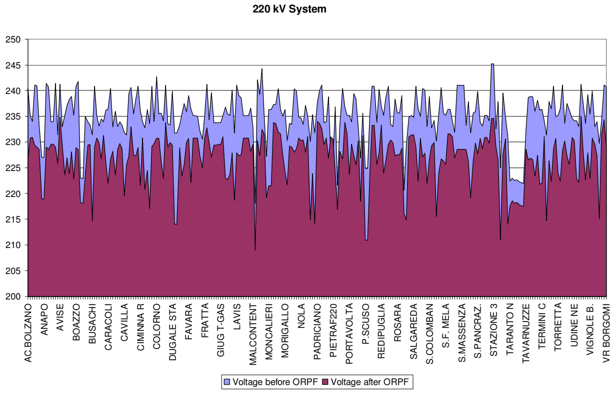

Fig. 4. Off peak load case: 220 kV system – voltages before and after optimization

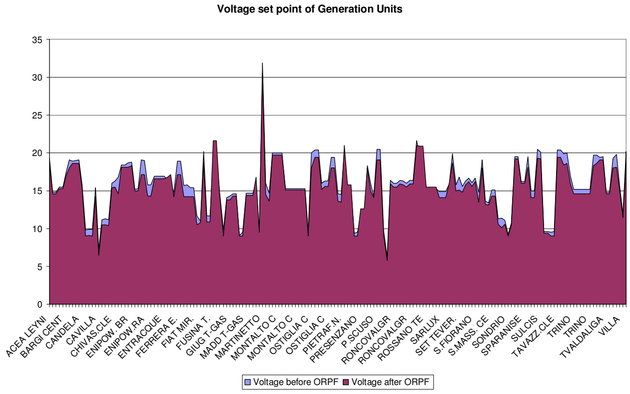

Fig 5. Off peak load case: Generation Units – voltages before and after optimization

For the peak load case, Fig. 6 compares the reactive margins of the generators before and after optimization: the reactive margin in over-excitation of the generation units is increased by the ORPF calculations, because of the chosen objective function (12).

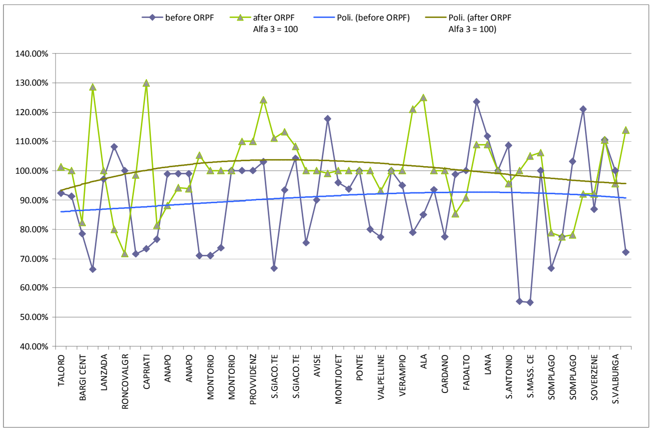

Fig. 6. Peak load case: Reactive margin in over-excitation before and after optimization

VII. CONCLUSIONS

This paper has described a procedure for the real-time optimization of active and reactive power production, at the minimum cost and with respect of market and network constraints, both under N and N-1 safety conditions.

The procedure is now used at TERNA National Control Center, where it is automatically used whenever a new snapshot of the real-time system, prepared by the on line state-estimation, is ready (at the moment every 15 minutes).

Further improvements of this procedure will be the implementation of N-2 constraints, and the scheduling of these functions every 5 minutes.

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Fabio Bassi received his Doctor degree in Electrical Engineering (Industrial Automation) in 2003 from the University of Pisa. In 2004 he joined G.R.T.N. S.p.A. in Rome (Italy), where his area of interest includes power system analysis, optimization and market procedures. Nowadays, he is with Terna S.p.A., the Italian TSO, in Dispatching and Facility Operation Division, where he is particularly involved in the definition of models for security and optimization of the electrical system and in the developing of tools and procedures for National Control Room.

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