Dynamic Performances of the Hierarchical Voltage Regulation: the Italian EHV System Case

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Summary

The problem of the reactive power and voltage control has recently drawn the attention of both researchers and operators, mainly because of the growing competition in the electricity market and the increased needs of improving security and quality of system operation. The voltage/var support is classified, in a liberalized framework, as an Ancillary Service and it has to be acquired by the Transmission System Operator (TSO) using suitable market mechanisms. The TSO can achieve an effective voltage regulation using different structures. In particular, in the recent years, a Hierarchical Voltage Control (HVC) has been proposed and applied in Italy and Secondary and Tertiary Voltage Regulation schemes have been chosen by the Italian System Operator (GRTN). The aim of the paper is to investigate the dynamic performance of such HVC solution, with respect to voltage instability phenomena, for both normal and contingency network conditions. The results of the study show the peculiar characteristics of the three levels of regulation and the impact of the different adopted schemes on the voltage security. The increase of the distance from the voltage collapse and the coordination of reactive power resources, attained respectively by the SVR and the TVR, are also highlighted.

Keywords: Voltage stability; Hierarchical voltage control; Dynamic simulation; Voltage Collapse; Network security.

1. Introduction

The recent events occurred in the European and American power systems clearly show that the electrical utilities are progressively operating the networks as closer as possible to their maximum transmission capability. Moreover, the increasing interconnection among grids of different sizes and characteristics (and with different connection rules) makes the voltage control more and more critical, in terms of voltage security.

The reactive power and voltage control needs to be dealt in a different way with respect to the vertically integrated framework. In the liberalized environment, the TSO has to develop suitable economic structures in order to acquire the voltage/var support as an Ancillary Service.

For this reason, several utilities are designing and applying tools for the evaluation of the power system margins with respect to the voltage security (voltage stability indices [1-6]) and for the enhancement of such margins (e.g. by a Hierarchical Voltage Control (HVC) [7-9]). The Italian HVC scheme is based on three main levels: the generators perform the simplest voltage regulation at a local level (Primary Voltage Regulation or PVR), setting the voltage for the Automatic Voltage Regulator (AVR) of each unit. The GRTN centralises the voltage regulation at a regional level, implementing the so-called Secondary Voltage Regulation (SVR) and, at a national level, by mean of the Tertiary Voltage Regulation (TVR).

The HVC dynamic performances with respect to voltage security are deeply investigated in the paper, with reference to the Italian EHV network. A short description of the HVC structure adopted is given in Section 2. The main features of the dynamic simulation tool are indicated in the following Section 3, in which a detailed description of the dynamic models of the three voltage regulation levels are reported. The results, reported in Section 4, allow the comparison of the different operational schemes that GRTN can operate in order to manage the HVC.

2. The Italian Hierarchical Voltage Control

The hierarchical structure of the voltage control, currently adopted by GRTN on the Italian transmission network [7][11][12][13], is represented in Fig. 1. It is made by a Primary Voltage Regulation – PVR , given by the AVRs of generators, a Secondary Voltage Regulation (SVR) and a Tertiary Voltage Regulation (TVR). The SVR provides a network subdivision into electric areas around the so-called pilot nodes. The pilot nodes are the load busses with the largest short circuit ratio in a given region. The generators controlling each pilot node are chosen through the analysis of the sensitivities of the pilot node voltages with respect to the generating unit reactive power: the largest entries in the sensitivity matrix define the generators most suitable for the control of each pilot node. In the choice of control areas, attention is paid to verify their reciprocal electrical decoupling, necessary to avoid oscillations due to undesired interactions among the area regulators.

In the SVR, the pilot bus voltage of each area is controlled by the relevant controlling generators; they change their reactive output according to the area reactive power production in pu (reactive level) computed by the Secondary Voltage regulator. All the generating units belonging to the same SVR area have to produce the same amount of reactive power in pu (alignment constraints).

In the TVR, a national regulator controls, in closed-loop, the voltage set-points of the pilot nodes for a secure and economic operation. It computes new set points for the pilot nodes, based on the differences between a) the actual network state continuously available and b) the optimal values of pilot nodes voltages and area reactive power levels. These are obtained by

This work has been supported by MAP (Italian Ministry for Productive Activities) in the frame of Public Interest Energy Research Project named "Ricerca di Sistema" (MAP Decree of 28 February 2003).

an Optimal Reactive Power Flow (ORPF) dispatching program, run off-line in the day-ahead time framework, or every 15 minutes on the very short-term forecasted system.

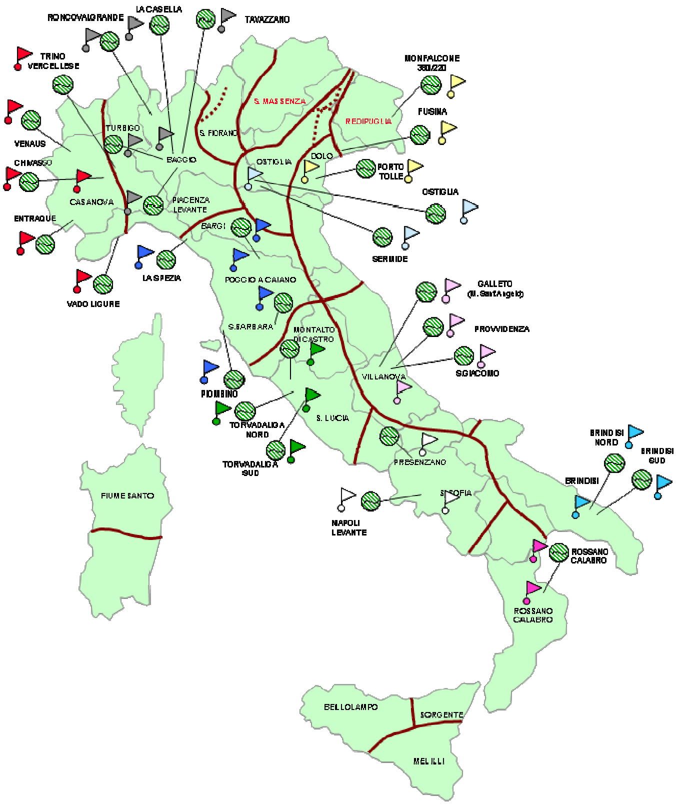

Figure. 1. The SVR areas in the Italian System.

3. The HVC dynamic simulation model

3.1 The SICRE dynamic simulator

The dynamic procedure adopted for this study is based on SICRE [10], an interactive power system dynamic simulator, covering different time-scale phenomena and modeling levels (grids, units, control systems and protections). SICRE can simulate both electromechanical and long-term dynamics. The implemented simulation modes are: Short Term Dynamics (STD), used for the dynamic analysis of fast and local control system performances; Long Term Dynamics, used for the analysis of mid-frequency transients, e.g., secondary voltage and frequency controls. In this case, the dynamic component models, are derived neglecting electromechanical oscillations and the fast dynamics.

The power system is modelled in SICRE by taking into account the model components separately, e.g., the electrical network equipment (bus bars, lines, transformers), the loads and the OLTCs, the generating units subsystems (turbines, excitation systems and primary controls, complete of capability limits and PSSs), the secondary frequency and voltage regulators, SVCs, the protection system and the automatic load shedding.

3.2 Discussion on the structure of the HVC

The Primary Voltage Regulation (PVR) is performed by the typical operation of AVRs, whose goal is to maintain the generator terminal voltages at some predefined values. It is important to keep in mind that no coordination exists between the voltage reference values of the AVRs.

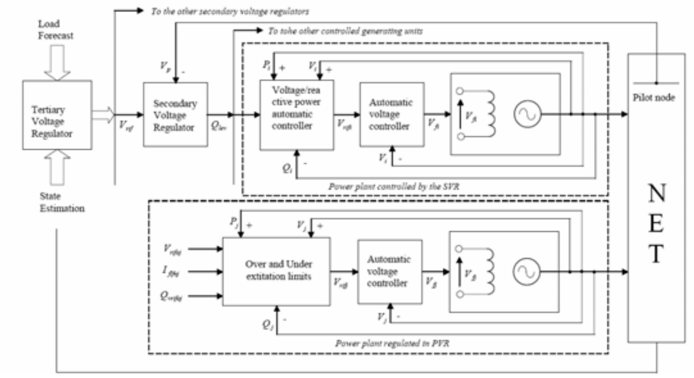

Figure. 2. The Hierarchical Voltage Control structure.

The SVR dynamic behaviour is modelled by the variables described in Fig.2. The TVR acts as a coordinator of the reactive resources available, in order to achieve the best compromise between the security requirements, in terms of availability of area reactive margins and good voltage profiles, and the economic operation. Starting from optimal reference values of both pilot node voltage and reactive power level of all the SVR areas (calculated by an Optimal Reactive Power Flow - ORPF) and from the actual measurements, collected by the SCADA, this level of voltage regulation, whose dynamic model is represented in Fig. 3, determines the new reference values for each pilot node. In other terms, the task of the TVR is to adapt the optimal reference values, initially determined for a forecasted scenario, to the current operating conditions, minimizing the following Objective Function (OF):

$$OF = \left[V_P - V_{p0}\right]^T M_V^2 \left[V_P - V_{p0}\right] + \left[Q_A - Q_{ref0}\right]^T M_Q^2 \left[Q_A - Q_{ref0}\right]$$ w

here:

- ✓ $\left[V_P - V_{ref}\right]$ is the vector of the differences between the actual pilot node voltage values and their reference values;
- ✓ $\left[Q_A - Q_{Aref}\right]$ is the vector of the differences between the actual reactive levels and their reference values;
- ✓ M_V^2 and M_Q^2 are diagonal matrices of constant values, selected in order to weight more either the economic or the secure operation of the system.

The network (Fig.3) is modelled by a system of algebraic equations and is a constraint for the optimization problem described in the following. The full model:

$$f\left(V_p, Q_{ref}, V_{ref}\right) = 0$$

can be simplified under the assumption that SVR is much faster than TVR. In this way, the constraint becomes:

$$f\left(Q_{ref}, V_{ref}\right) = 0$$

Introducing the variations of the control variables ΔV_{ref} and ΔQ_{ref} (Fig.3), the OF becomes:

$$OF = \left[V_{ref} + \Delta V_{ref} - V_{p0}\right]^T M_v^{\ 2} \left[V_{ref} + \Delta V_{ref} - V_{p0}\right] +$$
$$+ \left[Q_{ref} + \Delta Q_{ref} - Q_{ref0}\right]^T M_q^{\ 2} \left[Q_{ref} + \Delta Q_{ref} - Q_{ref0}\right]$$

where, through the sensitivity matrix S:

$$\Delta V_{ref} = S\, \Delta Q_{ref}$$

The solution of the modified optimization problem:

$$\begin{cases} \min_{\Delta V_{ref}} \left[\Delta V_{ref} - \Delta V_{P0}\right]^T \cdot {M_v}^2 \cdot \left[\Delta V_{ref} - \Delta V_{P0}\right] + \\ + \left[\Delta Q_{ref} - \Delta Q_{ref0}\right]^T \cdot {M_q}^2 \cdot \left[\Delta Q_{ref} - \Delta Q_{ref0}\right] \\ \Delta V_{ref} = S \cdot \Delta Q_{ref} \end{cases} \quad (1)$$

where $\Delta V_{p0} = V_{p0} - V_{ref}$ and $\Delta Q_{ref0} = Q_{ref0} - Q_{ref}$,
is obtained by zeroing the first derivatives with respect to ΔV_{ref} :

$$\begin{cases} {M_v}^2 \cdot \left[\Delta V_{ref} - \Delta V_{P0}\right] + {M_Q}^2 \cdot S^{-1} \cdot \left[\Delta Q_{ref} - \Delta Q_{ref0}\right] = 0 \\ \Delta V_{ref} = S \cdot \Delta Q_{ref} \end{cases}$$

Finally, the solution of the problem is:

$$\Delta V_{rif} = \left[{M_V}^2 + {M_Q}^2 \cdot S^{-2}\right]^{-1} \cdot \left[{M_V}^2 \cdot \Delta V_{P0} + {M_Q}^2 \cdot S^{-1} \cdot \Delta Q_{ref0}\right]$$

The set-point variation of the pilot node voltage is then obtained by an integrator-type device and a control loop whose typical time constant is some hundreds of seconds.

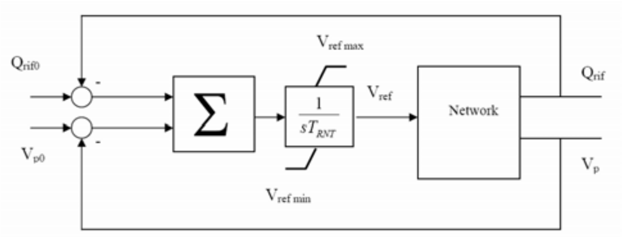

Figure. 3. Dynamic model of the Tertiary Voltage Regulation.

4. Tests and Results

The HVC structure adopted for the simulations on a model of Italian EHV system has been first investigated through a sensitivity analysis, in order to assess the above mentioned required electrical decoupling between the SVR areas.

Fig. 4 shows the sensitivities of the reactive power needed by each area to control the pilot node voltage with respect to the reactive power produced by each area. The decoupling criteria would require that this matrix is diagonal dominant.

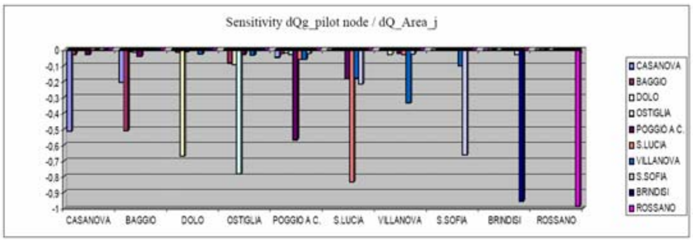

Figure. 4. Sensitivity of the reactive power production of the area i, with respect to a reactive load variation in the area j for the considered SVR configuration.

The results show a general very low interaction between the different SVR areas; however, this is not verified in some cases due to the saturation of the area reactive power resources and to the highly meshing of the EHV network in the North of Italy. The variation of the reactive power injection in each pilot node with respect to the reactive power produced by each controlling unit has been also calculated: the results show that the obtained decoupling is suitable.

Once the control structure applied to the Italian EHV network has been validated, the next step concerns the dynamic analysis of the performances of this scheme with respect to the voltage security. The procedure adopted is the following:

- Acquisition from the SCADA system of a snapshot of the Italian system (called Base Case – BC), without the SVR;
- ORPF calculation on the BC, in order to determine the optimal set-points for the pilot node voltages (the optimization procedure minimizes the active power losses, taking into account the SVR constraints);
- Dynamic simulation of a load ramp on the BC and ORPF calculations on the studied system in different operating conditions during the ramp, in order to trace the optimal voltage profiles for the pilot nodes.

The application of a load ramp to the BC aims at comparing the different following regulation schemes:

- PVR only, with the AVR set points taken from the BC;
- SVR: where the reference pilot node voltages are assumed equal to the voltage values of the pilot nodes in the BC and kept constant during the ramp;
- SVRO: where the reference pilot node voltages are computed by optimizing the BC operating scenario and kept constant;
- TVR: where the initial pilot node voltage and reactive power level set points are taken from SVRO and dynamically changed by the TVR block solving problem (1);
- SVRdisp: where the reference pilot node voltages are assumed equal to the optimal profiles calculated on discrete snapshots during the load ramp;
- TVRdisp: like TVR but where also the pilot node set points are discretely updated according to ORPF computations performed on some snapshot during the load ramp.

	$\partial V_{pilot} / \partial q_{area}$	$\partial V_{pilot} / \partial q_{area}$	$\partial V_{pilot} / \partial q_{area}$	$M_{Q'}$	$M_{Q''}$	$M_{Q'''}$
	29 January	*2 April*	*16 July*	*TVR1*	*TVR2*	*TVR3*
Poggio a C.	18	26	21	25	15	10
Baggio	18	20	24.5	20	10	5
Brindisi	111	98	126.3	100	50	50
Rossano	55	52	53	50	25	25
S.Sofia	12	10	13	10	10	10
S.Lucia	46	33	69	50	25	25
Villanova	8.5	8	7.6	10	10	10
Casanova	27.5	24	22	25	15	10
Dolo	33	28	31	30	15	10
Ostiglia	15.5	24	17	20	10	5

Table. 1. Sensitivity of the voltages of the pilot nodes with respect to the reactive power produced by the SVR areas, and M_Q entries.

When TVR is in operation, the TSO has to set M_V and M_Q: M_V has been assumed the identity matrix and M_Q a diagonal matrix whose constant entries can be set as the sensitivities of the pilot node voltages with respect to the reactive power productions of the considered area. Using three different BCs, related to a winter peak, a summer peak and a medium load scenario, the sensitivities have been determined and used to obtain three possible M_Q sets for the TVR tests; in particular, the M_Q entries in TVR1 are obtained as an approximated mean of the sensitivities in the three scenarios, while TVR2 and TVR3 are obtained also making use of empirical considerations (Tab. 1).

Tab. 2 shows the results of the loadability tests, performed using the dynamic simulator under the above mentioned control schemes: the enhancement of the system voltage security (measured by the increase in the loadability) under SVR ranges from 4.4 % to 9.4 % with respect to the PVR scenario, while the adoption of TVR allows an increase up to 13.8 %. The reduction of the loadability margins in TVR with respect to SVR, experienced in some cases, suggests that the analyses of TVR performances cannot be based on the distance from voltage collapse only. For this reason, we also performed a test, simulating a contingency, whose results will be presented afterwards.

Loadability [MW]	29 January	2 April	16 July
PVR	4961	4534	3855
SVR	5147	4868	3951
SVRO	5182	4964	4099
TVR1	5101	4775	3892
TVR2	5200	4915	4032
TVR3	5221	4940	4037
TVRdisp	5229	5159	4079

Table. 2. Loadability of the Italian system respect to different control voltage strategies

All the following numerical results are been obtained by simulation performed on a winter load peak scenario of year 2001 (29th January). Fig. 5 depicts the behaviour of the Casanova area. In the presence of SVR, the saturation of the available area reactive resources occurs after a load ramp of about 3000-3500 MW; the TVR is able to delay this saturation of about 1000 MW (Fig. 5b). The performances of the TVR with different M_Q are depicted in Fig. 5a: it is important to point out a that high M_Q do not necessarily guarantee increased reactive margins due to the consequent decrease of the voltages that also results in a decrease of the reactive power generated by the shunt capacitance of the electrical lines of the grid. This is why the TVR2 scenarios, although characterized by a M_Q lower than TVR1, can exhibit higher reactive margins when the system is heavily loaded: resulting in higher voltage profiles, TVR2 can better exploit the reactive production of the grid. Figg 5b and c show also the effect of the ORPF procedure: the optimization algorithm increases the optimum reference voltage in order to compensate the voltage drops due to the load ramp, resulting in an increased need of reactive power. Fig. 5d suggests that the operating conditions with high reactive power margins given by the TVR (especially TVR1), forces low voltage profiles and results in a reduction of the system loadability. Fig. 6 shows an example of an area (Baggio) where, due to the initial heavy loading conditions, the reactive resources available are exhausted after about 2000 MW of load ramp.

On the contrary, the behaviour of an area with high reactive margins is depicted in Fig. 7 (Dolo). The use of high M_Q, pertaining to the TVR1 scenario, allows maintaining remarkable reactive reserves during the load ramp, with a final fast saturation due to the low voltage profiles. The reduction of M_Q values (TVR2) results in higher voltage profiles and consequent increased reactive power production from the grid.

The performances of TVR can be highlighted assuming that the network configuration is changed with respect to the forecasted scenario. The goal is to show the ability of the TVR structure to adapt the voltage set points to the new conditions, resulting in greater loadability and robustness. The changes can result from a contingency as well as from unexpected generations schedules due to market uncertainties. For the scenario into analysis, the outage of the Turbigo power plant (400 MW), belonging to the Baggio area, has been simulated, assuming that the real power produced is supplied starting-up units in La Spezia (250 MW) and Piombino (150 MW), located in the Poggio a Caiano area. The voltage and reactive level reference values for both SVR and TVR are kept at the values calculated in the BC scenario (cases are defined like SVRdiss and TVRdiss respectively). Even with the Turbigo plant in operation, the Baggio area had a deficit of reactive resources (Fig.6). This implies that the further weakening of reactive margins caused by the outage needs to be compensated by the available resources in the neighbouring areas, e.g. Poggio a Caiano. The latter area, moreover, due to the units started up, presents increased reactive margins (Fig.8) and consequently the TVR increases the optimum voltage profile, in order to use these additional reserves. In Fig.8, also the effect of the rescheduling of voltages can be seen, at about 3400 MW, as well as the increase in the loadability obtained by the TVR in comparison to the other schemes (like depicted in tab. 3).

Base Case: 29 January	RPT	RSTdisp	RTTdisp
Contingency simulation	4969	5217	5274

Table. 3. Loadability of the Italian system respect to different control voltage strategies, contingency case

5. Conclusions

The paper investigates the dynamic performances of the Hierarchical Voltage Control (HVC) in the Italian EHV system, with particular attention to the features of the highest regulation level, the Tertiary Voltage Regulation (TVR).

The loadability tests, performed with different control strategies and in different network conditions, clearly show the enhancement of the system voltage security attainable by the adoption of the HVC: first, the SVR strongly increases the system loadability with respect to the PVR. Moreover, the TVR schedules the reactive power resources available coordinating the optimal voltage patterns, calculated for the forecasted system, with the actual operating condition. In addition, it allows maintaining high reactive margins during the load ramp, while the SVR quickly saturates the available resources. The TVR is also able to recognize automatically the changes in the power system conditions with respect to the scenario adopted for off-line ORPF optimization and to adapt in such cases (e.g. due to contingencies or to the energy market settlement) the pilot node voltage set points to the new operating conditions.

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Biographies

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Massimo Pozzi received his Doctor degree in Electronics from the Politecnico di Milano in 1987. From 1989 to 1999 he was active at the Automatica Research Center of ENEL in the field of the voltage control. Since 2000 he is working at CESI as Product Leader within the Business Unit T&D Networks in the framework of grid supervision and control.

Sandro Corsi received his Doctor degree in Electronics (Automatic Systems), from the Polytechnic of Milan (Italy) in 1973. In 1975 he joined to Automatica Research Center of ENEL. Research manager from 1997, as responsible of Power System Control & Regulation office. Member of CIGRE, IEEE-PES and CEI WG and SC; member of PSCC02-TPC and IREP Board of Directors.

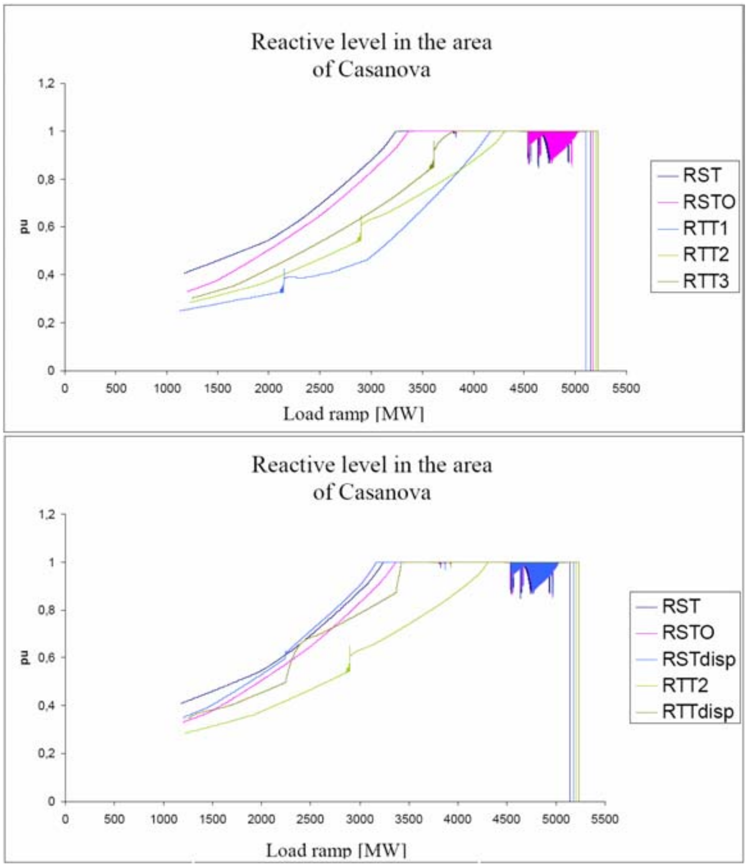

Figure 5 (a,b) Reactive power level of SVR area of Casanova.

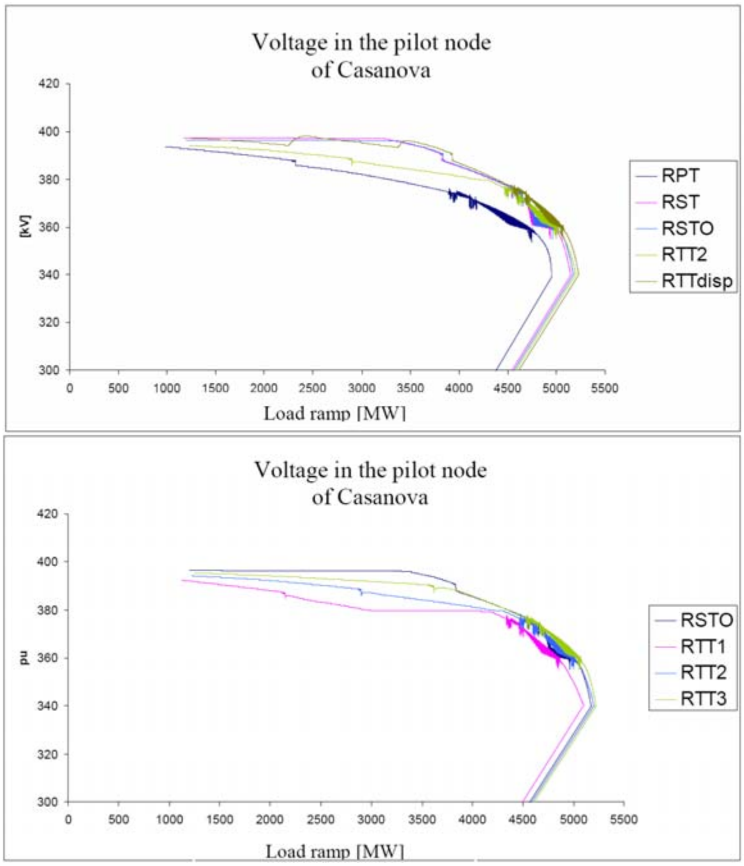

Figure 5 (c,d) Voltage profile of SVR area of Casanova.

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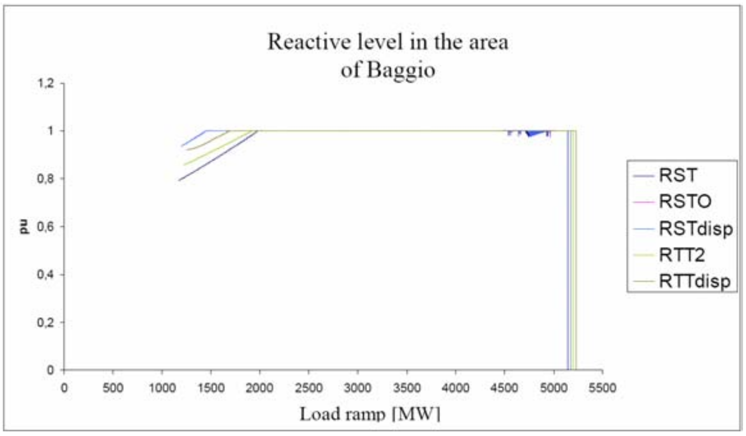

Figure 6. Reactive power level of SVR area of Baggio.

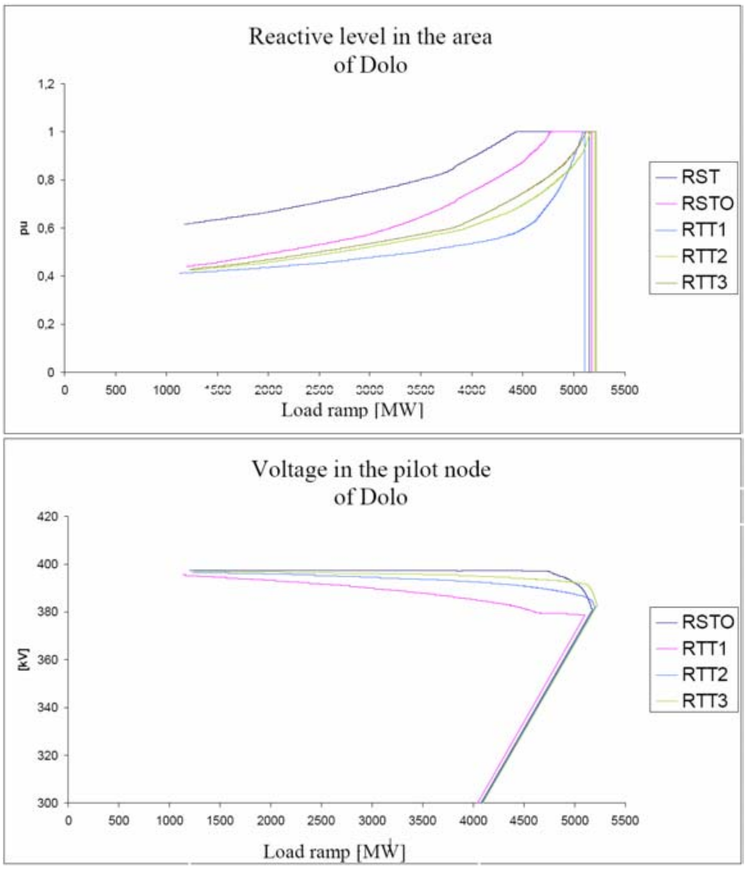

Figure. 7 (a,b). Reactive power level and voltage profile of the SVR Dolo.

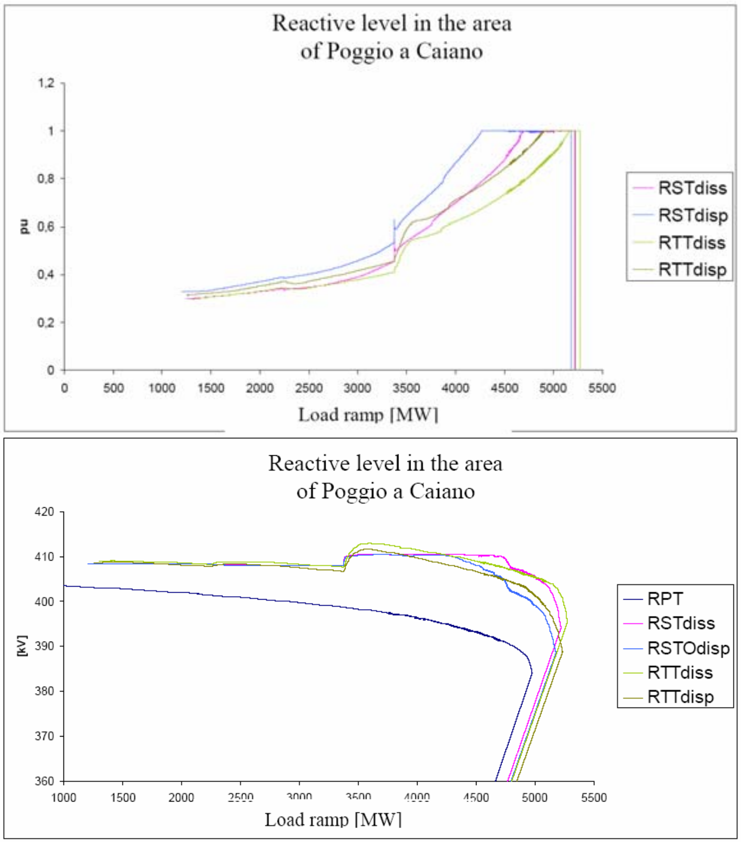

Figure. 8(a,b). Reactive power level and voltage profile of the SVR area of Poggio a Caiano (Simulation of a Turbigo generator contingency).