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Wide Area Voltage Regulation & Protection

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Abstract-- **A very promising Wide Area Voltage Protection (V-WAP) solution to face EHV voltage stability and system security problems is presented. Its unique ability is mainly due to an effective co-ordination with a Wide Area Voltage Regulation (V-WAR) modern system where the Secondary and Tertiary Voltage Regulations (SVR and TVR respectively) operate according with their hierarchy. Evidence is given to the practical feasibility and the simplicity in defining and developing a wide area voltage protecting solution, very effective to eliminate the risk of voltage collapse. The main simplification comes by the already existing and appropriate network subdivision in to areas given by the operating Secondary Voltage Regulation which also fixes the areas of the protection scheme intervention and gives, in real time, their control efforts for voltage support. On this base, a voltage stability index is proposed to operate the area load shedding according with simple and incontrovertible control logic. Dynamic simulation results related to North Italy power system shows the effectiveness of the proposed protection scheme that minimizes the load shedding amount to achieve the continuity and stability of the controlled power system, in front of a ramping load increase. The case the V- WAP has to operate alone, without the presence of any automatic voltage control system on the protected area, is also considered and analysed. In this case alternative protection functionality, less effective with respect to the case with V-WAR, is proposed and the simulation results demonstrate its interesting system security increase.**

Index Terms-- **Voltage, reactive power, voltage ancillary service, multivariable hierarchical control, secondary and tertiary voltage regulation, wide area monitoring and protection, stability margins, voltage stability index, coordinated control& protection.**

I. INTRODUCTION

CONSIDERING the transmission network voltages control we have to distinguish between:

- The continuous or discrete-time control actions devoted to sustain the network voltages around the nominal value, facing load changes and possible contingencies. These “Regulating Controls” are aimed to stabilize and maintain into operation the overall system feeding all the loads with continuity;
- The extreme step control actions, continuously ready to act but rarely operating on the real system and only during extreme conditions when the risk to lose the system or part of the system is high. These so called “Protecting Controls” aimed to confine the incoming problem and to minimize the part of the system to be lost and/or the part of load to be shed;

Both these controls are, in principle, required by a modern power system. The already developed protections are mostly related to independent protection units (component or system protections) and in some cases to the direct detection of predefined outages in a specific network: System Protection Scheme (SPS). Recently the subject of Wide Area Protection (WAP) is growing in the consideration, after the recent widespread blackouts round the world and the increased need of new and general protecting solutions able to increase the system reliability and the continuity of operation. According with its control objectives, WAP has to be considered an Emergency Control. Looking to the future, the objective to increase the power system security, reliability, management economy and operation quality is more and more considered by also taking advantage from the new technologies providing GPS-synchronized phasor measurements. In this perspective the system Wide Area Regulating controls (WAR) and the system Wide Area Protection solutions (WAP) represent the most concrete and feasible ways to achieve the waited objectives. Often WAR is not considered/available because it is beyond of the traditional understanding on power system control. In that case the system stability is only entrusted to the available “Emergency Control”, with less effective results with respect to those in the presence of WAR. WAR and WAP have to operate together and in a co-ordinate way, according with the different roles they play, taking reciprocally into account of their existence and operating states, including limitations, failures, saturation, out-of-service, etc. They can help each other in recognizing the phenomena in progress and in taking decisions for their specific control actions. Obviously it is very different for a protection system to operate in the presence or absence of a regulating system over the same grid area. Its control decisions in fact should be strongly related and coordinated with those of the regulating system taking also into account of its operating conditions. This co-ordination is, in general, not simple to be defined and strongly dependent on the characteristics, functionality and performances of the two WAP and WAR schemes. The development of WAP and WAR systems combined with Phasor Measurement Unit (PMU) technology, gives new and powerful opportunity for innovative and effective system regulation, protection and monitoring. Accurate, very fast and time-tagged phasor data, related to the main busses of a wide area network, can in fact be used by either the area WAR or WAP systems to better recognize the incoming phenomena and to appropriately select the corresponding most powerful control actions and to timely operate the correct control where needed. This, in accordance with advanced, intelligent and adaptive functionality, which has to be defined for both the WAR and WAP systems.

This paper reports on the main characteristics and promising protection functionality related to Voltage Stability and system security, when the WAR system is given by a transmission network coordinated voltage control: “ Secondary and Tertiary Voltage Regulations (SVR and TVR respectively)”. The paper will show the advantage to have into operation this kind of V-

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WAR (given by SVR and TVR) and an innovating V-WAP, based on SVR structure and strongly coordinated with the SVR operating state. Comparison with the case where WAP (Emergency Control) is the only operating system is performed showing the relevant advantages of the presence of SVR.
For each of the two protecting alternatives, the paper gives evidence of the main results in terms of innovating protection functionality and achievable performances through dynamic simulations related to the Italian power system.

II. SECONDARY AND TERTIARY VOLTAGE REGULATIONS

As well known [1-6], the main reasons supporting coordinated automatic real-time voltage control are hereafter summarized:

- the quality of power system operation is improved, in terms of reduced variation around the defined voltages profile across the overall transmission network;
- the security of power system operation is enhanced, in terms of reactive power reserves kept available by generating units for dealing with emergency conditions;
- the transfer capability of power system is improved, in terms of increased active power levels transmissible, with reduced voltage instability and collapse risks;
- the efficiency of power system operation is enhanced, in terms of minimization of active losses, reduction of reactive flows and better utilization of reactive resources;
- the controllability and measurability of voltage ancillary service is simplified, in terms of definition of functional requirements and performance monitoring criteria

A. Basic SVR and TVR concepts

The basic concepts of SVR are summarized here to permit understanding of the proposed control system's structure, performance and advantages:

- The idea of automatic real-time control of hundreds of transmission bus voltages is too complex, very critical, not reliable and therefore unrealistic and uneconomical;
- The generating units' reactive power is, obviously, the main resource already available in the field, low-cost and simple to control for network voltage support;
- A realistic simple voltage control system should consider the dominant buses only (a small amount), thus allowing a sub-optimal but feasible and reliable control solution;
- To more easily realize the dominant bus (pilot node) idea we call joint-buses those having high electrical coupling to form a "control area" with voltages close to each other;
- The control structure, based on the subdivision of the grid into control areas, automatically and, as much as possible, independently regulates each area pilot node voltage;
- The control resource is essentially based on the reactive powers of the largest units in the area (control plants), which mainly influence the local pilot node voltage.

The basic idea of TVR comes from the need to increase the system's operating security and efficiency through centralized coordination of the decentralized SVR structure:

- The pilot nodes voltage set-points must be adequately updated and coordinated with dynamics slower than SVR, considering the real condition of the overall grid and avoiding useless and conflicting inter-area control efforts;
- The pilot nodes voltage set-points can be computed and updated in real-time, considering the global control system structure and its real-time measurements;
- The pilot nodes voltage set-points have to be optimised to minimize grid losses while still preserving control margin.

An example of a control system based on the above concepts is the one operated by the Italian ISO based on a hierarchical control structure (Fig. 1) providing a network subdivision into electric areas around the so-called pilot nodes (Fig. 2: grid buses selected from the strongest ones on the basis of short-circuit powers and sensitivity matrices computation criteria.
In the SVR framework these areas are controlled by signals of "reactive power level", one for each area, provided by the Regional Voltage Regulator (RVR) apparatuses, which maintain the pilot nodes voltages at the desired values, through controlling in real-time the reactive powers of those generators

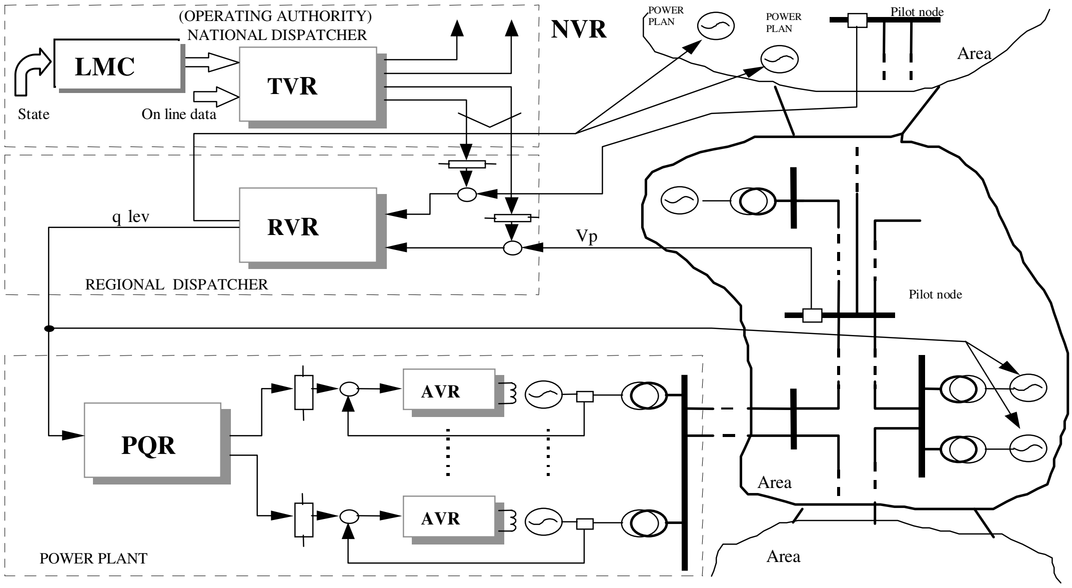

Fig. 1. Schematic diagram of the Italian hierarchical voltage control system.

which most influence the pilot nodes buses. The generators control is locally achieved at power plants by means of Reactive Power Regulators (PQR), directly acting on the Automatic Voltage Regulators (AVR) of the generating units.

In the TVR framework the National Voltage Regulator (NVR), at the national/utility level, controls in closed loop the RVRs voltage set-points for a secure and economic operation, establishing the "pilot node voltage" pattern, according to the actual network state and the long or short-term forecasting of optimal voltages and reactive power levels given by the Losses Minimization Control (LMC). By means of this hierarchical structure it is possible to operate in security the transmission network, very close to the highest voltage limits, through the real-time control of the main generators that are automatically forced to their limits only when needed. Clearly the basic SVR and TVR principle is the grid subdivision into areas, a single area consisting of an amount of busses having high electrical coupling each other. Therefore their voltages change in unison in front of local loads variation or network perturbations, according to the trend of the area pilot node voltage.

The SVR reactive power level qj(t) of the j-area, represents instantaneously the control effort under-way at the j-area and therefore the real-time reactive power load for the j-area control units. More precisely qj(t) value stands for the percentage of the j-area units reactive power with respect to their under or over-excitation limits: in particular when qj(t) reaches +1 the j-area voltage regulation is saturated, because the operating points of all the j-area control generators are fixed by their over-excitation limits. The pilot node voltage of a given grid area is therefore regulated through the SVR, changing the load, to the desired value unless all the area control units reach their over-excitation limits. Under TVR the approaching of this extreme operating condition determining the achievement of the area voltage instability limit [7]. Before to reach this limit RVR also operates, via rapid telecommunications, the turning on/off of reactor banks and shunt capacitor as well as the up/down of the OLTCs and FACTS controller set-points, up to the area OLTCs block.

Fig. 2. Application plan of the Italian hierarchical voltage control system

According to this and also considering that voltage degradation does usually take some minutes, for moving from the initial instability to the irreversible collapse, it appears reasonable, simple and effective to compute directly inside the SVR a real-time and on-line indicator of the j-area proximity to voltage instability, mainly based on the actual value of the area reactive power level qj(t) [7 – 9].

III. VOLTAGE STABILITY INDEX

With reference to the instantaneous reactive power level qj(t) of the j-area, the already proposed [7] proximity indicator VSIj(t) to voltage instability limit is given by:

$$VSI_j(t) = q_j(t) + \rho \frac{\partial q_j(t)}{\partial t} \Delta t$$

Where: ρ is a suitable weight coefficient for introducing a derivative term with an useful lead effect; -1 ≤ qj(t) ≤+1; in case some j-area units can be transiently overloaded with respect to their over-excitation limits, then: -1 ≤ qj(t) ≤+1+ ε j(t); ε j(t) normally kept at 0, under the RVR permit, can take positive growing values; Δt is the sampling time interval.

A. *Voltage stability index computation and meaning*

The definition shows that the real-time and on-line voltage stability index VSIj(t) is given by two terms: The proportional term is the control variable already defined and updated within a single time interval by RVR itself. The derivative term computing requires RVR for a single or a finite number of steps for a suitable filtering. The voltage stability index VSIj(t) computation can therefore be carried out by the RVR within an updating time of few seconds (a true real-time index). The derivative term takes into account of the qj(t) dynamics and expected short-term trend: the weight "ρ" allows an effective setting of such a "before time" contribution, which is mainly useful for possible control action based on VSIj(t): the greater is the positive value of the derivative term, the more is qj(t) rapidly reaching its maximum limiting value: 1+ε j(t);

When the derivative term is negative, its contribution avoids the prolongation of useless control action, because of the actual network and loads evolutions that will allow the SVR to recover distance from the limiting operation.

Usually, under TVR, the RVR operates for avoiding the units operation at their over-excitation limits. In fact this condition is strongly linked with the transformer tap-changers reverse action that anticipates the voltage collapse mechanism triggering. RVR achieves the objective by controlling in advance all the possible reactive power resources (capacitors banks, reactors, synchronous or static compensators, etc.) installed in the j-area, in such a way to reduce the qj(t) operating value and therefore the control effort of the area units. The RVR acts automatically on the reactive power resources under its control and moreover sends signals to the regional operator asking the manual switching of the remaining resources. In parallel TVR avoids the voltage plan request be unacceptable for the incoming heavy operating conditions. When all these control actions concerning the j-area voltage are accomplished and area control units do not allow additional excitation over-loading, then the difference "1-qj(t)" does clearly represent the distance of the j-area from its voltage stability limit: $\Delta_{SLj} = 1+ \varepsilon j(t) - qj(t)$.

B. *Voltage stability index control function*

The voltage stability index VSIj(t) represents an useful real-time and on-line information for the regional dispatcher which can be drawn by it, when given alarm thresholds are exceeded, to look over the critical state of the j-area voltages. Nevertheless, because VSIj(t) is a real-time updated variable which refers to few seconds before the current j-area operating state, it can be more effectively used for real-time automatic regulating and protective controls. More precisely exceeding VSIj(t) a first threshold value correspondent to the j-area consistent control effort and small voltage control margin, the proposed logic will order the automatic switching of capacitors banks, reactors and the set-points update of SVCs of the j-area according with a proper priority. A checking on-line of the switching fatigue of that equipment will restrict automatically the number of their commutations according to design prescriptions and network voltage criticism. The switching speed will be also related to the value of the VSIj(t) derivative.

After working out all the j-area reactive power resources and still persisting a local network working condition with small reactive power control margins, then VSIj(t) could reach a second critical threshold which allows the SVR to modify automatically the voltage set-points or the transformer ratio of the j-area OLTCs for obtaining a reduction of the load seen by the local transmission network.

After these "first barriers" of regulating controls, the VSIj(t) based logic could point out the overcoming of a considered very critical threshold, or the reaching and the permanence of all the j-area control units at the upper terminal voltage limit, or the pilot-node voltage reduction inhibit under the lowest allowable value by TVR. In any of the above-mentioned extreme working conditions, the control logic automatically shuts down the j-area OLTCs. Before this last step control the SVR will have operated all the possible automatic regulating controls at its disposal for supporting the j-area pilot node voltage. Besides the SVR will have drawn the operator attention, monitoring the j-area voltage value and the stability index value and asking for possible manual still available controls. At this advanced stage with the control system reaching its saturation condition, the j-area WAP should enter in to operation coming to the aid of j-area WAR (which can not contribute more) and substituting to it. The criteria through which the WAP will operate from now on are described in the following paragraph. When critical operating conditions will be left, VSIj(t) will decrease and the SVR will release the j-area OLTCs and reduce the operating reactive power resources. With PVR alone the possible, classic index is usually based on voltage bounds at each EHV bus or at the "potential" pilot node busses. In this case it is necessary to wait for very low voltage value at a given bus before to operate the protective action on it.

IV. WIDE AREA VOLTAGE INSTABILITY PROTECTION

From the above considerations, SVR will operate on its limits only when the transmission network voltages are low, not withstanding all the network reactive power resources are in operation for voltage support. In these conditions VSIj(t) becomes fully significant and reliable, because the j-area operating limits are reached despite of the reduced pilot node voltages plan and saturated reactive power control efforts. Therefore the Wide Area Voltage Protection system (V-WAP) can be simply defined in case the SVR-TVR (here also called V-WAR) is operating on the power system:

- The V-WAP structure simply follows the SVR areas and the possible changes of their edges. This is the first, very important, exchange of information between V-WAR and V-WAP for their alignment in terms of areas edges.
- The j-area V-WAP, adequately informed on the SVR operating conditions will leave the correspondent V-WAR task to regulate voltages and maintain stability in the j-area, till when SVR correctly works (information coming from SVR auto-diagnostics).
- The V-WAP system will be therefore authorized to operate only when it will be able to take the place of the V-WAR control significantly, that is when the two following conditions are verified:
- The j-area control system has reached its own saturation limits after operating all its available continuous controls on the generators and discontinuous controls on the other reactive power resources as well as on the OLTCs.
- The area real-time voltage instability index confirms the high instability risk in the area.

At that time V-WAP will enter operating on j-area and will command the confining of the power system part which is the first cause of the voltage instability (whenever this part has been recognized), shedding the local loads in the percentage and with the frequency required by the real-time needs. The sole objective is the removal of a serious voltage instability risk in the j-area under V-WAP control.

This relevant intervention is simply decided on the base of the reduced margins of the j-area control system with respect to its saturation. Therefore, it is here proposed an area protective decision guided by the vicissitudes of the correspondent (same area) control system. In this sense the proposed protective solution is not conventional and appears extremely simple because substantially based on the measurements and on the state of operation of the j-area V-WAR (see Fig. 1)

The V-WAP protective controls have to command:

1. If locally available, the paralleling of hot running reserves for reactive power support, already alarmed at the time the V-WAR regulator reached its saturation. The delay need by the reactive reserve to be thrown in the network should be coordinated with the VSIj(t) index threshold activating V-WAP. This first protective action, even if expensive, does not determine cuts on the feeding of the area users.
2. The progressive reduction of the local j-area loads, starting (if possible) from the prevailing inductive load, in case they were known. Priority is also given to confining the first cause of voltage lowering whenever the j-area nodes having very low voltages and high reactive power

absorption were recognizable: opening of the lines feeding those loads. After the selection of loads with given characteristics or connected to pre-defined busses, V-WAP sheds progressively the local area loads by following possible defined priorities, always maintaining a continuous monitoring on the persistence of the under way phenomenon,. The speed of the shedding will be also dependant from the VSIj(t) index trend and will be reduced to zero only when this trend will change slope as well as the local voltages again assumes normal values. The protective action will stop only when the SVR and TVR have reached again their normal operating conditions, outside their saturation limits.

3. Without SVR-TVR all the considerations fall again in to the conventional case where V-WAP is alone because V-WAR is not operating, with the exception of PVR. In this case the V-WAP protective controls are simply liked to low voltage thresholds.

V. SIMULATION RESULTS

To demonstrate the powerfulness of the proposed wide area protection scheme, simulation tests are performed on the North Region of the Italian Transmission system, strongly involved in the 2003 blackout. The adopted power system dynamic model is simplified for the low impact aspects on voltage stability phenomena: equivalents are used for some production and load areas, mainly for the South Italy and the European networks. Conversely, detailed models are adopted for the generators and their speed and AVR controls, also including the dynamic limits in over and under-excitation. Moreover the on-load tap changers of the grid transformers and their controls are simulated in detail as well as the load dependence on the voltage, which is of exponential type: with voltages higher than 0,85 p.u., the active and reactive power exponents are 0,5 and 0,8 respectively. At the lower voltage values the load decreases more heavily. As far as it concerns the SVR and TVR control systems, they refer to the Italian solution: a detailed model is used, correspondent to the on field application. The load shedding based on VSIj(t) index is commanded according with the protective criteria above defined, by using adequate filtering for VSIj(t) computation. The shedding of 5% of the J-Area nominal load is executed when VSIj(t) value reaches 0,99 and the pilot node voltage is lower than 0,95p.u. Persisting the load shedding need, the subsequent 5% step in the same area is operated 30s after the previous one. The load shedding without SVR also considers the "potential" pilot nodes and operates the 5% local load shedding with voltages below 0.82p.u threshold for more than 3s. Subsequent shedding steps after 30s, as above. These tests refer to the same percentage of load increase in all the areas under SVR control: 5 pilot nodes in North Italy; 1 equivalent pilot node for the Centre-South Italy. The load increases every 100s, starting from 20s, with the first two steps each of 2% of nominal load and the subsequent steps of 1% each, up to reach the last increase at 820s (Figs. 3 -7); 2% load steps for all the remaining cases. This large load increase allows to clearly giving evidence of the differences in the three selected cases:

- Fig. 3: Without SVR - voltage transients of the main EHV busses at peak load – voltage collapse.
- Fig. 4: With SVR -TVR and OLTC block - voltage transients of the pilot nodes at peak load
- Fig. 5: With SVR-TVR, OLTC block and load shedding VSIj(t) based - pilot nodes voltage transients.

Without SVR, the voltages collapse at 620s (Fig.3). To be noticed that the static V-P curve "nose" cannot be traced from these transients due to the dynamics introduced by the operating control loops. At the second step the generators reach their over-excitation limits and the subsequent transients are characterized by the alternating interventions of the generators limits and the OLTCs. The voltages in some areas reach very low values (few lower than 0,85p.u.) before to grow again due to the greater load reduction at low voltage. The collapse is a combination of the irreversible processes under way, pushed down by the further load step increase. With SVR and OLTC blocking based on VSIj(t), the collapse is avoided (Fig.4), with voltages around 0.9p.u. at 600s. The transients in Fig.5 show the overcoming of voltage lowering and instability problems, notwithstanding the load increase lasting up to 820s, with voltages controlled around 0,96p.u. The SVR effect is more evident after the first load step, even if it will work up to the end. TVR mainly operates along the subsequent load steps. The first load shedding (LS) correctly operates at 321s (after the fourth load increase) in the area with the lower voltage, being its SVR near the saturation from the beginning. Before and after the fifth load step increase, the second LS (at 405s) and the third LS (at 425s) happen in other two areas, due to their voltages ramping down. In synthesis, LS only operated in few areas and from two up to four steps: the smallest LS amount, thanks to the timely control based on data of voltage regulating system effort and on selection of the area unable to overcome its automatic V control saturation. The transient intervals characterized by alternating interventions of the generators limits and the OLTCs are far from load steps and LS. Voltages changes operated by TVR: reduction after load increase and recovery after LS, are shown by the transients in Fig.5. With distance protections, Fig.6 replaces Fig.3, showing the separation between North and South Italy, with South instable; analogously Fig.7 replaces Fig.5 showing a relevant stability result, notwithstanding the separation. The Fig.8 result (stable but with low voltages) is achieved by a protecting logic based on voltage thresholds. Lastly, Figs 9, 10, 11 with the untimely operation of distance protections replaces Figs 3, 8, 5 related to load increase: Fig.9 shows a cascade of events after the Lavorgo and Bulciago line openings, under PVR only. Fig. 10 shows a way to reverse the Fig. 9 instability by a voltage thresholds protecting system (shedding: 1892 MW, 6.90% of nominal). The ability of a WAP control based on VSI index is clearly evidenced by Fig.11 where the stability improvement is remarkable (load shedding 1750 MW, 6.39% of the nominal).

VI. CONCLUSIONS

Evidence is given of the practical feasibility of a V-WAP protecting solution, very simple and very effective to eliminate the risk of voltage instability in a given network area.

The main simplifications come from the fact that the network area where WAP is required to operate is already defined (dynamically) by the operating SVR which, as well known, is of decentralized type over an amount of power system areas. It is shown that, in the presence of TVR, the real-time index proposed for the voltage stability not only helps SVR in the control action but, above high risk thresholds, it also becomes the reference for the V-WAP intervention. This is the second, very important simplification. The third simplification comes from the ascertainment that, in the presence of TVR and SVR, the V-WAP is able to correctly and timely operate in a selective-precise way, by only considering measurements, voltage stability index, logic states, etc., coming from V-WAR and with very simple processing and computing of those data. Loosing SVR or in case of PVR alone, the proposed WAP protection based on the main busses (the pilot nodes if they are known) voltage thresholds can be easily used for a timely load shedding with acceptable, but not comparable with VSI, stability and voltage level improve. Simulation results confirm the powerfulness of the proposed coordination between Voltage Control and Voltage Protection, according with the "Area Concept" congenial to both the SVR and the WAP scheme. It has to be noticed that the proposed WAP based on VSI index takes advantages in recognizing a dangerous situation at relatively high voltages. Moreover the operated controls minimize the load shedding amount due to the timely-reciprocal co-ordination and support between WAR & WAP: in fact, the result is a compromise between the voltage values to be sustained, when greater than a minimum threshold, and the amount of loads to be shed to avoid the voltage collapse.

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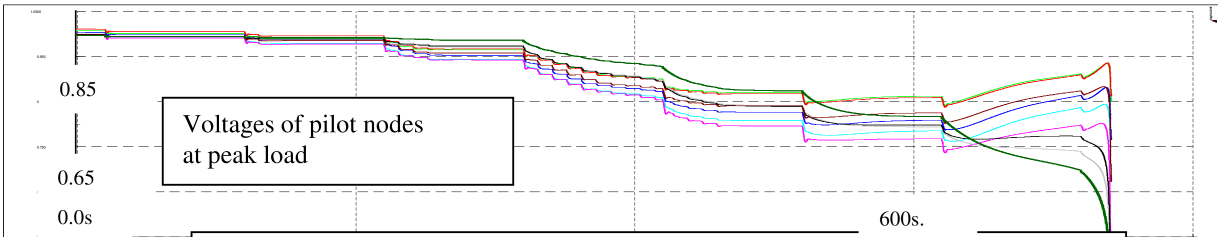

Fig.3 - Load increase, primary voltage regulation only, voltage collapse

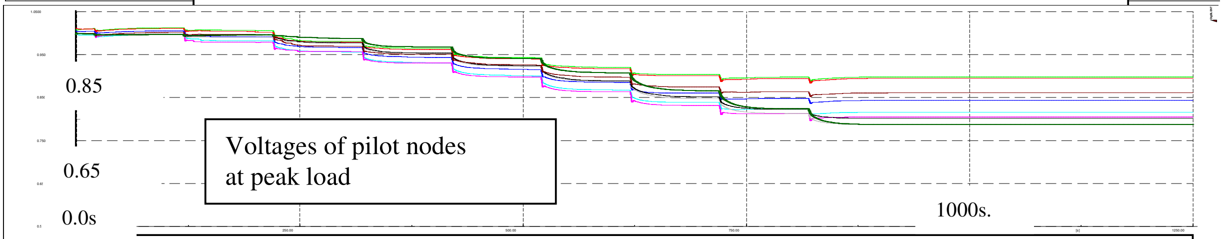

Fig.4 - Load increase, SVR –TVR – OLTCs block; Load Shedding based on voltage thresholds

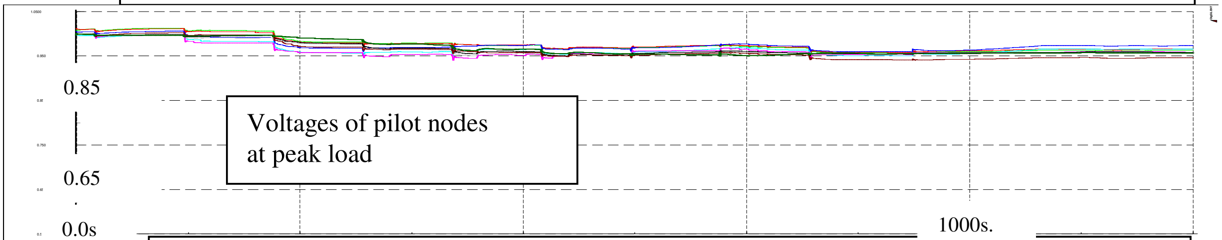

Fig.5 - Load increase, SVR –TVR – OLTCs block - Load Shedding based on **VSIj(t)**

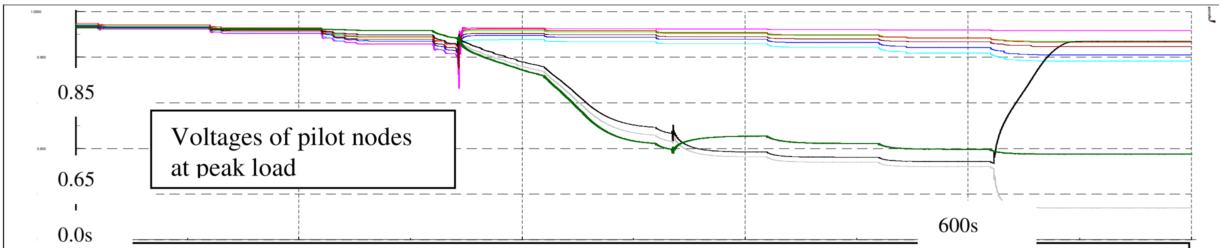

Fig.6 - Load increase, primary voltage regulation, Distance Protection, North-South separation

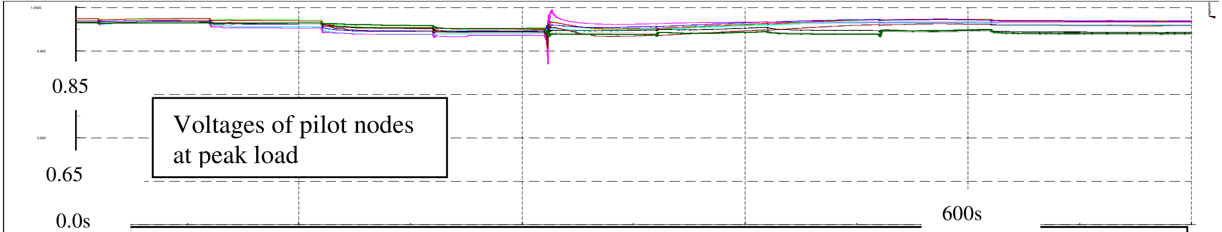

Fig.7 - Load increase, SVR –TVR – OLTCs block, Distance Protections, North-South separation, Load Shedding based on **VSIj(t)**

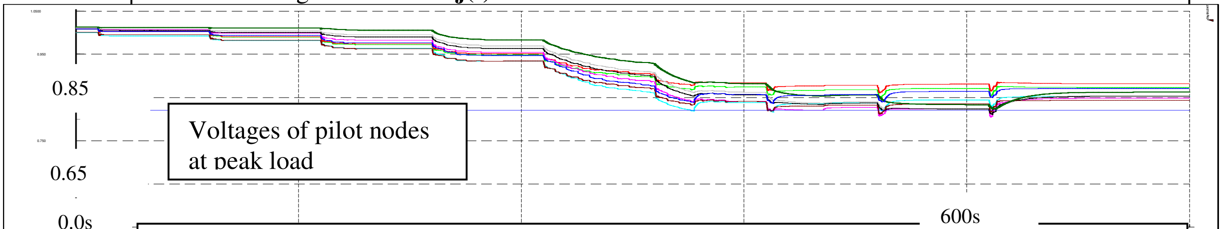

Fig.8 - North Italy main 400kV busses: load increase with only primary voltage regulation only, line protections and load shedding based on voltage thresholds

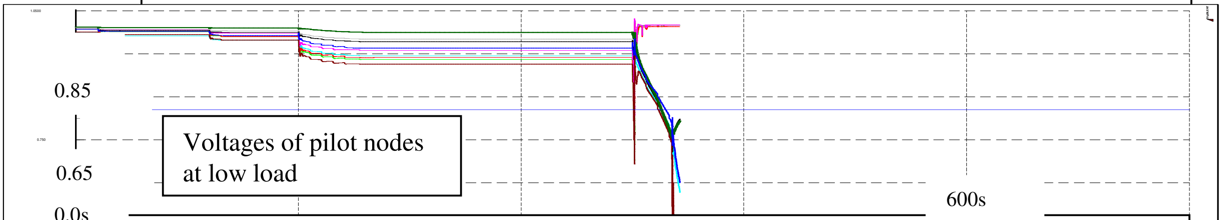

Fig.9 - North Italy main 400kV busses with PVR only and line protections: distance and max current Lavorgo (200s) and Bulciago (500s) lines opening; Separation

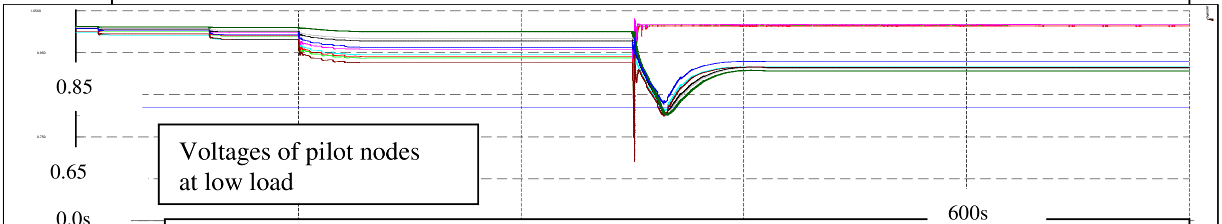

Fig.10 – As Fig.9 but including: Load shedding based on voltage thresholds. Separation

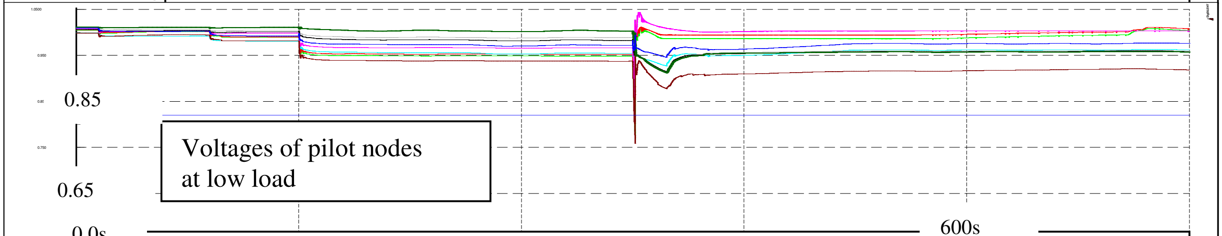

Fig.11 - North Italy main 400kV busses: loads increase with PVR - SVR -TVR and line protections: distance and max current. Load shedding based on **VSIj(t)**. Separation