Voltage and var support in electric power systems

Information from Cigré

The present environment for the operation of electric power systems (EPS) is complicated by environmental, economic as well as societal constraints. As a result EPS operate often close to their limits while trying to minimise costs and keep the quality of supply according to standards. The picture is complicated further by new types of generation and loads, market rules, and the increasing frequency and severity of weather events.

Currently, special attention is given to the development of active distribution networks within intelligent system architectures, facing new challenges including:

- Operating distributed generation in parallel with the distribution system
- Accommodating new flexible loads such as passenger electric vehicles (PEVs)
- Implementing advances in information and communication technology (ICT) and automatic meter management (AMM) service development
- Offering energy efficiency services based on AMM
- Bettering EPS security through microgrids
- Achieving enhanced operation economy and minimisation of losses
- The maximum utilisation of renewable energy sources (RES) through flexible loads
- Achieving a closer interaction between transmission operator (TSO) and distribution system operator (DSO)
- The implementation of mature new technologies such as HVDC, FACTS, WAMS with synchrophasors (PMUs), as well as smart-grid technologies.

The road map to smarter grids is more a journey than a destination. Economic feasibility is always important, while ancillary services control at dispatcher level, and distribution system operators are crucial in the implementation and operation of changing infrastructures.

Voltage and reactive power support is a central and crucial effort in EPS operation.

New developments on hierarchically coordinated voltage and var control at power plant and at dispatcher levels.

Architectural description of a presently operating hierarchical voltage control (HVC) solution

The functional design of the Italian voltage control system is based on a hierarchical decentralised solution, with the aim of regulating the voltage of the main high voltage (HV) busses (referred to as pilot nodes) through controlling in real-time the reactive power resources having the greatest influence on those buses. In this way it is possible to operate the transmission network very close to the highest voltage limits, through the real-time fast control of the main generators which are forced to their limits only when needed.

The originally designed solution (Fig. 1) foresees three different kinds of control apparatuses geographically distributed respectively at power plant, at regional and at the national TSO's dispatcher level. The pilot node voltage and related area of influence buses' voltages are controlled by a signal called "reactive power level"(one for each area) supplied to the main power plants in the area by the regional voltage regulator (RVR).

The closing of the real-time pilot node voltage control loop is achieved by control generators through the reactive power control loops implemented, at power plant level, by the automatic system for regulating voltage (ASRV) for electricity production plants [6] (named SART) directly operating on the set-points of the automatic voltage regulators (AVR) of the plant's units.

The AVRs very fast control is called primary voltage regulation. The combination of the SART and RVR [3, 4, 5] apparatuses realise the secondary voltage regulation (SVR). At the highest hierarchical level it is foreseen the tertiary voltage regulation (TVR) that should co-ordinate the actions of the regional controllers in real-time and in a closed-loop, establishing the voltage pattern of the pilot nodes and effecting slow corrections, in order to have a better balance of reactive power generation among the areas.

The TVR's task is to achieve an optimal compromise between both the objectives to reduce the differences in the actual and forecasted pilot nodes voltage values (for economy) and to maintain a control margin in the operating reactive power levels (for security). A non-real-time optimal reactive power flow (ORPF) functionality, for the losses minimisation control (LMC), computes the short-term forecasting of optimal voltages and reactive levels

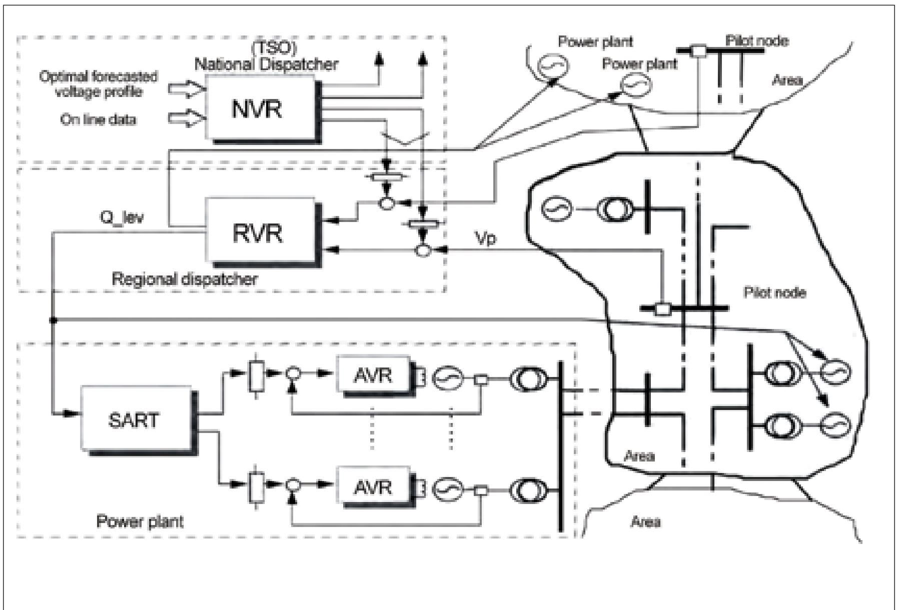

Fig. 1: Schematic diagram of the Italian HVC system.

taking into account the actual network's estimated state.

Short term future evolution of the HVC

The Italian TSO and CESI designed a new system solution where it is unnecessary to identify an intermediate regional control layer. Only one central general voltage regulator (RGT) application has been identified having in its responsibility the control of all the power system's voltage control areas1. Furthermore the integration of the TVR and SVR levels into a sole application will avoid redundancy with respect to the currently operating HVC control scheme.

The new HVC application, namely RGT, will display to control room operators the relevant MMI graphic pages completely merged with other SCADA-EMS pages already used for control, switching and dispatching functions, with the same aspect and with the same entrance modality.

In the new HVC control diagram (Fig. 2) the pilot node voltage and related area of influence buses' voltages will be controlled by Q_lev signals called "reactive power levels" (one for each power plant) elaborated by the RGT.

The closing of the real-time pilot node voltage control loop will still be achieved by control generators through the SARTs action, since one principle upon which the new control scheme has been designed is the necessity to avoid changes at AVR's and at SART's level in order to reduce the economical effort of project deployment.

The ORPF functionality [7], already available being integrated with TERNA's control and switching system (SCCT) framework, and realised outside the HVC project, will be exploited at the highest hierarchical level establishing the voltage pattern of the pilot nodes, and the SVR participating power plants optimal reactive power output, whereas slow corrections, in order to have a better real-time balance of reactive power generation among the areas, will be, if necessary, implemented to the pilot nodes voltage set-points by the OTLR function within the RGT application.

The integration of the ORPF's and RGT's databases, in the SCCT framework, will make it possible to conduct the optimal dispatching computation relying on updated knowledge, not only of the network components status, but also of the actual operating conditions of the topological architecture of the HVC system (by varying the HVC's regulators status it is

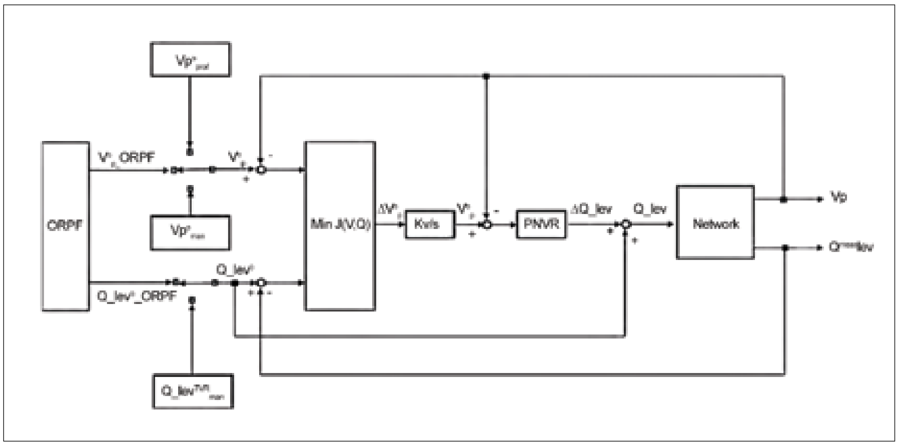

Fig. 2: Schematic diagram of the short term future Italian hierarchical voltage control system.

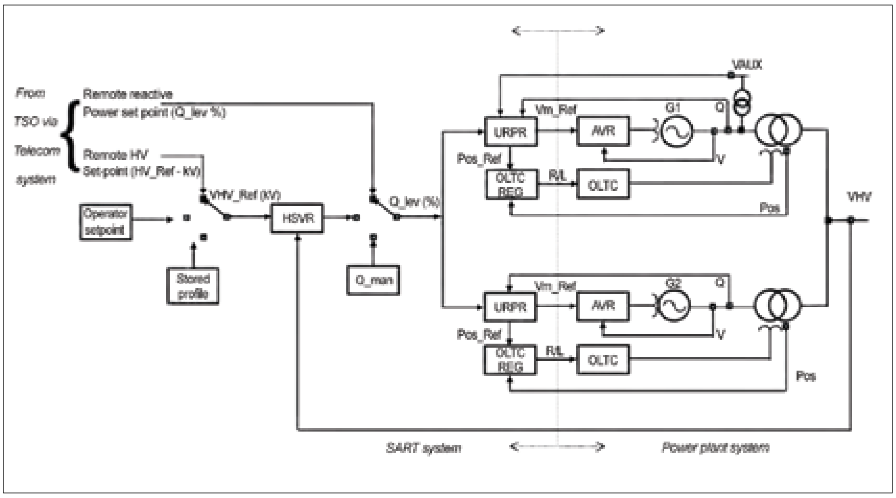

Fig. 3: SART system control block diagram with OLTC position control.

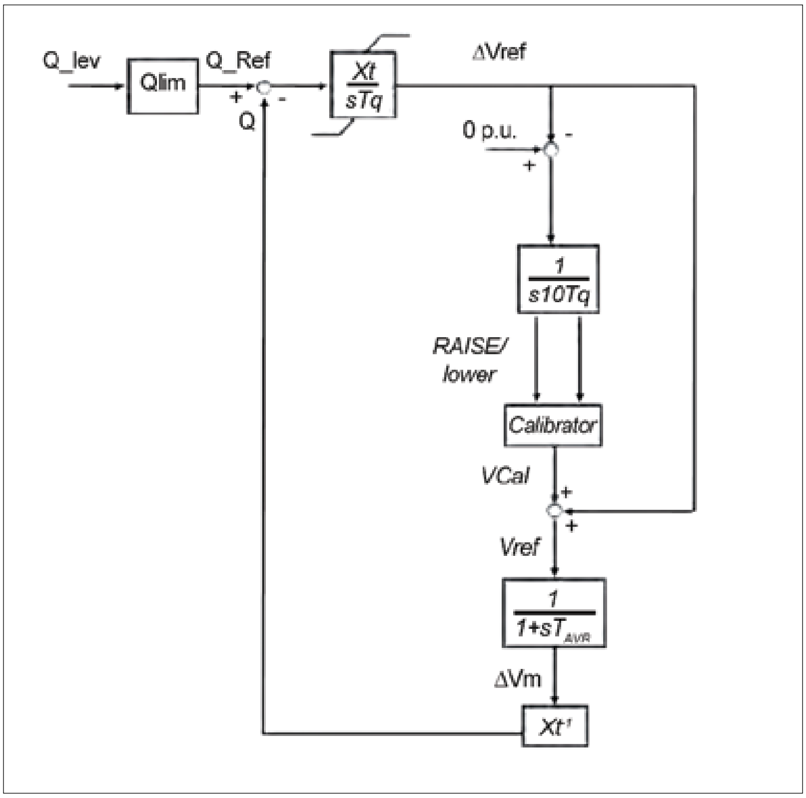

Fig. 4: Hybrid analog and digital AVR's set-point control.

potentially possible to introduce either constraints or unknown quantities to the optimisation procedure).

In fact, thanks to the availability of another SCADA-EMS functionality, (SENSIT), realising the computation of sensitivity coefficients and the selection of the pilot nodes and the association of the power plants to the network voltage areas2, the on-line and operating network subdivision into areas will be real-time defined and updated, when needed, adapting the control architecture topology on real network operating conditions.

This will improve system's control adaptive capabilities, also positively impacting the ORPF processing attainable performances, with respect to the presently operative HVC control scheme where only a batch evaluation of possible subsets of control parameters is performed based on a fixed identification of voltage areas.

Recent developments at dispatcher level

A new interface between the TSO's dynamic security assessment platform (DSA) [8] and the RVR systems has been developed in order to make direct data exchange with the OPRF functionality possible.

In fact, at the moment the ORPF function is run [9] inside the DSA platform, this being already in operation in the NDC in order to permit the TSO's operators to increase their general awareness of the power system security, as well as to clearly display systems data and to evaluate from grid snapshots the system behaviour following contingencies. On this platform it has therefore been possible to develop a very sophisticated static security assessment (SSA), a dynamic security assessment and to identify optimal power flows (OPF) and ORPF manoeuvres necessary to better manage contingencies. This last feature has been exploited in this transitional HVC project phase.

The implemented communication interface allows an online updating, in the DSA's database, of the RVR's regulations operating mode (activation/deactivation of a pilot node voltage regulator - PNVR, modification of the selected bus bar and relevant set-point modifications, etc.), these having a direct impact on the output of the optimal calculation performed by the ORPF engine, and the possibility to subdue the RVR system's operation to the direct control by the ORPF function, this acting on the RVR's pilot nodes' voltage set-point: in this way the RVRs system could be seen as field actuators of the manoeuvres necessary to purse the objectives of power system's operation security and economy.

The pilot node selection is based mainly on both the determination of network buses' short-circuit power computation – which has to be sufficiently significant in order to guarantee that the pilot node voltage represents the same area's other network buses voltage – and on the assessment that a sufficient decoupling exists between two prospective pilot nodes buses.

The ratio of power plants to voltage areas is based upon a sensitivity matrix, using the information of the coupling degree between generating units and pilot nodes, and on the criteria that a sufficient capacity of controllable reactive power has to be made available in order to master voltage changes in each defined area. These adaptive algorithms are based on the computation of the reduced matrices to be used as RVR's control law. This calculus relies on the parametric characterisation that the control system receives, at the configuration stage, consisting in the HRS and in the CSS matrices.

The former matrix represents the pilot nodes' voltage sensitivity (Eqn. 1) and the latter expresses the generating units' reactive

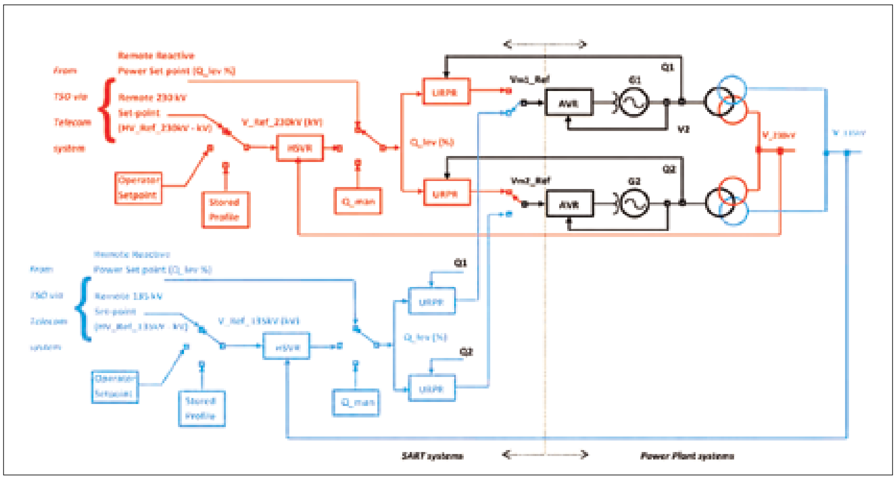

Fig. 5: Multilevel voltage levels bus bar control block diagram.

power output sensitivity both with respect to the generating units' terminal voltage variations (Eqn. 2). These SENSIT matrices are evaluated considering the whole set of possible power plants foreseen in the HVC project deployment.

$$HRS = \frac{\Delta V_p}{\Delta V_g} \qquad [1]$$

$$CSS = \frac{\Delta Q_g}{\Delta V_g} \qquad [2]$$

The process to be controlled is characterised by the transfer function identification expressed in Eqn. 3, where the Qlim matrix value is real-time updated thanks to the SART managed field data acquisition process concerning the central SCADA/EMS TSO's systems, and the SRS is given by (Eqn. 4). These matrices are valid with reference to the actually SVR participating generating units, therefore the aforesaid matrices (Eqn. 1) and (Eqn. 2) can be used to evaluate the control law matrix, approximately expressed by (Eqn. 5), where (Eqn. 4) can be calculated as (Eqn. 6).

$$P = \frac{\Delta V_p}{\Delta Liv_q} = SRS_{SVR,SERV}\ x\ Qlim_{SVR,SERV} \qquad [3]$$

$$SRS_{SVR,SERV} = \frac{\Delta V_p}{\Delta Q_{gSVR,SERV}} \qquad [4]$$

$$S_{cont} = \left[SRS_{SVR,SERV}\ x\ Q_{lim,SVR,SERV}\right]^{-1} \qquad [5]$$

$$SRS_{SVR,SERV} = HRS_{SVR,SERV}\ x\ CSS_{SVR,SERV}{}^{-1} \qquad [6]$$

However in the evaluation of (Eqn. 6) particular modifications, differentiated upon the fact that the foreseen generators are not actually grid-connected or they are on line but not SVR participating, have to be performed to the original matrixes (Eqn. 1) and (Eqn. 2) in order to obtain the correct product's involved factors.

These modifications represent the original contribution to the HVC's adaptive performances. In particular as the number of the generating units actually involved in the SVR operation varies the control problem dimension varies accordingly and therefore the control law matrix (Eqn. 6) will have to change not only its rank (as it happens when varying the order of currently on-line generating units) but also the value of each and every one of its elements since the original matrix terms would have to be taken into account to prevent the PVR from regulating units in an improper manner.

Recent developments at power plant level

At power plant level the HVC role is played by the SART system. This system is the natural evolution of the previously adopted voltage and reactive power regulator (REPORT) [3]. New hardware with improved performance and flexibility features has made it possible to develop new control features aimed at improving the generating unit's network voltage support.

OLTC position control

The coordinated superimposed regulation of the power plant's generating units' reactive power output integrated with the control of the OLTC position of the step-up transformers [10] fully automates the exploitability of the generating units' contribution to the EPS operation, simplifying the power plant control room operators managing effort by automatically fulfilling the applicable grid code requirements, while improving the equipment's operation reliability by allowing a proper use of the auxiliary services busbar voltage level taking into consideration the assignment to reduce the number of the OLTC transitions.

Fig. 3. illustrates the control block diagram implemented into the system incorporating three different control actions:

- The unit reactive power regulator (URPR), which controls the unit's reactive power output, based on the required reactive power level (Q_*lev*) signal: this represents the requested reactive power output to the generating units expressed as a percentage of the actual reactive power capability. In performing this task the URPR takes into account the operating conditions both of the generator and of the unit auxiliary services busbars, requiring, if necessary, a tap changer position change.
- The regulator of the unit's step-up transformer's tap changer controls the tap changer position (Pos) on the basis of the position set-point (Pos_Ref) demanded by the related URPR in order to enlarge the generator's exploitable region.
- The high side power plant busbar voltage regulator (HSVR) directly controls the annexed substation high side busbars voltage level (VHV).

The SART exposes to the TSO an innovative functional interface allowing it to send to the power plant either a signal representing the required power plant reactive power output level (Q_*lev*) or the required power plant high side substation bus bars voltage level (*HV_ref*). This could be used for further HVC developments automating the process of implementing the generating units' optimal reactive power dispatching.

Hybrid analogue and digital AVR's set-point adjustment

In order to attain the required dynamic performances of the reactive power control it is mandatory to act not only through the AVR's calibrator but also with a direct analogue action on the relevant node where the set-point is formed.

The control (Fig. 4) consists of two dynamically decoupled loops: an integral analogue regulation computes the ΔVref quantity acting on the AVR's set-point giving a fast regulation response. This control variable could anyway assume significant values exposing a generating unit to sizable transients in front of a connection fault between SART and the controlled AVR; for this reason the "raise" and "lower" commands generated by the SART will act on the AVR's calibrator keeping ΔV_{ref} as small as possible.

Multilevel busbar voltage control

Fig. 5 shows the block diagram of a regulator for the control of a power plant equipped with multiple voltage level busbars.

The control strategy consists of a double SART system functionality introduced into a single customised SART. Each regulator controls the voltage of one busbar section, and manages the interaction with the other by means of a negative reactive power droop action applied on the high side control and by exchanging the information necessary to characterise the other regulator's active operating status. The complex busbar system, with two voltage levels, implements suitable control logics to identify opportunities to exploit the reactive power output modulation of a generating unit in order to control one of the two voltage levels. Each SART's control function checks that the generating unit is actually connected to the related busbar system and that it has not been already allotted to the other SART's control action. The power plant operator has the responsibility to assign the control of a generating unit to one of the two SART functionalities.

The contemporary acquisition of the high-side voltage levels, and of the relevant switching devices, protects the system from an undesirable effect caused from a control action on the voltage of the non-controlled busbar section. This control functionality makes it possible to maximise the exploitation of the reactive power produced by the plant's facilities.

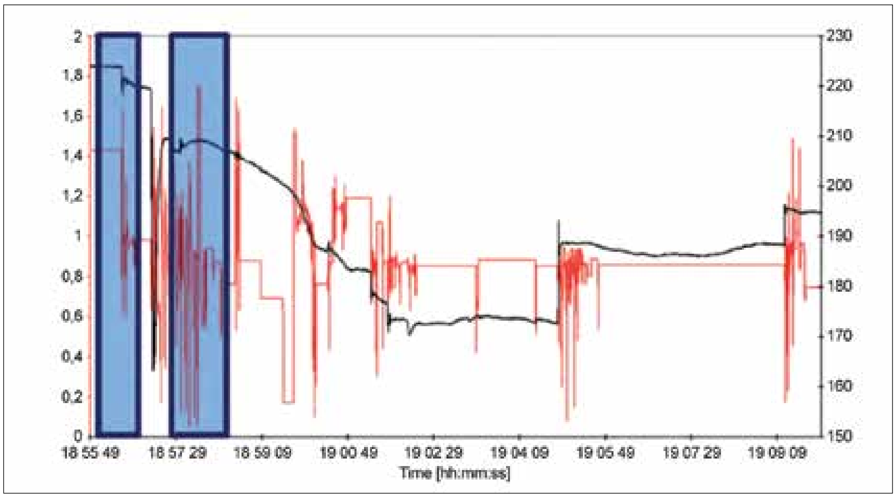

Fig. 6: SDI index response against bus voltage during a real transient.

New solutions for voltage/reactive ancillary services functional monitoring

Power system security, reliability and safety rely on many variables that should be maintained within specific ranges. One of these variables is an efficient voltage control of all nodes of the transmission grid which is mainly handled by voltage or reactive power controls of qualified generators connected to the grid. As far as voltage and reactive power ancillary services are concerned, settings and efficiencies of controls are strongly dependent on the characteristics of excitation systems and control systems of the generating units. Furthermore, the real performances of excitation systems can be different from design because of process and ageing reasons or because of wrong settings of controls.

In the past few years, a lot of countries have assisted to an important introduction of renewables into their power systems. Since the performances requirements for renewable of generation were generally less extensive than those for conventional generation, this has led to the replacement of ancillary services qualified generators with lower performances renewable generators, causing issues for reserve margin and power system security.

These aspects cause system operators to accurately monitor the quality of its grid frequency and voltage controls as they represent key performances indicators of power system security, reliability and safety.

In Italy this monitoring activity was performed through two methods:

- Auto-certification: power plants owners have to periodically certify their power plant compliance with grid code rules. Particular emphasis is put on voltage control with specific requirements related to evidence of static precision of control systems, capability curves, PSS effectiveness, positive ceiling and low voltage ride through capability [14].
- Inspections: TSO have the possibility to ask producers for technical documentation on frequency and voltage controls systems and to schedule specific tests to evaluate performances of generators. Usually, TSO requires inspections on new grid connected power plants or on power plants which have shown an unexpected behaviour during a grid transient [14].

These kinds of tests require physically being on site to make connections and system simulations.

In order to continuously monitor the governors' behaviour for the present and the future , traditional methods are reinforced with a platform installed in the TSO national control centres with the purpose of performing a real time monitoring activity of the qualified generators. The platform computes key performance indicators (KPIs) of the quality of generators voltage ancillary services and provide operators with elements to evaluate the grid overall of voltage and frequency controls. The KPIs taken into account in the monitoring applications are related to:

- Voltage range verification
- Reactive power reserve calculation in relation with the voltage point of work

To avoid errors due to measurements and data transmission errors, the KPI calculations are made through predictive algorithms (extended Kalman filter).

The main characteristics (current and future) of the application of monitoring are:

- TSO real-time data processing (4 s sampling) aggregated in 15 min files.
- Downloading of data inputs through a FTP secure connection
- Updating ancillary services KPI on a power plants scale, a grid area scale and national scale every 15 min
- Activating warning signals through the definition of alarm thresholds every 15 min
- Elaboration of graphs for all the variables taken into account in the calculus algorithms
- Elaboration of automatic reports on ancillary services monitoring activities
- Storage of historical data and results in databases for further elaborations
- Possibility of analysing historical data
- Triggering of transients due to grid fault or particular events
- Easily exploring and analysing all the stored data
- Visualisation through geographical (map or satellite) points of view of the plants taken into account

The role of PMUs on voltage security

The Italian wide area monitoring system collects measurements from more than 20 power stations all over the Italian grid and exchange real-time data with two European partners, Switzerland and Slovenia. The system is based upon a private communication network which connects remote PMU devices to Terna's national control centre (NCC) in Rome. Each PMU provides voltage, current, frequency and other status information at a rate of 50 samples per second and continuously sends data packages to NCC through its communication link.

Voltage stability assessment

Regarding voltage stability functions CESI and TERNA planned to develop a voltage collapse detection algorithm to be embedded into the WAMS environment [11]. A few theoretical studies were carried out in 2004 and 2005 to identify the most effective approach to voltage monitoring within the Italian power system. Different voltage stability indexes, such as VIP, and VIP++, were investigated on simulated voltage collapses with a detailed model of the HV Italian transmission system. An SDI index showed transient responses during collapse simulation closest to the expected theoretical trends, although system modelling also included active line losses and voltage dependency of loads.

Voltages are functions of relatively local extent, that's why specific attention has been focused on monitored load buses, under a two-fold perspective:

a. Load buses particularly prone to voltage degradation

b. Load buses whose voltage is representative of a significant portion of the network:

$$\frac{\Delta V_i}{\Delta Ql_i} \qquad [7a]$$

$$\frac{\Delta Q_{g_j}}{\Delta Q_{l_i}} \qquad [7b]$$

Concerning item (a.) the nodes presenting lower loadability margin had been chosen for monitoring, based on operational experience and extensive simulation of critical scenarios. Additionally, weakness indices, reflecting structural properties of the network, have been computed.

For each load bus, the indices Eqn. 7a and Eqn. 7b provided, respectively, the sensitivity of load bus voltage Vi and of the reactive production Q_{gj} with respect of the reactive load variation ΔQ_{li}. The former index provides the weakness of load bus voltage, with respect to bus load increment, the latter the trend of the bus load to draw reactive power from generators, thus it can be related to the generators' tendency toward saturation.

Concerning item (b.), pilot nodes of the secondary voltage regulation (SVR), already implemented in Italy, have been selected, as they are representative of the voltage behaviour of a large set of nodes. As such, pilot nodes are suitable for a general monitoring of the network voltage and reactive support. SDI-monitored load buses were eventually identified combining the above indices [13].

S-difference indicator

In the vicinity of voltage collapse the transmission losses start to block the reactive power transfer, especially when long transmission paths begin limiting the reactive power supply. The most heavily load lines become big reactive consumers. This can cause unstable operation of other lines, since the reactive power flow increases on the lines connected to the affected node. This operation state is the starting point of voltage instability in the affected node. Finally the system fails to supply the desired reactive power to the affected load node by all lines.

The SDI indicator is based on two successive samples of apparent power of a line. In proximity of voltage collapse all increase in power flow at sending end only supplies line losses. The increase of apparent power at the sending of a line no longer yields to an increase of apparent power at the receiving end. This means that all increase in power flow only supplies transmission losses.

Thus $\Delta S = 0$ at the receiving end of the line when voltage instability occurs. The voltage collapse condition is expressed in terms of the SDI indicator value by the relationship:

$$SDI = 0 \qquad [8]$$

SDI algorithm

The algorithm evaluates the SDI index for a given power station in the Italian grid [12]. It uses all voltage and current phasors relative to the electrical node at which is applied. A low pass digital filter processes voltage and current measurements, and then one index is calculated for each branch connected to the protected bus bar. Filtering is necessary since random variations of recorded data can turn into misleading SDI values.

Because system operators are rather interested in what degree the electrical node is endangered as a whole, a joint indicator is calculated. The joint (nodal) SDI index is calculated as:

$$SDI = min_i SDI_i \quad i = L, \dots, n \qquad [9]$$

where

n is the number current phasors relative to lines and transformers connected to the monitored busbar.

SDI stability index response

Fig. 11 shows an early response of the SDI index against a real transient, calculated during an outage. Although the index was still heavily affected by the noise content in the collected measurement, the figure clearly depicts how the index quickly moves towards zero every time there's a sharp decrease in reactive power supply, which turns into a sudden change of voltage first derivative.

Shortly after the first tripping the SDI index falls under 0,5 (leftmost blue box). Although the system seemed to have recovered, the indicator started to assume even lesser values (lesser than 0,2). The indicator's behaviour shows that the system is in the proximity of voltage instability; with transmission losses blocking any reactive power transfer. After the voltage instability actually occurs (rightmost blue box) the voltage started a rapid decrease leading to very low values (around 170 kV).

Conclusions

Results presented in this paper show that the indicator and the algorithm for real-time identification of voltage instability proximity using PMUs and based on the Thevenin equivalent network model parameters is sensitive enough to capture the influence of topological changes in the network, and of generation units in operation at major power plants for the voltage stability margin estimation.

Acknowledgement

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