2.5 Wide-area voltage stability monitoring, instability detection and control

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2.5.1. Overview of voltage stability monitoring

Synchronized phasor measurements [1], fast communications, and powerful computational facilities, as the core WAMPAC technologies open possibility to achieve a comprehensive solution for wide-area voltage stability monitoring, instability detection, and control. Expected financial benefits of wide area monitoring and control deployment are related to congestion management (more accurate computations of available margins for voltage stability limited systems) and/or reducing the risk of catastrophic blackouts (and all associated societal and economic costs).

Figure 1 illustrates a general framework for wide-area voltage stability monitoring, instability detection and control. As shown in the figure a comprehensive solution should, in principle, include the following tasks:

1. measurements collection and pre-processing;
2. computation of an appropriate voltage stability index that quantifies system degree of stability;
3. voltage instability detection through checking the chosen index against thresholds;
4. voltage instability control through corrective controls.

Figure 1 also refers to preventive control to enhance voltage stability, to event-based corrective controls (activated by specific System Integrity Protection Schemes – SIPS - not relying on phasor measurements), as well as the need to continuously present results to the system operator in the control center.

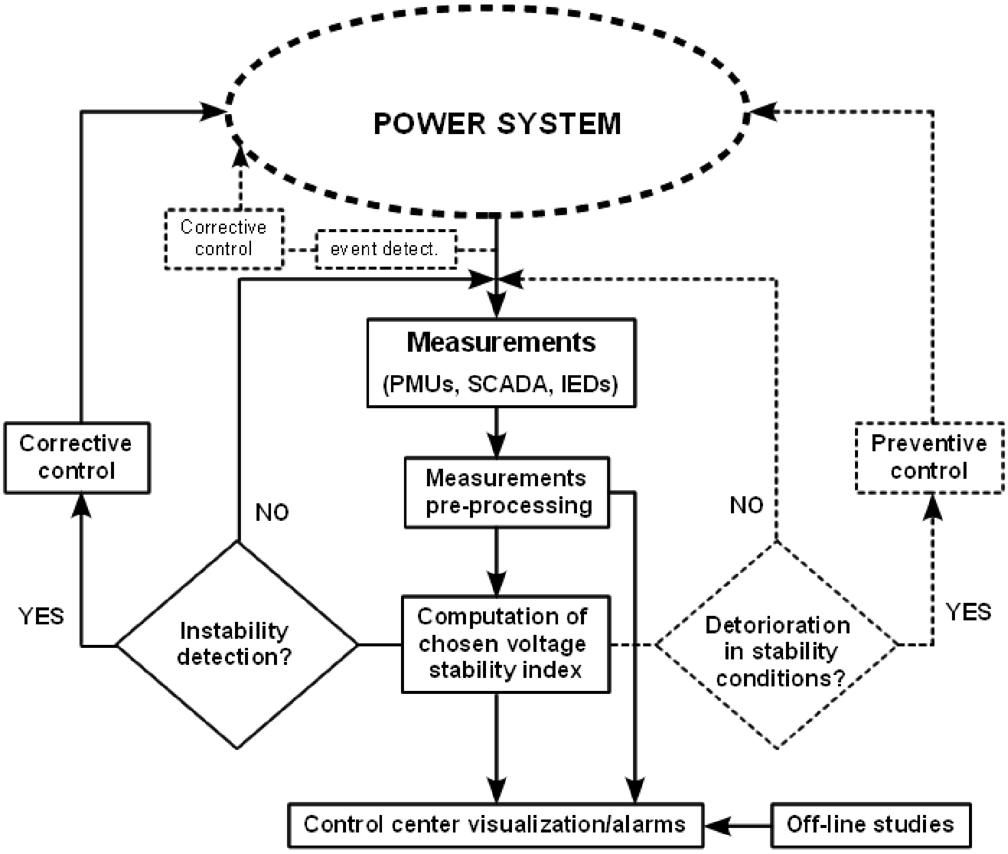

Figure 1: General framework for wide-area voltage stability monitoring, instability detection and control

As any other monitoring scheme, voltage stability monitoring starts with measurements collection and their pre-processing. Other ingredients of the monitoring include computation of an appropriate stability index and presentation of the results to the system operator.

2.5.1.1 Measurement collection and pre-processing

Information about the current system operating conditions is obtained through the measurements spread over the system. Supervisory Control And Data Acquisition (SCADA) system, advanced Phasor Measurement Units (PMU), Intelligent Electronic Devices (IEDs) or a combination of these can be used.

Traditional SCADA systems gather system-wide data at a rate of 2-10 seconds and usually provide measurements such as voltage magnitudes, active and reactive power flows and injections requiring further processing to obtain the system state information.

On the other hand, PMUs are GPS time-synchronized instruments that measure voltage and current phasors. When supported by a fast communication infrastructure, these devices gather system-wide data at much higher rate (10-120 samples/second) than traditional SCADA [1]. PMUs are high-precision instruments, time-synchronized with the precision of less than 1μs and magnitude accuracy better than 0.1%, although the overall accuracy of the PMU data is limited by that of the current and potential transformers, transducers, etc. as well as by the ability to adjust the digital signal processing to fast changing frequency conditions. PMUs are thus able to provide successive system state "snapshots" at a higher rate than SCADA [1]. In principle, detecting long-term voltage instability does not require a "high" rate (f.i. one index computation every second seems reasonable), while it would be mandatory to deal with short-term voltage instability .

Measurements pre-processing includes the following tasks:
1. recognize data drop-outs and false zero values,
2. account for and filter inevitable errors in measurements as well as "noise" introduced in measurements by the system dynamics not directly linked to voltage instability (short-term dynamics, low frequency electromechanical oscillations, etc.).

Pre-processing may also consist of deriving non directly measured quantities, transforming phasors into the network reference frame if needed, etc.

One possibility to filter the gathered measurements is to resort to a state estimator (nonlinear in case of traditional SCADA, linear if only PMUs are used, or hybrid).

2.5.1.2 Computation of chosen voltage stability index

The voltage stability index reflects the system stability degree. It has to be chosen so it reflects phenomena directly linked to voltage instability in the power system of concern. At the same time, it should be to be simple and practical. A wide variety of voltage stability indices have been proposed so far [2-5]. Many of them were aimed at being computed at the operating point estimated by a SCADA-based state estimator while some of them were devised with the phasor measurement technology in mind.

New technological solutions will give real advantages only together with algorithmic developments, which can take place in two directions:
1. adaptation of existing voltage stability assessment techniques which were not developed to take advantage of the new technological solutions, and require adaptation to the new conditions;
2. development of new algorithmic solutions with the aim to take more advantage of the newly available information and produce a synthetic indicator of stability conditions.

Furthermore, new or adapted algorithmic solutions should scale up well to the amount of information available, i.e. from a limited number to a rich information environment, and should be adaptive with respect to changing system conditions.

If computing the chosen voltage stability index requires the system model and network topology (model-based monitoring) then the latter have to be included in the scheme and updated at adequate rate using the gathered measurements. Static system models are considered satisfactory for long-term voltage stability monitoring [2-5] while the level of details varies from one voltage stability index to another, and also depends on the prevailing system conditions and characteristics. Alternatively, it is also possible to assess voltage stability in a more approximate manner through some indices using the available measurements only (model-free monitoring).

The computation of a chosen voltage stability index can be complemented with the stored results of off-line studies and observations. For some heuristic indices, the latter can help selecting an appropriate alarm threshold.

2.5.1.3 Control center visualization/alarms

Voltage stability monitoring should include proper presentation of results to system operators in the control center [6]. These visualizations/alarms have to be easy to interpret and intuitive. Options that could effectively serve this purpose are the following:

- time evolution of computed stability index,
- off-line computation of nomograms and tracking with PMUs the current operating state within the nomograms,
- visualization using geographical information systems (GIS) and/or one-line diagrams,
- etc.

2.5.1.4 Relationship with Voltage Security Assessment

It may be appropriate to recall the respective roles of Voltage Security Assessment (VSA) and voltage stability monitoring.

VSA aims at answering “what if” questions, by considering the impact of likely contingencies on system security, more particularly voltage dynamics. An on-line VSA tool can be used in the control center to measure the distance to insecure operation at a specific point in time. This may take on the form of nomograms showing the region of secure operation, i.e. the region of the space of operation variables within which the system will respond in a satisfactory manner to any of the predefined contingencies. Alternatively, for voltage stability issues, the above distance can be identified on PV or QV curves, usually relative to post-contingency operating conditions.

Voltage stability monitoring, and its variants based on synchronized phasor measurements, aims at detecting an impending instability. Here, the operating conditions prevailing after an effective weakening of the system are of concern, not those that would result from a likely but still hypothetical disturbance as considered in preventive security assessment.

Three types of system weakening are of concern in long-term voltage stability:

1. outage of transmission equipment increasing the electrical distance between generation and load centers;
2. outage of generation near loads causing additional active power flow from remote generators, the loss of reactive power production near loads, and the disappearance of a voltage-controlled point;
3. load increase that cannot be accommodated by the system, possibly due to a weakening of the former two categories.

The vast majority of experienced voltage instability incidents pertained to the first two categories, on which wide-area voltage stability monitoring should focus (load increases are considered when determining security margins in VSA).

Besides their main application to emergency detection, PMUs can also prove useful in some preventive aspects:

- by improving accuracy and reliability of state estimation, which, in real-time applications, provides the base case (initial, pre-disturbance) operating point for contingency analysis;
- by providing some distance to instability through the difference between the voltage instability index and its alarm threshold;
- by allowing to better track the system operating point within pre-determined security boundaries.

2.5.2 Objectives, challenges and promises of a wide-area voltage stability monitoring

One issue is how synchronized phasor measurements can enhance the capability of detecting a developing voltage instability *with some anticipation*. This could serve as early warning signal sent to operators or, even better, at the heart of an advanced SIPS.

By way of illustration, the curves in Fig. 2 show unstable voltages evolutions following a three-phase fault cleared by permanently opening the faulted transmission line. They relate to the test system used in [25]. The initial operating point is insecure with respect to the considered disturbance. The three curves relate to various proportions of induction motor load.

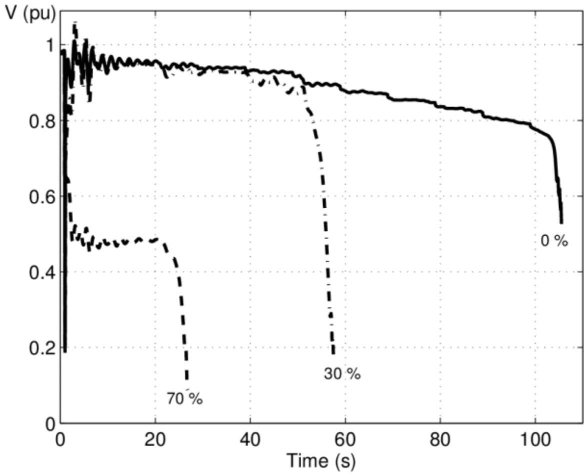

Figure 2: Unstable voltage evolutions following a disturbance

The curve with no motor load shows a long-term voltage instability leading to collapse in a bit less than 2 minutes after the fault occurrence. The system evolves under the effect of OverExcitation Limiters (OELs) and Load Tap Changers (LTCs). The relatively slow degradation prevailing before the final collapse allows using the shown transmission voltage as triggering signal for emergency controls, such as undervoltage load shedding. The latter acts when the voltage stays below a threshold lying typically between 0.85 and 0.95 pu, depending on the system specifics [30, 32, 33]. Load curtailment takes place after a delay of at least 2 to 3 seconds leaving time for voltage to recover after fault clearing (i.e. avoiding to react to normally cleared faults) [33].

In such an instability scenario, the objective of an advanced voltage instability detection would be to detect the onset of the instability itself, rather than its consequences. Standard SIPS based on fixed voltage thresholds could then be replaced by adaptive schemes, i.e. schemes that would trigger emergency actions at time instants dictated by the instability condition itself. This would also yield an unambiguous identification of instability allowing, for instance, to distinguish an unstable voltage evolution from a low but stable voltage situation.

Coming back to Fig. 2, the curve obtained with 30 % of induction motor load shows a much more severe situation where voltage stays at a rather high value, before it drops sharply. This is due to induction motor stalling, caused by the vanishing voltage support from generators switched under field current limit by OELs. In this situation, the voltage decline is so fast that one cannot envisage a SIPS relying on voltage only. Indeed, that protection should react to the voltage decline in a much shorter time than the above mentioned 2 to 3 second delay allowing voltage recovery after fault clearing. In this case even more than in the previous one, it is crucial to anticipate the instability before it shows its effects. This is a typical example of application of wide-area monitoring.

Finally, the leftmost curve in Fig. 2 relates to a short-term voltage instability, where induction motors cannot re-accelerate after the fault has been cleared [2,3]. So far few publications have been devoted to the fast detection of short-term voltage instabilities, other than by monitoring low voltage and/or slow voltage recovery [7]. It remains a challenging application for synchronized phasor measurements.

Because monitoring voltage magnitudes is simple and cheap, the performance of any more advanced voltage instability detection should be compared to that simple voltage check, in terms of anticipation capabilities. Some publications show indices capable indeed of identifying a voltage unstable situation, but issuing their emergency signal when the system has reached such low voltages that a simple check of the latter would outperform the proposed index.

2.5.3 Voltage instability detection methods

Voltage instability detection usually involves comparing the computed value of a stability index with its pre-defined alarm threshold.

Figure 3, derived and slightly modified from [8], offers an overview and categorizes a sample of proposed approaches (indices) for voltage instability detection based on wide-area measurements. This survey of methods is non exhaustive, although it is representative, hopefully, of a large part of the literature.

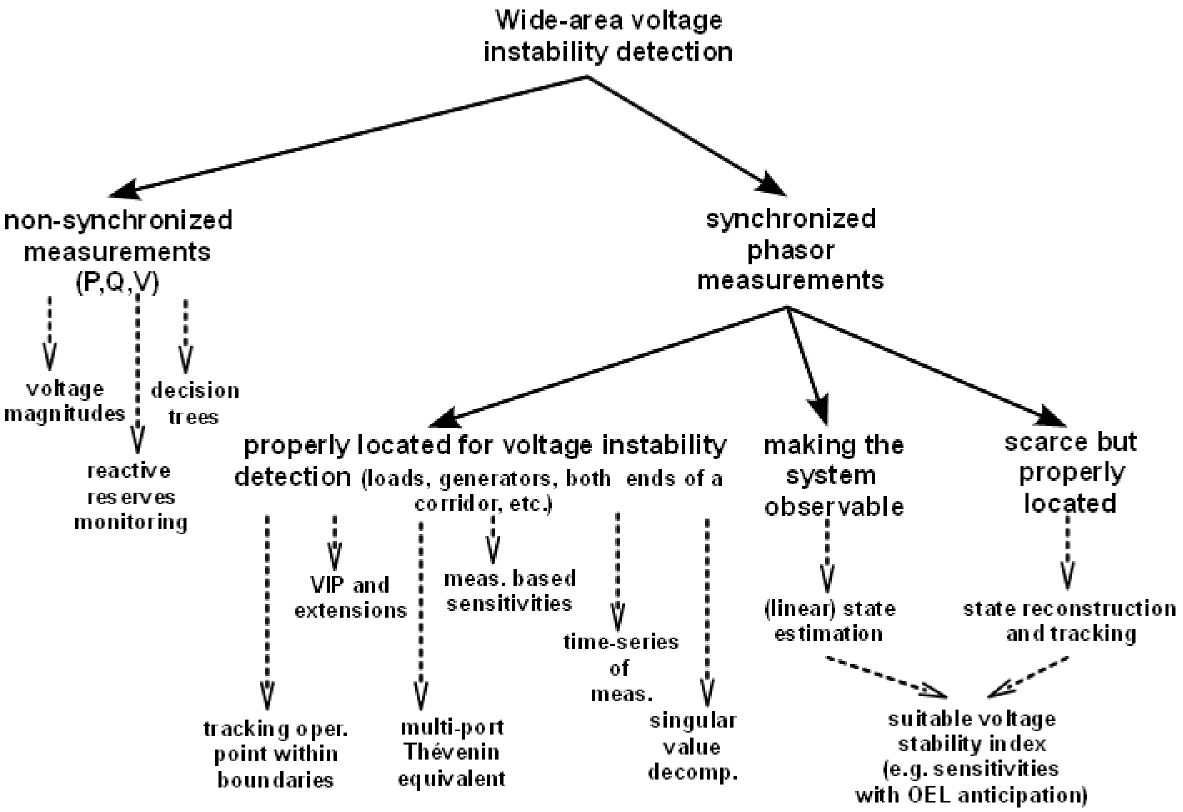

Figure 3: Voltage instability detection methods

The methods are grouped in those relying on non-synchronized and those relying on synchronized measurements, respectively [8].

The methods using non-synchronized measurements include for instance: decision trees, reactive power reserves monitoring and voltage magnitudes at selected system buses.

For voltage instability emergency conditions detection decision trees automatically built offline on the basis of learning set and a list of candidate attributes can be used in real-time to assess quickly any new operating state, in terms of the values of its test attributes [9]. The latter are readily available from real-time measurements.

Reactive power reserves are generally sensitive indicators of voltage stability conditions [10,11]. This method essentially monitors reactive reserves available at key generators and other reactive power sources identified in extensive off-line simulations. A problem lies in the identification of effective reactive power reserves, taking into account that reactive power must be close to the affected area to be effective.

Voltage magnitude is the simplest indicator of deteriorating voltage conditions [2-5]. However, the limitations have been discussed in Section 2.5.2.

Although the above methods have been discussed in the context of non-synchronized measurements, all of them in principle all of them can be used with synchronized measurements [12].

Various methods using synchronized measurements were derived from the Thévenin impedance matching condition. This condition applies to a simple two-bus system and identifies the maximum load power point as the point where the load and Thévenin impedances are equal in magnitude [2-5]. Voltage Instability Predictor (VIP) is one such method based on recursive measurement processing in order to identify the equivalent Thévenin impedance of the system seen from a single load bus. Several extensions of VIP were derived [13-19]. For instance, the so-called “corridor VIP” was proposed in [13]. This VIP extension avoids the processing delay of recursive least-square estimation in VIP, by taking synchronized measurements at both ends of a transmission corridor yielding a wider-area view [15]. After grouping all the lines of the corridor into a virtual link, the parameters of the latter are estimated from measurements taken at both ends. The VIP extension known as VIP++, introduced in [18], takes advantage of availability of synchronized measurements at several load buses. Other extensions include load identification [16], and load representation by REI-equivalent [18]. VIP and its extensions are able to provide information on voltage stability of a small, radial part of the system. A wide-area extension of this concept was introduced in [17] assuming a rich synchronized measurements configuration (with a PMU placed at every generation and load bus) and combining VIP with information on the status of generators reactive power capability.

Relying on the fact the power flow Jacobian matrix is singular at the point of collapse, Ref. [6] proposed the use of singular value decomposition of a measurement matrix yielding a model-free method that uses synchronized measurements from several locations spread over the system. This matrix, updated at every time a new measurement sample is collected, is formed so that each column includes the measured values provided at a given time by the various PMU devices, and the various columns correspond to successive times. The largest singular value of that measurement matrix is used as voltage stability indicator.

The multi-port Thévenin equivalent extension aims at preserving generators and loads in the region of interest instead of lumping all generators and all but one loads into a single-port equivalent. The so-called L-index proposed in the early Ref. [20] used that formulation.

As already mentioned in Section 2.5.1.4, the position of the system operating point can be tracked with respect to security boundaries. This essentially extends the idea of two-dimensional nomograms in two ways:

- using multi-dimensional nomograms computed off-line [21] as piece-wise linear approximation of the boundaries usually in three dimensions (independent quantities characterizing system operating point) chosen based on experience and extensive off-line simulations);
- computing voltage stability boundaries based on power flow model, adapted to incorporate PMUs, in two-dimensional space (usually chosen power flows) with refreshment of these boundaries with every standard state estimation results as outer loop of refreshment and every SCADA sample is collected as inner refreshment loop [22].

A method based on time-series of a single PMU [23] is an example of approach not based on any previously proposed voltage stability index. Based on experience from other fields (finance, ecological systems, etc.) the method is aimed at detecting critical transitions in the stream of synchronized measurements based on the so-called critical slowing down. It is derived from statistical properties of a signal ahead of transition: increased signal variance from the mean trajectory, increased kurtosis (flicker and asymmetry), and increased recovery time from perturbations.

If the system (or at least the region of interest) is fully observable through synchronized phasor measurements then linear state estimation can be used together with a system model to compute a voltage instability index [24,25]. A proven approach is to use the sensitivities of the total reactive power generation to individual load reactive powers. Although they involve a system-wide analysis, they are computationally inexpensive [24]. By way of illustration, Fig. 4 shows, for the test system used in [25], the time evolution of such sensitivity in a long-term voltage unstable case resulting in system collapse some 150 s after the initial disturbance. The curve shown with solid line was obtained by computing sensitivities from the complex bus voltages provided at regular time intervals by a detailed time simulation, and corrupted by simulated measurement noise. PMUs were assumed to provide 48 measured synchrophasors ensuring full system observability. The developing instability is revealed by the sensitivities jumping from large positive to large negative values. This behaviour is related to one real eigenvalue of Jacobian matrix crossing zero, the inverse of that matrix being used in the sensitivity computation. It is seen from the figure that this detection takes place some 40 seconds before the final collapse. At that time, transmission voltages exhibit still normal values.

Some recent research results have opened the possibility to use these sensitivities in situations when the number of available PMUs is limited. This uses algorithmic solutions to reconstruct and track the system state using either a limited number of PMUs together with some prior knowledge about system state, or an efficient combination of SCADA and PMU measurements [26, 28]. The system state is reconstructed and tracked in a recursive manner, by solving at each reconstruction step a constrained least-square problem involving the synchronized phasor measurements together with the reconstructed values of load and generator injected powers obtained at the previous execution of the algorithm.

The sensitivity evolution shown with dotted line in Fig. 4 has been obtained from such reconstructed system states.

In this case a limited number of PMUs provided 10 synchrophasors. It is seen that the instability is diagnosed a few seconds later, which is not detrimental for long-term voltage instability detection. This delay decreases as the number of available synchrophasors increases [26-28].

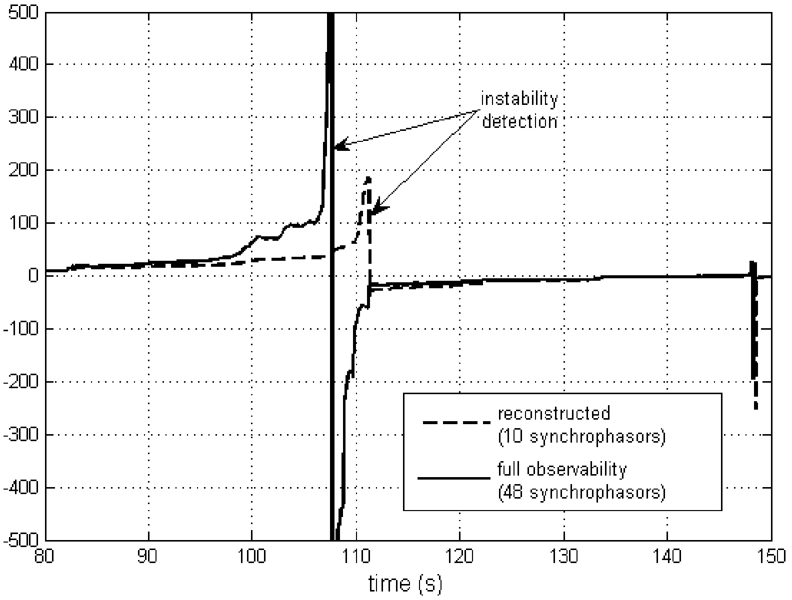

Figure 4: Sensitivity computed with PMUs providing full system observability and a limited number of PMUs

Approximate computation of sensitivities from consecutive phasor measurements (change in reactive powers in lines connected to chosen bus with respect to change in voltage magnitude in the bus) was proposed in [29]. The method applies to a chosen bus; its extension to wide-area monitoring would require installing PMUs at least in all key buses (identified from off-line studies). Another approach to monitor and detect voltage instability by sensitivity computation solely from synchronized phasor measurements is presented in [30].

2.5.3 Emergency control of voltage instability

2.5.3.1 Overview of corrective controls

Voltage stability emergency control first involves selecting countermeasures in order to avoid voltage collapse and restore some security margin. This involves components that have impact on voltage stability, such as [3,4,31]:

- shunt reactive power compensation devices: mechanical switching of capacitors or reactors, voltage control of static var compensators and synchronous condensers;
- generating units: control of terminal voltage, starting of fast units;
- loads: modified load tap changer control, reactive compensation switching, curtailment;
- HVDC modulation if properly located with respect to load centers;
- possibly, series compensation : reinsertion of by-passed series capacitors.

The future deployment of demand side management and dispersed generation connected to distribution systems also opens new perspectives regarding, for instance, the control of appliances during emergencies (through smart meters) and the support of transmission voltages by distributed generation units.

For the sake of completeness, let us mention measures taken at planning stage (transmission system reinforcement, construction of generating stations near load centers) or in operational planning (commitment of out-of-merit units, starting-up of gas turbines). When reinforcing a system, an optimal combination of “slow” (such as capacitor switching) and “fast” (such as SVCs or generators) reactive power reserves should be sought.

The dominant trend is to integrate emergency control in a System Integrity Protection Scheme (SIPS) [38]. In this context, corrective controls can be broadly classified into [31]:

- open loop controls: they use actions assessed off-line based on simulations of postulated scenarios and do not re-adjust their actions to follow up system evolution;

- closed-loop controls: they assess the disturbance severity through measurements and adjusts their actions correspondingly, following system evolution and repeating their actions if the previously taken ones are not enough. This allows compensating modeling inaccuracies and makes the control scheme more robust.

This classification applies to emergency voltage stability control in particular.

Emergency control aims at acting on the system after an unexpected disturbance has actually occurred and impending voltage instability is detected. In principle, corrective voltage stability controls are used to [31-37]:

- stop (or slow down) the load restoration mechanism. This is usually achieved by transformer LTC control. The controls include: tap blocking, tap reversing, tap moving to a pre-determined position and LTC set-point reduction.
- move the system to a new equilibrium. This is usually achieved by increasing the maximum deliverable power (shunt compensation switching, fast increase of generator voltages) or reducing the load consumption (decrease of LTC voltage set-point or load shedding).

Usually, LTC control alone is unable to quickly correct voltages, but it slows down system degradation thus giving some more time for other controls to stabilize the system. An advantage of LTC control, when combined with other control actions such as load shedding, is that it usually helps decreasing the amount of those actions.

Load shedding is a very effective countermeasure against voltage instability [31,32,34-37]. Load shedding schemes have been most often designed to rely on local measurements only, typically one or several bus voltages, possibly complemented by a few other signals (such as the reactive power produced by nearby generators). This is preferred for simplicity and, hence, reliability of the SIPS with respect to communication failures or delays. However, wide-area control can be thought of as well, provided the communication failure issue is taken into account through some redundancy. A wide-area load shedding scheme, for instance, offers possibilities for adaptive control in so far as the actions would be decided from a real-time, system-wide analysis instead of being based on pre-defined thresholds. This analysis would rely on a voltage stability index of the type discussed in the previous sections. Several forms of adaptation can be thought of, depending on the information extracted from the wide-area analysis: for instance, sensitivities computed at the critical point for ranking load involved in load shedding [37], voltage thresholds adjusted in real-time [39], participation factors identifying the degree of involvement of various power system components in a developing instability, etc.

2.5.3.2 An example of adaptive hierarchical voltage instability SIPS

By way of illustration, the SIPS recently proposed in [39] is briefly presented, as it illustrates some of the concepts mentioned in the previous section. This two-level SIPS is adaptive and acts in closed-loop. Its principle is outlined in Figure 5.

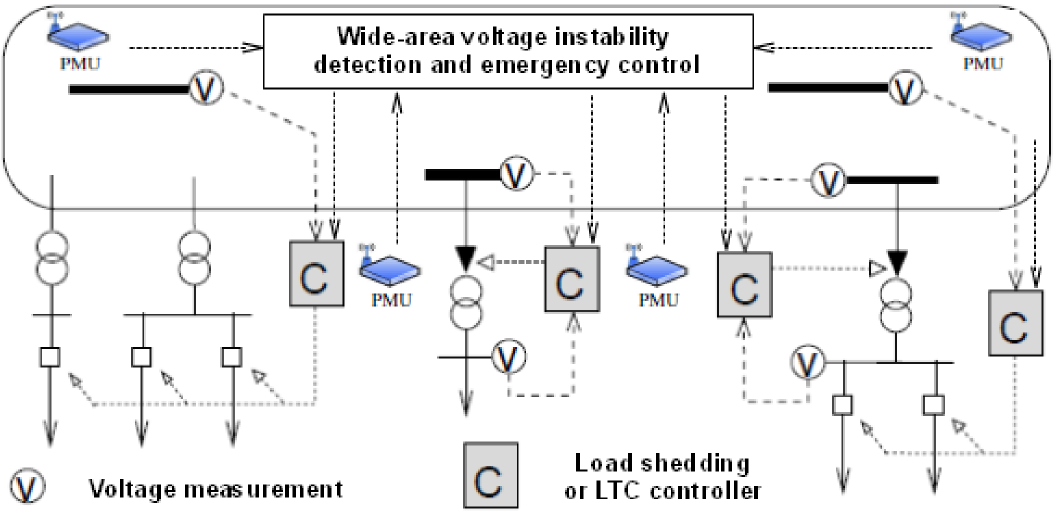

Figure 5: A two-level adaptive hierarchical voltage instability SIPS

The scheme is aimed to deal with emergency conditions by acting on a number of LTCs and loads. A set of distributed, local controllers [33] constitutes the lower level:

- each load shedding controller monitors the voltage at a transmission bus, acting once the voltage at a monitored transmission bus settles below a threshold value. It acts on a set of loads at distribution level, located close enough to the monitored bus, so that their curtailment allows increasing the monitored voltage;
- each LTC controller measures the voltage of both the transmission and the distribution terminal of the transformer it is controlling. In normal operating conditions, it regulates the distribution voltage as usual, while once the transmission side voltage settles below a threshold value, it preserves that transmission voltage.

The upper level, assumed to embed a WAMS receiving real-time measurements, gives the overall scheme its adaptive nature by adjusting in real-time the voltage thresholds used by the above mentioned local controllers. This can be performed by merely sending an alarm signal to the local controllers at the moment it is identified that the system has crossed a critical point. At the moment this signal is received by the local controllers, they take the voltages they currently measure as threshold value for load shedding and LTC control, respectively. By so doing, the local controllers act to maintain transmission voltages at or above the voltages prevailing at the critical point identified by the upper level. The critical point identification can be based on various criteria. In [39], sensitivities from reconstructed states are used to this purpose, based on the previous work in [24, 25, 26, 37]. The whole scheme has been shown to be robust with respect to communication failures, load behavior uncertainty, or failures of local controllers to act as intended.

2.5.4 Conclusion

Analyses of the past and recent power system blackouts revealed voltage instability as the one of major causes. Preventing blackouts and better utilization of existing assets in voltage stability limited power systems through design of advanced voltage stability monitoring, instability detection and control schemes based on WAMPAC technologies is thus of paramount importance. This section discussed several features of those schemes and shortly presented existing algorithmic solutions and available controls. Further research and development should include items from the following, non-exhaustive list:

- further improvement of existing solutions to cope with the uncertainties brought by increase in wind, solar, and other renewable generation;
- incorporation of new controls (not considered in this section) such as: D-STATCOM and its variant known as D-var, energy storage, emergency demand response, renewable sources, and plug-in hybrid electric vehicles;
- improvement of existing voltage stability assessment tools to be compatible with real-time requirements (fast simulations tools, high-performance computing techniques), preferably validated by hardware-in-the-loop simulation tools;
- development of algorithmic solutions taking advantage of PMUs to deal with short-term voltage instability or more generally fault-induced delayed voltage recovery;
- improvement of existing methods to deal with a limited number of PMUs, with an expected improvement of performances once more devices will be installed;
- integration into SIPS with due attention paid to response-based, closed-loop and adaptive control.

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