WIDE-AREA MONITORING AND CONTROL FOR POWER SYSTEM GRID SECURITY

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Abstract – Probably the most significant development in the future is the evolution of the EMS to a more intelligent, automated system to analyze, predict and prevent events leading to a total system collapse. The transition to a highly automated system is possible in part by the recent advances in communication technology, hardware architecture, web services and installation of synchronized phasor measurements to support wide-area system monitoring, protection and control. This paper addresses some issues and defines a strategy towards the coordination of local and wide-area controls and protections to ensure power system grid security. The strategy relies on the integration of the latest PMU technology and data processing to deploy different types of control actions and special protection schemes.

Keywords: Wide-area Monitoring, Power System Control, Synchronized Measurements, Dynamic Security.

1 INTRODUCTION

The August/14/2003 blackout experience of the East cost and previous critical events are driving the industry to develop a more automatic, adaptive control system to prevent and contain catastrophes. Postmortem analysis and other investigative reports have concluded that the power system must be provided with means and tools to avoid system-wide power failure under extreme contingencies.

The system deterioration starts with alarming of steady-state violations and gradually evolves to faster dynamic phenomena with the system reacting quickly and defending itself with pre-determined protection schemes and relays setup. The analysis of short-term/mid-term states must be considered. Angular transients, voltage transient stability and security, frequency stability and small signal analysis tools would certainly help to devise dynamic actions and reconfiguration strategies; the process is expected to be highly automated and bounded by the latest communication technology and PMU allocation strategies. The following issues should be considered as part of any development plan to address catastrophic events:

- Early detection and monitoring of system security indices
- Analysis of critical real-time information to trigger the dynamic security assessment process
- Wide-area information, control and protection schemes
- Deployment of control actions for dynamic adjustment and reconfiguration

The following are some of the challenges the industry is facing:

- Reliable and accurate state estimation (SE) under stressed conditions
- Proper representation of existing protective devices and schemes
- Proper implementation of utility practices and regulations
- Proper processing of the information and simulation of decision making for each network structure, i.e. RTO, ISO, etc.
- Modularity and adaptability to any potential scenario
- Ability to provide affordable hardware and software to link different platforms, such as the on-line steady-state security applications, energy markets, voltage, transient and small signal security and other third party systems with acceptable performance
- Accurate and acceptable defense plans against disturbances

To address these challenges there is the need of simulation, proper modeling and fast computation of the dynamics of the system.

2 STRATEGY FOR WIDE-AREA CONTROL

Wide area control addresses automatic healing capabilities to some extent by proposing smart topology changes and control actions. The Aug/14 blackout in the East coast has pushed new development in reliability and security. Dynamic islanding and fast load shedding are schemes available to maintain as much as possible a healthy transmission system.

The strategic plan for islanding requires a critical review of all steady-state and dynamic tools that are available at the control center. The work will include the development of new tools and the coordination of the existing applications for detecting and adjusting the configuration using PMU (Phasor Measurement Unit) technology [1] and emergency condition methods.

The evolution of a disturbance and the time frames involved to address the problem properly needs to be analyzed. When the network is subjected to large disturbances, and the security index (or margin) indicates that the system is approaching a catastrophic failure, control actions will need to be enforced to limit the extent of the problem. The strategic plan includes, among others, the following issues:

- Robust and reliable steady state estimation and assessment
- Proper system response and lines of defense
- Dynamic state assessment and prediction
- Optimal PMU allocation and processing
- Wide-area information
- Dynamic adjustment and re-configuration

3 WIDE-AREA MONITORING

The capability to model and simulate electricity grid behavior over a range of time domains, frequency domains, and topological resolutions need to be devloped. The applications comprise fast dynamic tools for angle transient and voltage stability and mid-term, long-term modeling to simulate all sorts of power plants and non-linear devices. The consideration of fast time domain techniques such as quasi-dynamic simulations may help to evaluate cascading and islanding during the system recovery. The EMS will be the source of periodic snapshots to update the network topology and information for on-line dynamic simulation. The topological adaptability will consider a wide range of structures, especially RTO, security coordinators and others. The proper identification of events and conditions of the system will trigger a particular time frame over which simulation and modeling is needed.

3.1 Synchronized phasors for stability, protection and control

The introduction of PMU technology can significantly improve the observability of the power system dynamics, and it can enhance different kinds of wide-area protection and control. The control actions can either be preventive, or corrective. During the normal operation the focus is always on the economics of the system, but during cascading conditions the focus is on control shifts towards ensuring power system grid security. The objective here is to keep as much as possible an intact electrical network with all generators connected to the grid.

The infrastructure combines EMS software, PMU, fast processing and communication of information to the transmission level. All PMU information is captured at the substation level, and it is used for local control, where actions are taken to adjust equipment settings, taps, FACTS etc.

PMU quantities are collected and concentrated for further exploitation in a PDC (Phasor Data Concentrator), from where the information is sent to a central place for EMS use. The applications use the information to improve the results, detect problems and consequently trigger emergency control actions via remote control and SCADA/EMS. Within this context the operator could get a quick and reliable assessment of the system under stressed or chaotic conditions to determine:

- System security under large disturbances and unexpected events, and
- System evolution to an emergency state that can lead to restorative conditions

The EMS applications can improve the security margin using optimization techniques or sensitivity routines that along with time domain simulation could predict the control actions to return the system to normal. The actions depend on the system state and problem and definitely the following applications will use synchronized information:

- State estimation
- Fast time domain simulation
- System state prediction
- System recovery

3.2 Monitoring and Instrumentation

Quick and fresh information right now is available from the synchronized measurements. The utilities are placing these devices to measure the voltage and current phasors at the same time in selected locations, they are transmitted to a central place where they are compared, analyzed and processed. The PMU is like a conventional RTU equipped with a GPS receiver, synchronizing the measurements with a time stamp.

The PMU capability of providing same time information offers a lot of advantages, one of which is the dynamic trending. This facilitates the prediction of frequency behavior, active load and reactive power immediately after disturbances to assess stability and identify overall security indices. Although, the following issues are still under analysis:

- Communication bandwidth for PMU
- PMU calibration and accuracy
- PDC Input/Output
- PMU-to-PDC and PDC-to-PDC communications

Most of the utilities are currently considering the following integration layers:

- *Measurement layer*-which may consist of a set of PMUs from different vendors and IED passing the information to the PDC at the substation level
- *Data collection layer*-which consists of several PDCs and data sharing before the information is sent to the EMS
- *EMS layer*-The information can be accessed via the Internet using a variety of protocols to exchange information with several databases, data archiving, planning model validation, SCADA and SE.

One of the problems is the introduction of errors by the instrumentation channel. The hardware solution is expensive so a software alternative is not discarded. A lot has been learned from the off-line applications experience, as the first step towards online applications.

3.3 State estimation periodicity

All network oriented applications (steady-state and dynamic) need the initial conditions as the starting point. SE solution must be guaranteed by any means necessary, either using approximated solutions or reducing the scope to take full advantage of PMU and PDC information at the local and wide-area level. The SE can run at the scan rate at the substation level and every minute at the wide-area level to assess the security with the latest information from the field. It has been proved that the PMU technology has had a positive impact regarding:

- Observability
- Accuracy
- Convergence
- Bad data processing

3.4 Wide-area state estimation

It has been mentioned the possibility of running SE in two levels and periodicities, the substation level (scan-rate) and the transmission level (~1 minute). It would be good to take advantage of the existing substation infrastructure to identify and correct data problems to get more accurate solutions at the wide-area level. A justification for this could be that in the RTO business there is a lack of detailed models (breaker-node), as opposed to the substation level where all the details are available. The usual SE error problem in the vicinity of failures will not happen with the use of substation based applications. Topology problems can be identified very quickly.

3.5 Substation based state estimation

The current substation technology already has already infrastructure to deal with the PMU work, there are relays in feeders, and devices connected to the high side and low side of the transformers. PMU technology can be integrated with the possibility to extend this technology to a wide range of network applications. The use of the substation technology will change the way the RTO business is modeled. A lot of data filtering and cleanup can take place before the data is used by the transmission level. The whole configuration, switches, breakers, flows, etc. can be monitored, there is no limit about what can be done at this level. The topology processor is probably the first candidate before state estimation.

4 PMU IMPACT ON THE EMS

The PMU must be accurately synchronized, since all measurements must be around the milliseconds (or microseconds) time frame. If the PMU technology is used there must be a definition about how much information can be send and where to allocate the devices. The biggest problem right now is communication, it seems like not all the customers have enough infrastructures and there are very few utilities that do have and can actually get the data out of the substation.

A uniform set of synchronized measurements across the system, let us say once a minute is possible. Anything faster than that could be difficult, since there are some delays involved in data transfer, it takes something around 5 to 30 seconds to get the data back to the center. For faster application (dynamic analysis) high speed links, proper priorities setup and a lot of data processing and handling must take place. The main issue is the cost of investment in the communication to handle PMU all over the grid.

4.1 PMU Allocation, Redundancy and Communication Cost

So far the utilities have installed a few number of PMU devices in the field, most of the work is focusing on the definition of requirements and exploitation of the current information for monitoring only. There are however some issues than need to be addressed sooner or later:

- Allocation
- Redundancy
- High-speed communication facilities for sending real-time data to a central place.
- PMU-PDC Communication backup

For wide-area control a redundant set of measurements is desirable, in the event of a failure of one PMU, other adjacent PMUs and information from connected devices can provide reasonable results.

The PMU allocation problem needs to be addressed; there have been some developments already to conceptualize the problem. Some of the alternatives use graph theory, SE observability [4] and the cost of communication as part of an optimization problem. Other customers prefer to focus on the practical problems first, such as the damping of oscillations (modes) as part of the wide-area control stabilization process. Regardless of the choice, it is desirable to allocate a minimum number of PMU devices to reduce the installation and communication cost.

5 WIDE-AREA CONTROL

On-line dynamic analysis could be conducted based on the most recent wide-area system information PMU data, analogs, statuses and topology structures. The security of the system could anticipate failures of more than one critical component and simulations will be available to prevent actions or correct situations. The interface with short-term simulations will provide a list of devices whose behavior could drive the system to instability given the current conditions.

The on-line dynamic simulation will process PMU measurements of the actual disturbance and scan rate data to perform true feedback control as much as possible, assuming fast communication. The investment in communication is really the big issue for true feedback control.

The measurements can come from several sources: SCADA, EMS applications, PMU, PDC and disturbance monitors. Up to now only the EMS network applications have been the primary source for on-line dynamic simulation. SCADA offers a lot of measured parameters that are updated at a relatively fast rate and can be used directly.

PMUs have substantial advantages in that they provide fast, accurate, continuous and time synchronized data for virtually any voltage and current phasors in the system. The dynamic simulation helps to address the following issues:

- Current dynamic system security
- Short-term system security (~minutes ahead)
- Operation risk reduction
- Control actions deployment to secure the grid

The dynamic engines are fast enough right now to assess the security risk and control action evaluation for the next few minutes. The on-line dynamic secure region is something available right now and it can be displayed to the operator as a point in a diagram or as a trend in time oriented displays. The secure region is constrained by the following set of limits:

- Relay settings
- Thermal limits
- Steady-state stability limit
- Transient voltage dip/rise
- Voltage stability limit
- Transient stability limit
- Small-signal stability
- Frequency stability
- VAR reserve limit

The assessment of the limits is done by full time domain simulation and approximate methods.

5.1 Dynamic analysis triggers

Some of the events that may trigger the dynamic assessment are:

- Frequency oscillations
- Slow voltage decline
- Frequency decline and rate
- Margin stability decline
- Sudden outages

Once the proper engines are executed and control actions are suggested, the following actions may happen:

- Protection triggering and SPS deployment
- Corrective Actions
- Islanding schemes

The dynamic applications must be highly automated and capable of completing the tasks under varying conditions with little help (or none) from the operator. The new reliability requirements point to highly automated wide-area solutions.

5.2 System state prediction (look-ahead)

There is definitely a need of predicting in advance where the system goes before the control actions are deployed. A simulation environment is proposed using fresh real-time information from the EMS in addition to historical data recordings that can be feed into the on-line dynamic simulation. The accuracy of the system state prediction simulation environment depends on how reliable our schedules and limits are in the short-term time frame. Under catastrophic conditions a few minutes ahead window may help to reduce the risk of system operation.

For fast state prediction simulation, a change of simulation scope and region of interest may help. The state prediction could be triggered automatically (or on demand) to assess control movements and reconfiguration plans under disturbances, a lot of potential problems can be catch after control deployment. For emergency conditions, a model including only the measurements that are delivered on the quickest time to the control center are required. These measurements may include items such as:

- Important generator outputs
- Frequency and voltage measurements
- Important flow measurements

- The most important high transmission backbone lines internal to a specific control area
- Important new measurements (angle measurements)

The goal is to estimate where the system is heading and what the security level is going to be. If the trips that took effect (energy imbalance) are known, the angular and voltage stability assessment simulation could avoid further cascading that otherwise could drive the system to total collapse. The purpose of the state prediction is to assess the long time (~2 hours) condition before a system collapses. Dangerous states could be alarmed in advance to conduct analysis. The use of the latest SE snapshot combined with time domain analysis and historical information provide a good opportunity to exploit consecutive snapshots and identify any system trend. After the look-ahead task the operator would be in position to identify:

- System security after large disturbances
- System evolution to insecure conditions

5.3 Automatic System Recovery

This task has been the target of many utilities in the past and very recently (Aug/14 blackout); it has been the focus of studies to avoid cascading events and total system collapse. The system recovery depends very much on the topological structure. The short-term, mid-term and long-term applications provide enough simulation to support intelligent grid control actions to avoid cascading incidents, although again the communication is really the big issue in the wide-area context.

5.4 Closed-loop control

The dynamic reconfiguration (islanding) assumes the possibility of the so called self-healing, the on-line dynamic simulation will recognize and characterize situations, it will predict collapse and unstable behavior and it will recommend re-adjustment to prevent or corrections to recover from failures. The dynamic engines will react to disturbances by suggesting topology changes and isolating devices to protect the rest of the system against cascading and total system collapse, The control actions will be honored in all time frames of analysis (short-term, mid-term and long-term) and are referred as remedial actions. If the system has insufficient stability margin for any event, control actions must be determined which will ensure enough security.

6 WIDE-AREA PROTECTION

When an abnormal condition/failure is not eliminated but spread, it can lead to catastrophic conditions. Work should be conducted to determine a security index and proximity to blackout in order to prevent or otherwise correct the system condition. The power system should be prepared to deal with the problems created by:

- Deregulation rules and restructuring
- Power system operation very close to limits
- Transmission congestion and stressed conditions
- Weak connections
- Unexpected events
- Stability threats
- Hidden failures in protection system

6.1 Power system reaction to catastrophes

Any of the above conditions could trigger a catastrophic event, and hopefully the system will react as follows:

- Wide-area monitoring will catch the proximity of a catastrophic failure
- The applications will trigger to optimize and adjust remote controls to avoid the evolution of the failure
- SPS will react to reduce the risk of operation
- The local protection devices will shed enough load to maintain acceptable frequency
- If the power system continues reacting in an unpredictable fashion, dynamic reconfiguration will separate the grid to avoid further deterioration

6.2 Lines of defense for predefined events (SPS)

The aim of actions taken by SPS is to provide uninterrupted power supply by the use of “last defense” methods that can not be used under normal conditions. The objective of any SPS is to maintain the power system security considering global and local conditions. These systems, using data from several locations as well as acting with a wide area orientation have been proposed, designed and installed to handle disturbances. They are designed for the following reasons:

- Detect abnormal contingency related system conditions
- Initiate pre-planned corrective actions to mitigate the problem
- Provide acceptable system performance

The controllers involved have some or all of the following characteristics:

- They can be armed or disarmed depending on the system conditions
- They are usually “sleeping” systems
- They employ discrete controls and feed forward control laws
- The control actions are predetermined in most cases
- Some form of communication is involved in the control action

Excessive reliance on these schemes may result in security risk due to:

- Failure to respond
- Unwanted overlap with other schemes
- Accidental operation

6.3 SPS replacement by closed-loop control

With the possibility of wide-area control, some utilities are in the process of replacing their SPS to a direct detection and control process. Some of the disadvantages of the current SPS are the fact that they work only for pre-defined events, sometimes they are complex and usually expensive. The current trend is to employ strategically placed sensors to react to the arbitrary disturbances and provide:

- *Single discontinuous stabilizing actions* - generator/load tripping or capacitor switching
- *Closed-loop control* -where the need for discontinuous action is determined and commanded. The system is observed and then further discontinuous action is taken as necessary.

7 WIDE-AREA SYSTEM STABILITY COORDINATION

The wide-area control should be developed in incremental phases, as it is currently done in some utilities [2, 3]. Some of them are working on the voltage subsystem (slow dynamics), while others are focusing on the slow frequency subsystem. In Europe and recently in USA there is a lot of concern about inter-area oscillation, so the small-signal subsystem is being implemented to damp some frequency modes by feeding PMU information to the power system stabilizers (PSS). Closed-loop forces the coordination of all dynamic results for deployment. As the stability coordination is developed and implemented several issues will pop up that must be resolved immediately.

7.1 Model validation

Existing SPS and load shedding schemes controlled by PLCs are currently designed to work for pre-defined scenarios but can be replaced once the stability applications have been properly tuned and tested for some critical and trivial scenarios. During the transition from feed forward to feedback control the following problems may arise:

- Modeling issues
- Wrong network parameters
- Wrong dynamic parameters
- Improper protection settings
- PMU data errors due to calibration problems and lost data
- Relay settings

All these issues must be addressed as they appear.

7.2 Global and Local warning signals

Synchronized information is collected by the PMUs; this is the global information that if properly processed, can trigger some of the stability applications. All PMUs transfer stamped flat files to one or more PDCs and the architecture, redundancy and communication is yet to be defined. The PDC may reside in the substation so the possibility to exploit the information to support the transmission level state estimation by filtering, screening and identifying topology errors is feasible. The PDC and PMU information is placed in SCADA or may be transferred to the transmission control center using a standard communication protocol.

7.3 Stability triggering

The global and local information is available at the control center so the following triggers are proposed for wide-area control:

- *Slow voltage decline or a specific load level*- If this is the case the wide-area voltage stability subsystem will execute and it will provide the proper set of switching actions and remedial actions considering a time frame of about ~10 seconds or more
- *Considerable phase angle separation on remote locations, Frequency decline or rate of frequency*- The global warning signals, such as considerable angle difference, global and local frequency information can trigger the transient stability subsystem whose time frame ranges at the millisecond level.
- *Inter-area oscillations*-If some power flow oscillations are detected, they can be addressed by the small-signal subsystem.
- *Margin decline*-if reactive reserve is the issue, the voltage stability engine can assess the problem. Transient stability will address the angle problem.
- *Cascading*-with the help of trending cascading can be detected so the system state prediction subsystem could be initialized with the most recent real-time snapshot and disconnected equipment. The focus is on conducting a ~10 minutes ahead simulation to detect dangerous conditions.

7.4 Wide-area coordination issues

The most immediate activity is to use the data to improve the accuracy of existing topology and SE applications, the customers see the benefit in the monitoring level so they wish to use the information as much as possible to get a better (accurate) solution. The ultimate goal in mind is closed-loop wide-area control and protection. The stability subsystems will estimate the control signal and send them to the devices that are very far apart geographically. This could be a problem, so maybe a strategy would be to concentrate in a reduced portion of the network and extending to wide-area implementation until better and faster communication facilities are available.

The control coordination is really an issue during blackout conditions, the interaction of all preventive/corrective actions can pull the system apart if they are not properly coordinated. Taking advantage of the overall effectiveness provided by the global control, turns to be complicated by several factors:

- Communication time lag
- Remote control signal loss
- The use of extremely fast data availability
- Proper architecture for wide-area control
- Communication protocols and networking
- Database access of the PDC data
- PMU instrumentation errors and noise
- Remote calibration

8 DYNAMIC ISLANDING

If all lines of defense are exhausted there is another possibility, separate the network into small f-V controllable islands. The control actions should be highly automated and they should be provided with enough intelligence to figure out the right alternatives.

8.1 System drift

After the event happens, the system drifts and the generators react to it depending on its nature. They share the frequency tendency and rate of change; oscillating units are detected and grouped into critical sets. The applications process the critical sets and provide the list of potential cut sets linking oscillating groups, there may be more than one, but system controllability and restoration guidelines are imposed to select one.

8.2 Trends and triggers

The need to use recent and previous wide-area information to provide trending of selected electrical variables or composite indices to catch potential problems (frequency rate, voltage rate, increased oscillations, angle and voltage stability margins etc.) is very important for islanding determination. The analysis of all PDC information available will confirm and warn about potential problems.

8.3 Network partition

From the list of alternatives to split the network, estimate the island frequency and select the one with the least generation-load imbalance to avoid further cascading. As a condition the islands must be easy to restore and synchronize with the rest of the system. A fast optimization function will guarantee enough active/reactive control capability to push the frequency and voltages back to the nominal values.

8.4 Re-synchronization

When the system goes to the restorative state after the dynamic islanding happens, the operator should be able to re-synchronize the system easily by using remote actions and assessing the actions while the restoration is taking place.

9 CONCLUSIONS

This paper has described a high-level plan for wide-area control implementation in an EMS, to improve power system grid security.

The primary intent is to protect the electrical interconnection from a widespread collapse. Wide area controls are meant to protect the grid. In some cases the appropriate action would be islanding and blacking out a portion of the grid in order to prevent widespread collapse.

A key element is to evaluate the optimal approach towards using PMU data in the EMS steady state and dynamic applications. State estimation is the obvious first application to be leveraged, since PMUs will improve SE reliability and accuracy. Furthermore, the SE forms the basis and foundation of any additional steady-state or dynamic security analysis. Later each dynamic engine should be integrated to utilize PMU data, along with the latest state of the art communication and hardware to respond quickly against any disturbance.

The approach entails analysis, prediction and determining the appropriate wide-area control actions. Communication has been identified as the big challenge to introduce fast, automated closed-loop operation to deploy these control actions.

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