Special protection schemes in electric power systems
literature survey

Report

Author(s):
Zima, Marek

Special Protection Schemes in Electric Power Systems
Literature survey

Marek Zima

June 6th, 2002

Table of Content

Abstract

The report represents the initial study for PhD project that aims at designing SPS (System Protection Scheme) having following characteristics:

- wide area approach
- capability of mitigation one or more dangerous phenomena having a system wide nature (e.g. voltage instability, frequency instability etc.)
- emergency protection function (preventive protection can be sufficiently provided by SCADA/EMS systems)
- execution of control, not only monitoring which does not include the effect of change of power system behaviour when subjected to control inputs (load shedding etc.)
- acceptance by utilities

This report briefly summarises available information in the area of SPS. It is based on the survey of scientific literature (Conference Proceedings, Journals) and partly on the author's personal experience (meetings with representatives of utilities and work in R&D in this area) with focus on above listed features.

The structure of the report is as follows. In the first part, the historical background, definition of the problem and some fundamental questions are shortly outlined. The second chapter is divided into sections. Each section concentrates on one major instability phenomenon, starts with the description of instability principle, the countermeasures that might be taken followed by an overview of what has been done in that area – research activities both by the utilities and in academic environment emphasizing the ones which have been brought to final realization.

Background, Needs, Demands and Expectations of Utilities

In this chapter dangerous power system phenomena and instabilities are defined. The historical background of their evolution is described as well. Special Protection Schemes (SPSs) preventing occurrence of such situations are briefly discussed as well as the features of existing and installed ones. The main criterions for SPS design are stated.

Power systems have originally arisen as individual self-sufficient units, where the power production matched the consumption. In a case of a severe failure, a system collapse was unavoidable and meant a total blackout and interruption of the supply for all customers. But the restoration of the whole system and synchronisation of its generators were relatively easy thanks to the small size of the system.

Power systems size and complexity have grown to satisfy a larger and larger power demand. Phenomena, having a system/global nature, endangering a normal operation of power systems have appeared, explicitly:

- Frequency Instability – is inability of a power system to maintain steady frequency within the operating limits.
- Voltage Instability – is the inability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system conditions causes a progressive and uncontrollable drop in voltage. A system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude decreases as the reactive power injection in the same bus is increased [Kundur, 1993] .
- Transient Angular Instability (also called Generator's Out-of-step) – is the inability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator angles and is influenced by the nonlinear power-angle relationship [Kundur, 1993] .
- Local mode of Small-signal Angular Instability (also mentioned as Generator's Swinging or Power Oscillations) – is the inability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purposes of analysis. *Local modes* or *machine-system modes* are associated with the swinging of units at a generating station with respect to the rest of the power system. The term *local* is used because the oscillations are localized at one station or small part of the power system [Kundur, 1993] .

With the rising importance of the electricity for industry (and the entire society), the reliability of supply has become a serious issue. Interconnection of the separated/individual power systems have offered a number of benefits [Heydt, 2001]   , such as sharing the reserves both for a normal operation and emergency conditions, dividing of the responsibility for the frequency regulation among all generators and a possibility to generate the power in the economically most attractive areas, thus providing a good basis for the power trade. Although this has reduced some negative features mentioned above, on the other hand it has created even a new problem:

- Inter-area mode of Small-signal Angular Instability – *inter-area modes* are associated with the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines being interconnected by weak ties [Kundur, 1993] .

Nowadays, when environmental and other restrictions make building of new power plants and transmission lines more difficult and utilities face continuous grow of power demand and power market deregulation, power systems are operated closer to their stability limits. When an abnormal condition/failure is not eliminated but spread, it can lead to catastrophic scenarios [Taylor, 2000], [Kosterev, 1999], [Vargas, 1999], [Hiskens, 1999]. If this happens, an extremely complicated and complex restoration procedure must take place [Gomes, 2002].

In the beginning, attempts to apply local protection devices have been made. To mention some typical ones: under frequency relay, under voltage relay.

However, the character of the dangerous stresses mentioned above, is usually global, not local. Therefore the protection systems, using data from more locations as well as acting with a wide area orientation, have been proposed, designed and in some cases installed to handle them. These are most often referred as Special Protection Schemes (SPS) or sometimes System Protection Schemes.

According to [Anderson, 1996], they are defined as: ***"… a protection scheme that is designed to detect a particular system condition that is known to cause unusual stress to the power system and to take some type of predetermined action to counteract the observed condition in a controlled manner. In some cases, SPSs are designed to detect a system condition that is known to cause instability, overload, or voltage collapse. The action prescribed may require the opening of one or more lines, tripping of generators, ramping of HVDC power transfers, intentional shedding of load, or other measures that will alleviate the problem of concern. Common types of line or apparatus protection are not included in the scope of interest here."***

According to [Kundur, 1993] , there are five states of operating conditions – Normal, Alert, Emergency, *In Extremis* and Restorative. In case of highly reliable SPS with a good performance, a normal power system operation could be shifted from the Normal state to Alert state. This confidence in SPS would allow much better utilization of existing assets (transmission lines etc.).
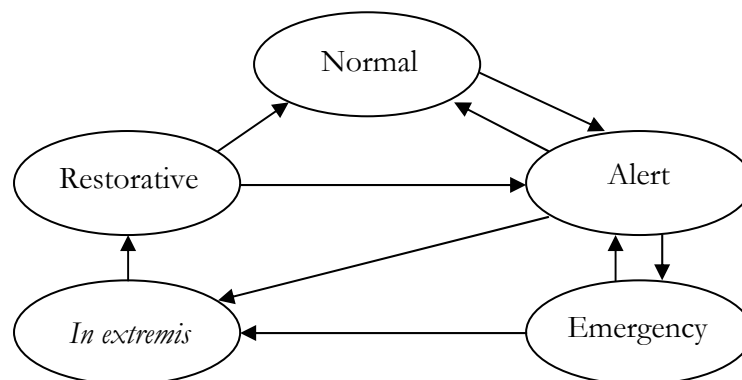

Figure: Power system operating states. Arrows express possible transitions among them.

In 1992, CIGRE and IEEE performed a survey about the installed SPSs among the utilities. The detailed statistical results of the answers reporting 111 installed SPSs can be found in [Anderson, 1996]. Very important and interesting observations and information can be extracted from it, although they are not explicitly stated there:
- The trend is quite obvious; the most SPSs have been commissioned in the nineties. The degree of complexity is rapidly increasing and the solutions are more and more sophisticated.

- All installed SPSs are **dedicated solutions** for particular power systems. There is no scheme that could be applied to another power system with minimal modifications.
- All installed SPSs are either fully or in major part designed and installed by utilities. **There is no company that would offer a SPS to utilities as a complete solution ranging from data acquisition to execution of control actions,** except ABB [Rehtanz, 2002]. Only some parts of existing SPSs have been supplied to utilities from an external environment, e.g. algorithm, software package etc.
- SPS should be armed (i.e. ready for operation) all the time, not only in the periods when the power system is heavily stressed.
- "…the costs of the false trips is generally much lower than the cost of failure of the SPS to operate when required…" This implies, that even with the risk of malfunction, SPS installation is **economically beneficial/profitable**.

Regardless of the third last bullet, some utilities look for assistance from the vendors' side of two kinds:
- A complete "turn key" solution – they don't specify the way in which the problems should be resolved but only provide a description of the problems and critical scenarios.
- Delivery of a part of the solution – they have their own ideas, algorithms or studies but they need a help to set up the system/platform, build an infrastructure etc.

The four main design criteria, which should be used for SPS, are [CIGRE, 2000]:
- Dependability – The certainty that the SPS operates when required, that is, in all cases where emergency controls are required to avoid a collapse.
- Security – The certainty that the SPS will not operate when not required, does not apply emergency controls unless they are necessary to avoid a collapse.
- Selectivity – The ability to select the correct and minimum amount action to perform the intended function, that is, to avoid using disruptive controls such as load shedding if they are not necessary to avoid a collapse.
- Robustness – The ability of the SPS to provide dependability, security and selectivity over the full range of dynamic and steady state operating conditions that it will encounter.

Another very important relevant questions have been raised in [Nielsen, 1988]:
- Reliability of SPS (the author means basically the availability of the system, i.e. inability of the system to operate due to the failure of one or more of its components should be minimal, similar to Dependability as defined by CIGRE).
- Impact on daily operation of a grid (i.e. acceptance by the operators and required effort for the training of the operators).
- Documentation of SPS.

The content of the report can be interpreted:
- SPS has to be designed with the highest possible degree of reliability and it has to be properly coordinated with the existing protection systems, mainly of the local nature.
- Involvement of a grid operator should be kept to minimum contrary to SCADA/EMS (i.e. dispatchers' actions and maintenance effort).
- All aspects of SPS construction and operation have to be clearly documented and all information has to be quickly accessible.

A supplier of SPS should treat these concerns with care and be ready to provide answers to a SPS user.

A special attention to reliability is given also in [Anderson, 1996]. Detailed example of risk assessment calculations is provided in [Fu, 2002].

The abbreviation SPS actually expresses only one function of the wide area systems what is term appearing more and more often nowadays. Wide area system may be a platform serving various purposes. It acquires data (measured synchronously), communicates them into one central location where they can be processed. The use of this data may include:

- Wide area monitoring – the system can offer continuous very accurate information (synchronized measurements with a high sampling rate) about the states which would not be otherwise observable, such as oscillations, load dynamics etc. (the displayed quantities may range from power flows, magnitudes and phase angles of voltages and currents to stability indicators)

- Wide area protection – SPS in traditional, conventional understanding. In case of situation endangering the power system (detected incipient instability), SPS executes a single action.

- Wide area control – the system continuously, after the recognition of a state prone to instability, influences the behaviour of power system to follow a certain trajectory to avoid instability and keep the power system within the safe boundaries. Feedback control loop is employed to do so.

- Wide area optimisation – there are two interpretations of this term. Both of them are basically economical in nature and aim at the operation of the network in the most profitable way. The first one, minimization of losses and similar tasks are usually done by Energy Management Systems.
  The other one expresses possibility to fully utilize the network, i.e. operate it close to its limits, what is allowed by above mentioned wide area control, thus implicitly fulfilled by it.

Research, Development and Installations of SPSs

This chapter is divided into sections according to the instability phenomena – frequency instability, voltage instability, transient angle instability, small-signal instability, plus an additional section containing another issues relevant to the SPS. In the beginning of each section the principle of instability is freely explained again as well as origin and possible countermeasures. After a brief description of today's handling of the problem, an overview of the most significant research activities aiming towards the mitigation of the instability is provided. This overview contains references to the research, development and implementation work documented in the professional journals or presented at the conferences.

Frequency Instability

Keeping frequency within the nominal operating range (ideally at nominal constant value) is essential for a proper operation of a power system. A maximal acceptable frequency deviation (usually 2 Hz) is dictated by an optimal setting of control circuits of thermal power plants. When this boundary is reached, unit protection disconnects the power plant. This makes situation even worse – frequency further decreases and it may finally lead to the total collapse of the whole system.

For the correction of small deviations, Automatic Generation Control (AGC) is used and larger deviations require so-called spinning reserves or fast start-up of generators. "When more severe disturbances occur, e.g. loss of a station (all generating units), loss of a major load centre or loss of AC or DC interconnection, emergency control measures may be required to maintain frequency stability. Emergency control measures may include [Larsson, 2001]:

- Tripping of generators
- Fast generation reduction through fast-valving or water diversion
- HVDC power transfer control
- Load shedding
- Controlled opening of interconnection to neighbouring systems to prevent spreading of frequency problems
- Controlled islanding of local system into separate areas with matching generation and load"

Common practice in utilities is that most of the above actions are executed manually by a dispatcher/operator of the grid.

Automatic local devices used for the load shedding are UFLS (Under Frequency Load Shedding) relays. They are usually triggered when frequency sinks to the predefined level and/or with a predefined rate of change. They are in principle same although they might be sorted in various categories, see [Delfino, 2001]. Their action is disconnection of the load in several steps (5 - 20 % each) from the feeders they supervise. However, their effective use is strongly dependent on their careful tuning based on prestudies, since there is no on-line coordination between them. Another disadvantage is, that they can only react to the under frequency, increase of frequency is not covered by them at all. In some cases the impact of their operation may be negative, since they are not capable of the adaptability to the present situation (e.g. production of distributed/decentralized generation varies in time so quite often the distribution voltage level feeders feed the energy back into the network. So they don't appear as loads and their disconnection makes situation even worse).

The mentioned weakness of UFLS relays (uncoordination) can be overcome by centralized shedding schemes. Some of them have already come into the operation. One part of the SPS included in a new Hydro-Québec's defence plan [Trudel, 1999], commissioned in 2000, is Remote Load Shedding System (RLSS). RLSS is triggered by Extreme Contingencies Detection Systems (ECDS) monitoring and supervising the highest 735 kV transmission network [Coté, 2001]. RLSS calculates the power to be shed depending on the severity of the event. RLSS sends the commands to the communication processors. Each of them communicates with 24 Programmable Load Shedding Systems (PLSS). PLSSs are in operation in Hydro-Quebec for more than 20 years, currently installed in 140 distribution substations. PLSS is a device that executes the received load shedding commands and in extreme cases it works as a back up using the same criterions as any conventional local UFLS relay. It is also capable of taking measurements, performing self-diagnostics etc.

Using of Neural Network to estimate the dynamic response of the power system to the under-frequency load shedding is proposed in [Mitchell, 2000]. This information is then used to calculate an optimal amount of load to be disconnected.

Advanced algorithm applying predictive control is described in [Larsson, 2002]. In contrast to all other algorithms (to the author's knowledge), this one takes into account both frequency and **voltage** sensitivity/dependency of loads. Immediately after a disturbance, the load behaviour is observed and the load model parameters are determined as well as the average system frequency, disconnected generator and actual generated power. These are then used in predictive control shedding procedure.

Voltage Instability

Voltage instability is basically caused by an unavailability of reactive power support in some nodes of the network, where the voltage uncontrollably falls. Lack of reactive power may essentially have two origins. Gradual increase of power demand which reactive part cannot be met in some buses or sudden change of a network topology redirecting the power flows such a way that a reactive power cannot be delivered to some buses.

The relation between the active power consumed in the monitored area and the corresponding voltages is expressed by so called PV-curves (often referred as "nose" curves). The increased values of loading are accompanied by a decrease of voltage (except a capacitive load). When the loading is further increased, the maximum loadability point is reached, from which no additional power can be transmitted to the load under those conditions. In case of constant power loads the voltage in the node becomes uncontrollable and rapidly decreases. However, the voltage level close to this point is sometimes very low, what is not acceptable under normal operating conditions, although it is still within the stable region. But in the emergency cases, some utilities accept it for a short period.

There are also other alternative graphical representations, e.g. QV-curves (amount of needed reactive power to keep a certain voltage).

The emergency stabilizing actions which might be taken are in principle same as in case of the frequency instability, plus:
- Change of the generator voltage set point
- Automatic shunt switching
- Control of series compensation
- Blocking of Tap Changer of transformers

- Fast redispatch of generation

Under voltage relays are a conventional local solution. The criterion triggering the load shedding action is a predefined voltage level in the supervised node (for example 88% and 86% of the nominal voltage in IEC network, which are quite low values).

A little bit more advanced local approach for detection and evaluation of voltage instability has been presented in [Vu, 1999], [Julian, 2000] and [Gubina, 1995]. The grid is in the supervised node represented/replaced by Thevenin equivalent and the load is modelled by impedance. The point of equal impedances (rule known from the basic circuit theory) is then representing a boundary between stable and unstable conditions.

The analyses of real voltage collapses have shown their wide area nature and that they can be sorted basically into two categories according to the speed of their evolution – Transient Voltage Instability and Long-term Voltage Instability [Taylor, 1994]. Transient Voltage Instability is in the range of seconds (usually 1 – 3 s) and the main role in the incidents played the dynamics of induction motors as a load (majority of air conditioning systems) and HVDC transmission systems.

The time scale of the Long-term Voltage Instability ranges from tens of seconds up to several minutes. It involves mainly impact of a topology change or graduall load increase, i.e. fairly slow dynamics. Therefore the major part of the research activities in this area has focused on the steady state aspects of voltage stability, i.e. finding the maximum loadability point of the PV-curve. The solution of the Newton – Raphson power flow calculations becomes unfeasible close to this critical point due to the singularity of Jacobian matrix. This provides a basis for a number of indices, expressing the proximity to the voltage collapse, which has been derived, e.g. [Chiang, 1995], [Belhadj, 1996], [Wang, 1996]   , [Berizzi, 1996].

An idea of preventive analysis conducted in regular on-line cycles adopting N-1 rule and applying the results immediately after the detected contingency, is probably the only solution for the phenomena on very fast time scale. In the voltage instability case it means calculations of a minimal load shedding necessary to stabilize the power system subjected to any contingency from the selected range. Thus, an optimisation problem can be formulated, where the function to be minimised is the amount of load shedding subject to the following constraints: solvability of static power flow equations (this essentially means, that minimal feasible solution can be found in the maximum loadability point), allowed voltage limits, angle stability inequality constraints and dynamic equality constraints [De Tuglie, 2000].

Continuation Power Flow (CPF) can overcome the numerical problems indicated above. In principle, it is slightly reformulated conventional power flow. The equations are augmented by the term quantifying the load increase and containing new variable – load parameter. A new equation is introduced, which basically forces a continuation parameter chosen in the predictor step to hold its value in the iterative correction process. This continuation parameter is optimally loading in the beginning of the PV –curve and when approaching to "nose", voltage. Various techniques have been developed for predictor step in order to speed up the computations and increase the accuracy. Very good explanatory example of tangent method is in [Ajjarapu, 1992]. Secant predictor (in fact linear approximation estimate) can be found in [Chiang, 1995b]. An application on inter area power transfer security evaluation is demonstrated in [Flueck, 1996]. CPF has probably become the most widely accepted tool for the voltage instability assessment/evaluation and a huge number of papers have been written about it.

PV-curve approach has been implemented in practice and proven to work properly [Kolluri, 2000] when the automatic load shedding system VSHED, installed in Entergy (utility serving Arkansas, Mississippi, Louisiana and a portion of Texas), successfully operated in case of major disturbance on September 22nd, 1998.

The exclusion of the system dynamics might bring a risk of missed information about a kind of inertia of the system, with which it responds to disturbances. An attempt to include it and optimise the load shedding may involve a genetic algorithm [Moors, 2000]. However, there is a danger, that an important scenario can be omitted from the training/tuning procedure of the algorithm and failure of SPS in case of occurrence of such situation in reality. Alternative solutions proposed by the same research group for implementation in Hydro-Québec network are more or less rule based relying on the off-line studies and setting of local relays [Van Cutsem, 2002]. The roots of these considerations and probably the most complete coverage can be found in [Arnborg, 1997] and in a bit more condensed form in [Arnborg, 1998]. The author explores the dynamics of loads, especially the timing aspect of load shedding and its location.

A step forward is QSS (Quasi Steady-State) approximation proposed in [Van Cutsem, 1997]. This method consists of voltage stability evaluation based on the time domain simulation with a simplified description of power system dynamics, such as load behaviour etc.

For the optimal control measures, Model Predictive Control can be employed [Larsson, 2000] to keep the voltages within the pre-selected limits. Including stability constraints not based on the voltage levels appears to be computationally very expensive, consult the reference for details.

Another way of voltage control within the boundaries given by simple stability indices is using hierarchical structure [Corsi, 2000]. Two additional higher levels – Secondary Voltage Regulation (SVR) and Tertiary Voltage Regulation (TVR), enrich primary voltage regulation. National TVR shall coordinate SVRs that control the areas voltage profiles. The implementation of SVRs is reported to be already finished in the Italian power system.

Transient Angle Instability

In case of transient angle instability, a severe disturbance is a disturbance, which does not allow a generator to deliver its output electrical power into the network (typically a tripping of a line connecting the generator with the rest of the network in order to clear a short circuit). This power is then absorbed by the rotor of the generator, increases its kinetic energy what results in the sudden acceleration of the rotor above the acceptable revolutions and eventually damage of the generator.

Therefore the measures taken against this scenario aim mainly to either an intended dissipation of undelivered power:
- braking resistor, FACTS devices etc.
, or reducing the mechanical power driving the generator:
- fast-valving, disconnection of the generator etc.

An application of traditional measure of transient angle instability – equal area criterion (expressing a balance between the accelerating and decelerating energy), on emergency control has been presented by [Ernst, 2000] who describes the method called SIME (single machine equivalent), developed under lead of Pavella at University of Liege. The angles of the generators in the system are predicted approximately 200 ms ahead. According to it, the machines are ranked and grouped into two categories. For the generators from the critical category, OMIB

(one machine, infinite bus) equivalent is modelled and extended equal area criterion is applied to assess their stability. Pre-assigned corrective action is executed if an unstable generator is identified.

In principle the similar procedure/algorithm is used in the commercially available program TSAT intended for both off-line and on-line use [Kundur, 2000], developed by Powertech Labs. Here the Dynamic Extended Equal Area Criterion is employed for screening of the most severe contingencies that are then analysed in the detail.

Simple rules derives from the classical relations of OMIB equivalent are proposed in [Minakawa, 2000] and compared with the conventional step-out relay. The simulation results of Tokyo Interconnected Network show that the prediction of the loss of synchronism is 0.7 second faster, thus providing longer time for countermeasures.

Simulation results show how the blackout of Taiwan's power system on July 29th, 1999 could have been avoided employing a protection scheme against transient instability described in [Wang, 2000]. The proposed algorithm aims to the protection of EHV-tie line connecting the generation area in the south with the load area in the north of the country. Therefore the line power flow limit was used to modify the Equal Area Criterion for stability of the generators in the south.

[Karady, 2002] suggests an algorithm, which does not require knowledge of the system and uses only the on-line measurements of generator's rotor angles and power mismatches to predict the transient angular stability of the generator. It implies that there would not be any need for tuning/adaptation procedure when applied this method on another power system. The valve affecting the mechanical input of a generator is controlled in order to stabilize the generator. Simulation tests on the WSCC system have been carried out.

The experience with the transient stability control systems (TSC Systems) is reported in [Koaizawa, 2000]. CEPCO (Chubu Electric Power Co.) has commissioned two systems, one in June 1995 and the other one in May 1996. In the paper, mainly the statistics are listed. The principle behind, as mentioned, is an on-line pre-calculation cycle including all possible operating scenarios but no details are provided. In case of dangerous situation, the result of pre-calculations is recalled and appropriate generator is disconnected. The calculation time of the cycle is always less then 5 minutes (usually 3) for 30 cases and power system model consisting of 300 nodes, 400 branches and 30 generators. This impressive number is achieved by employing several arithmetic units performing parallel calculations. The TSC system has the features:

- recognition of change in operating conditions of generators and transmission lines automatically and determines the generators to be controlled for stabilization
- CEPCO system is stabilized with the minimum amount of generation shedding, since the controlled generators are chosen on-line
- coping with an extension (new built generators or lines) of the CEPCO system is relatively easy by update of network data database

Small-signal Angle Instability

Some power systems lacks a "natural" damping of oscillations, which may occur, and they would be unstable when subjected to any minor disturbance and sometimes even under normal operation conditions [Uhlen, 2001] if no measures increasing the damping were introduced. As stated in [Shim, 2000] extension of the transmission capacity by adding a new line does not

necessarily improve the damping significantly and solve the problem (as the authors claim based on the eigen-sensitivity analysis applied on Korean network).

A traditional way of damping the oscillations is using of Power System Stabilizer (PSS), which controls/modulates the output voltage of the generator. The coordinated tuning of PSSs is a complex task, since they should be robust - work in the wide range of operation conditions and provide the best possible performance. This process is done off-line.

But there are also another precautions that may be taken in order to damp the oscillations: control of FACTS devices etc.

Various techniques aiming to the identification of oscillation modes from measurements of various quantities have been reported.

For estimation of NORDEL inter-area oscillation modes, the frequency measurements from the common distribution network have been utilized [Hemmingsson, 2001]. However, the distribution network is probably not the best choice since the measurements contain quite a lot of noise (distortion from higher harmonics) and extraction of information about the two typical NORDEL oscillation modes was difficult. The monitoring of frequency on the transmission level, triggered by disturbances, shows more promising results [Breulmann, 2000], although another important factor, which has played certain role, is size of the system and thus frequency of the oscillations. UCTE/CENTREL system is multiple larger than NORDEL, so the recorded oscillations (measurements have been taken directly on the transmission level) have much lower frequency and the measurement noise is more easily filtered out. The authors also make an important statement about the increase of meaning/importance of inter-area oscillations monitoring using WAMS (Wide Area Measuring System) due to the growing size of the power systems.

The oscillations along the north-eastern Australian coast (Queensland) have been investigated by [Ledwich, 2000]. The voltage angle at the ends of two long lines have been measured and analysed. The author states that the angle signals have greater potential for modal identification than power. Promising simulation results with voltage angles measured with PMUs and fed into the PSS designed for it and placed at two generators in Norwegian network are demonstrated in [Uhlen, 2001].

The analysis of active power flow for a purpose of the oscillation modes identification is described in [Hiyama, 2000]. Although it aims to a real-time application, the nature of the procedure makes it a bit difficult. First the FFT (Fast Fourier Transform) is carried out and then the decomposition of spectra into individual modes is done. The test results on 500kV line in Kyushu Electric Power System are provided, too. The author proceeds in the work in [Hiyama, 2002], where the stability evaluation functionality is added and used for the tuning of conventional PSS and Fuzzy Logic PSS.

A Remote Feedback Controller (RFC) design methodology using PMU measurements is presented in [Snyder, 2000]. The simulation results show a robustness and good performance of the RFC applied on the damping of low frequency inter-area oscillations.

Research group in Hydro-Québec under lead of Kamwa has done significant work in the field of damping of inter-area oscillations. In [Kamwa, 2000] two-loop PSSs are proposed. The speed sensitive local loop operating the usual way is extended with a global loop using wide-area measurements from two suitably selected areas, in this case frequency measurements. Five control sites comprising of 4 generators and one synchronous condenser have been chosen for

implementation of the proposed method. The simulations (without considering a time delay caused by communication synchronization of values, processing and execution of a command) have proved a significant improvement in the damping of inter-area oscillations, which have been excited by a contingency (trip of one of the major lines). The device that is assumed to be used for measuring in the practice is Phasor Measurement Unit (PMU). The locations for their placement are shortly discussed. The author suggests placement of 65 PMUs for multifunctional SPS in Hydro-Qébec system. The described work has been slightly extended in [Kamwa, 2001].

System solutions and related issues of SPSs

In the previous chapters, the focus was on the principles of SPSs, the practical design details have been omitted. However, they very often influence the feasibility and put very strict constraints on the algorithms of SPS. Therefore the practical considerations are of great importance.

One such aspect is the measurement technique. The best trend, which has appeared in the last decade, is Synchronized Phasor Measurement Technology. The main idea is to measure the voltage and current phasors in the same time at the selected locations in the network, transmit them into a central point, where they can be compared, evaluated and further processed. The devices performing the measurements are called PMU (Phasor Measurement Unit). PMU is basically a conventional RTU (Remote Telemetry Unit) equipped with the receiver of GPS signal synchronizing the measurements and tagging the time stamp to them. PMU is also capable of pre-processing of data (Fourier transformation etc.). The PMU technology was originally developed in eighties by Thorp, Phadke and others at Cornell, Virginia Polytechnic Institute and American Electric Power.

[Bhargava, 1999] writes about the plans and experience with PMU measurements for monitoring and post fault-analysis purposes in Southern California Edison Company (SCE). SCE is one of the participants within WSCC (Western Systems Coordinating Council) in the PMU research project started in 1995 by EPRI. In SEC, 50 phasors are collected from different locations at rate of 30 samples per second in the unit called Phasor Data Concentrator and used for analysis of the stresses in the network. Among the author statements, is also plan for the future use of synchronized measurements for the following purposes, which shows their great general potential:
- system monitoring/state estimation
- event recording
- analysing and understanding system/load characteristics
- system control

PMU capability of providing the measurements taken in the same time offers a lot of advantages. The major one is that the dynamic behaviour of the system can be observed. This together with a high sampling frequency can be utilized for precise load modelling (voltage and frequency dependency). This allows a good prediction of the future behaviour of the loads if the evolution of consumed active and reactive power of the loads is observed immediately after a disturbance. That may give a basis for new algorithms assessing stability, for application on voltage instability see [Rehtanz, 2001] and frequency instability [Larsson, 2002].

An importance of precise load modelling is demonstrated in [Hiskens, 1995] where the impact of load dynamics on damping of oscillations is examined.

Since the quantities measured by PMUs are voltage and current phasors, the linear relation between them holds when modelling the branches in the network (i.e. π - equivalent of line and

transformer). This feature/property permits linear State Estimation process, thus avoiding repetitive manipulations with large matrices in iterative procedure as it is in the traditional case. This significantly reduces the computational time and errors level. This approach has probably been derived first time in [Phadke, 1986] where the authors have formulated the linear State Estimation equations and applied them on 118 buses IEEE test system. The authors assume that all substations are equipped with PMUs measuring all voltages and some selected currents. The high cost of both PMUs themselves (although nowadays this is not as critical issue as it used to be, the price of PMU is approximately 3 500 USD) and the communication links to all substations force to keep the number of installed PMUs to a minimum. [Baldwin, 1993] has presented a method for placement of a minimal number of PMUs such a way that the system is still observable and all relevant quantities (all bus voltages and all branch currents) can be extracted from measurements by employing linear State Estimation. According to the authors' simulation results, only each third or fourth bus has to be provided with PMU. Another paper contributing to this topic is [Cho, 2000]. However, the authors in both papers examine what they call *topological observability* of the power system. That means that the measurements coming from the given placement of PMUs are sufficient for State Estimation yielding all voltages and all branch currents under an assumption that the **topology is known**, although it is not so clearly/explicitly formulated but it is obvious. If the system relying only on PMUs is being built, other criterion is of bigger importance – observability of topology. That implies that statuses of all elements (lines, transformers, shunt elements, generators, loads) can be determined only from the delivered PMU measurements as well as the ratio of ULTC transformers. Another issue, which was neglected by the authors, is a redundancy, i.e. what to do in case of an outage of the communication or PMU. In the practical applications these factors have to be considered as outlined in [Rehtanz, 2002].

The criterions for PMU placement, not directly related to the execution of State Estimation, are used in [Kamwa, 2001b]. There the main goal is to achieve the highest degree of information contained in the time-response signals under all possible contingencies and realistic operating scenarios with a minimal set of PMUs. Thus this criterion is probably less demanding than those above. Very important feature is that the methods described in the paper incorporate mandatory locations for the placement of PMUs, such as tie-line buses and large generator step-up transformers. This criterion is really crucial for observing some phenomena like angle and frequency instabilities. Therefore it should be adopted in the PMU placement procedure as an important constraint also in the case of PMUs installation for intended State Estimation purpose.

The linear State Estimation and use of PMUs as measurement means, brings the protection system on a qualitatively new level. The further development of computers and reduction of cost of the wide band communication links (fibre optics or conventional modem connection can be utilized but the capacity and reliability/availability are important) will make possible to establish the centralized system serving functions of protection, control and optimisation of existing power systems assets as envisioned in [Fardanesh, 2002].

The work of Hiskens is certainly worth mentioning although it cannot be so easily included in one of the above categories. Hiskens promotes use of the method called Trajectory Sensitivities applied on various power systems problems. In [Hiskens, 1999] authors explore the factors influencing the large disturbance behaviour of the NORDEL system and identify some important parameters (e. g. weak line).
The differential, switched algebraic and state-reset equations (DSAR) are used for a description of hybrid system behaviour in [Hiskens, 2001] explicitly tap changing transformer. Hybrid systems are the systems with continuous dynamics (e.g. voltages) and discrete events (in this case for example transformer's tap changing, lines switching etc.). Moreover, the paper illustrates a possibility to model a large system using modular approach.

In [Hiskens, 2001b] Hiskens concentrates on the so-called inverse problem, extraction of the model parameters and its description when its behaviour is known. This can be used for a reconstruction of a power system event from the fault recordings (disturbance measurements). Here he defines differential-algebraic impulsive switched (DAIS) model description.

The two last papers are partly merged and the topic is further developed in [Hiskens, 2001c]. [Hiskens, 2002] contains a slight extension of the previously discussed topics by a brief section about use of sensitivity trajectories for optimal control.

Concluding Remarks

This report briefly summarizes the information about SPSs available to the author. The literature survey has served as a main source. The trends in all relevant categories of SPS research in the last decade is presented although due to the broad character of the topic and intensive research activities, only selected contributions could be mentioned.

References

[Ajjarapu, 1992]   V. Ajjarapu, C. Christy: "The Continuation Power Flow: A Tool For Steady State Voltage Stability Analysis", IEEE Transactions on Power Systems, Vol. 7, No. 1, February 1996.

[Anderson, 1996]   P. M. Anderson, B. K. LeReverend: "Industry Experience with Special Protection Schemes", IEEE Transactions on Power Systems, Vol. 11, No. 3, August 1996.

[Arnborg, 1997]   S. Arnborg: „Emergency Control of Power Systems in Voltage Unstable Conditions", PhD Thesis, Royal Institute of Technology in Stockholm, Department of Electric Power Engineering, 1997.

[Arnborg, 1998]   S. Arnborg, S. Andersson, D. J. Hill, I. A. Hiskens: "On Influence of Load Modelling for Undervoltage Load Shedding Studies", IEEE Transactions on Power Systems, Vol. 13, No. 2, May 1998.

[Baldwin, 1993]   T. L. Baldwin, L. Mili, M. B. Boisen, R. Adapa: „Power System Observability With Minimal Phasor Measurement Placement", IEEE Transactions on Power Systems, Vol. 8, No. 2, May 1993.

[Belhadj, 1996]   C. Belhadj, R. Mohamedi, S. Lefebvre, P. J. Lagacé, X. D. Do: "Voltage Stability Modelling and Real-Time Monitoring Using Expert System for Operation Assistance", IEEE Transactions on Power Systems, Vol. 11, No. 2, May 1996.

[Berizzi, 1996]   A. Berizzi, P. Bresesti, P. Marannino, G. P. Granelli, M. Montagna: „System-Area Operating Margin Assessment and Security Enhancement Against Voltage Collapse", IEEE Transactions on Power Systems, Vol. 11, No. 3, August 1996.

[Bhargava, 1999]   B. Bhargava: "Synchronized Phasor Measurement System Project at Southern California Edison Co.", IEEE Power Engineering Society Summer Meeting, 1999.

[Breulmann, 2000]   H. Breulmann et al.: „Analysis and Damping of Inter-Area Oscillations in the UCTE/CENTREL Power System", CIGRE, 38-113, Session 2000.

[Chiang, 1995]   H. D. Chiang, R. Jean-Jumeau: "Towards a Practical Performance Index for Predicting Voltage Collapse in Electric Power Systems", IEEE Transactions on Power Systems, Vol. 10, No. 2, May 1995.

[Chiang, 1995b]   H. D. Chiang, A. J. Flueck, K. S. Shah, N. Balu: "CPFLOW: A Practical Tool for Tracing Power System Steady-State Stationary Behavior Due to Load and Generation Variations", IEEE Transactions on Power Systems, Vol. 10, No. 2, May 1995.

[Cho, 2000]   K. S. Cho, J. R. Shin, S. H. Hyun: "Optimal Placement of Phasor Measurement Units with GPS Receiver", IEEE Power Engineering Society Winter Meeting, 2000.

[CIGRE, 2000]   CIGRE Task Force 38.02.19: "System Protection Schemes in Power Networks", Final Draft v 5.0, 2000.

[CIGRE, 2001]   CIGRE Working Group 34.08: "Isolation and Restoration Policies against System Collapse", June 2001.

[Corsi, 2000]   S. Corsi, M. Pozzi, U. Bazzi, M. Mocenigo, P. Marannino: "A Simple Real-Time And On-Line Voltage Stability Index Under Test In Italian Secondary Volage Regulation", CIGRE, 38-115, Session 2000.

[Coté, 2001]   P. Coté, S. P. Coté, M. Lacroix: "Programmable Load Shedding Systems – Hydro-Québec's Experience", IEEE Power Engineering Society Summer Meeting, 2001.

[Delfino, 2001]   B. Delfino, S. Massucco, A. Morini, P. Scalera, F. Silvestro: "Implementation and Comparison of Different Under Frequency Load-Shedding Schemes", IEEE Power Engineering Society Summer Meeting, 2001.

[De Tuglie, 2000]   E. De Tuglie, M. Dicorato, M. La Scala, P. Scarpellini: „A Corrective Control for Angle and Voltage Stability Enhancement on the Transient Time-Scale",IEEE Transactions on Power Systems, Vol. 15, No. 4, November 2000.

[Ernst, 2000]   D. Ernst, M. Pavella: „Closed-Loop Transient Stability Emergency Control", IEEE Power Engineering Society Winter Meeting, 2000.

[Fardanesh, 2002]   B. Fardanesh: "System – Wide Automatic Real – Time Voltage and Power Flow Control for Power Systems – Coordination of Injection (Shunt) Controllers with Routing (Series) Controllers", IEEE Power Engineering Society Winter Meeting, New York, January 2002.

[Flueck, 1996]   A. J. Flueck, H. D. Chiang, K. S. Shah: "Investigating the Installed Real Power Transfer Capability of a Large Scale Power System Under a Proposed Multiarea Interchange Schedule Using CPFLOW", IEEE Transactions on Power Systems, Vol. 11, No. 2, May 1996.

[Fu, 2002]   W. Fu, S. Zhao, J. D. McCalley, V. Vittal, N. Abi-Samra: „Risk Assessment for Special Protection Systems", IEEE Transactions on Power Systems, Vol. 17, No. 1, February 2002.

[Gomes, 2002]   P. Gomes, A. P. Guarini, A. C. S. de Lima, M. S. Rocha: "Guidelines for Power System Restoration in the Brazilian System", IEEE Power Engineering Society Winter Meeting, New York, January 2002.

[Gubina, 1995]   F. Gubina, B. Strmcnik: „Voltage Collapse Proximity Index Determination Using Voltage Phasors Approach", IEEE Transactions on Power Systems, Vol. 10, No. 2, May 1995.

[Hemmingsson, 2001] M. Hemmingsson, O. Samuelsson, K. O. Helgesen Pedersen, A. H. Nielsen: "Estimation of Electro-Mechanical Mode Parameters using Frequency Measurements", IEEE Power Engineering Society Summer Meeting, 2001.

[Heydt, 2001]   G. T. Heydt, C. C. Liu, A. G. Phadke, V. Vittal: "Solutions for the Crisis in Electric Power Supply", IEEE Computer Applications in Power, 2001.

[Hiskens, 1995]   I. A. Hiskens, J. V. Milanovic: „Load Modelling in Studies of Power System Damping", IEEE Transactions on Power Systems, Vol. 10, No. 4, November 1995.

[Hiskens, 1999]   I. A. Hiskens, M. Akke: „Analysis of the Nordel Power Grid Disturbance of January 1, 1997 Using Trajectory Sensitivities", IEEE Transactions on Power Systems, Vol. 14, No. 3, August 1999.

[Hiskens, 2001]   I. A. Hiskens, P. J. Sokolowski: „Systematic Modelling and Symbolically Assisted Simulation of Power Systems", IEEE Transactions on Power Systems, Vol. 16, No. 2, May 2001.

[Hiskens, 2001b]   I. A. Hiskens: „Nonlinear Dynamic Model Evaluation From Disturbance Measurements", IEEE Transactions on Power Systems, Vol. 16, No. 4, November 2001.

[Hiskens, 2001c]   I. A. Hiskens: „Inverse Problems in Power Systems", Bulk Power System Dynamics and Control V, Onomichi, Japan, August 26-31, 2001.

[Hiskens, 2002]   I. A. Hiskens, M. A. Pai: „Power System Applications of Trajectory Sensitivities", IEEE Power Engineering Society Winter Meeting, New York, January 2002.

[Hiyama, 2000]   T. Hiyama, N. Suzuki, T. Funakoshi: „On-line Identification of Power System Oscillation Modes By Using Real Time FFT", IEEE Power Engineering Society Winter Meeting, 2000.

[Hiyama, 2002]   T. Hiyama, N. Suzuki, D. Kojima, T. Funakoshi: "Background Oscillation Based Real Time Stability Evaluation", IEEE Power Engineering Society Winter Meeting, New York, January 2002.

[Julian, 2000]   D. E. Julian, R. P. Schulz, K. T. Vu, W. H. Quaintance, N. B. Bhatt, D. Novosel: „Quantifying Proximity To Voltage Collapse Using The Voltage Instability Predictor (VIP)", IEEE Power Engineering Society Summer Meeting, 2000.

[Kamwa, 2000]   I. Kamwa: "Using MIMO System Identification for Modal Analysis and Global Stabilization of Large Power Systems", IEEE Power Engineering Society Summer Meeting, 2000.

[Kamwa, 2001]   I. Kamwa, R. Grondin, Y. Hébert: "Wide-Area Measurement Based Stabilizing Control of Large Power Systems – A Decentralized/Hierarchical Approach", IEEE Transactions on Power Systems, Vol. 16, No. 1, February 2001.

[Kamwa, 2001b]   I. Kamwa, R. Grondin: „PMU Configuration for System Dynamic Performance Measurement in Large Multi-area Power Systems", submitted to IEEE Transactions on Power Systems.

[Karady, 2002]   G. G. Karady, A. A. Daoud, M. A. Mohamed: "On-Line Transient Stability Enhancement Using Multi-Agent Technique", IEEE Power Engineering Society Winter Meeting, New York, January 2002.

[Koaizawa, 2000]   M. Koaizawa, K. Omata, M. Nakane, Y. Kokai: "Actual Operating Experience of On-Line Transient Stability Control Systems (TSC Systems)", IEEE Power Engineering Society Winter Meeting, 2000.

[Koessler, 2001]   R. J. Koessler, J. D. Mountford, L. T. G. Lima, J. Rosende: „The Brazilian Interconnected System: A Study on Transfer Limits, Reactive Compensation and Voltage Collapse", IEEE Power Engineering Society Winter Meeting, January 2001.

[Kolluri, 2000]   S. Kolluri, K. Tinnium, M. Stephens: „Design and Operating Experience with Fast Acting Load Shedding Scheme in the Entergy System to Prevent Voltage Collapse", IEEE Power Engineering Society Winter Meeting, 2000.

[Kosterev, 1999]   D. N. Kosterev, C. W. Taylor, W. A. Mittelstadt: „Model Validation for the August 10, 1996 WSCC System Outage", IEEE Transactions on Power Systems, Vol. 14, No. 3, August 1999.

[Kundur, 1993]   P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1993.

[Kundur, 2000]   P. Kundur, G. K. Morison, L. Wang: „Techniques For On-Line Transient Stability Assessment And Control", IEEE Power Engineering Society Winter Meeting, 2000.

[Larsson, 2000]   M. Larsson: "Coordinated Voltage Control in Power Systems", PhD Thesis, Lund University, 2000.

[Larsson, 2001]   M. Larsson: "Protection against frequency and angle instability with PSGuard – An Initial Study", Internal Technical Report, ABB Corporate Research, Switzerland, September 2001.

[Larsson, 2002]   M. Larsson, C. Rehtanz: "Predictive Frequency Stability Control based on Wide-Area Phasor Measurements", to appear at IEEE Power Engineering Society Summer Meeting, Chicago, July 2002.

[Ledwich, 2000]   G. Ledwich, E. Palmer: „Modal Estimates from Normal Operation of Power Systems", IEEE Power Engineering Society Winter Meeting, 2000.

[Martins, 2000]   A. C. B. Martins et al: "Criteria and Methodologies Established in the Ambit of GTAD/SCEL/GCOI Voltage Collapse Task Force for Studies on Voltage Stability in the Brazilian North/Northeast, South/Southeast and North/South Interconnected Systems", IEEE Power Engineering Society Summer Meeting, 2000.

[Minakawa, 2000]   T. Minakawa: "The Required Technological Breakthrough in Developing Universal Emergency Control Systems in Terms with Transient and Dynamic Stability", IEEE Power Engineering Society Winter Meeting, 2000.

[Mitchell, 2000]   M. A. Mitchell, J. A. Peças Lopes, J. N. Fidalgo, J. D. McCalley: "Using a Neural Network to Predict the Dynamic Frequency Response of a Power System to an Under-Frequency Load Shedding Scenario", IEEE Power Engineering Society Summer Meeting, 2000.

[Moors, 2000]   C. Moors, D. Lefebvre, T. Van Cutsem: "Design of Load Shedding Schemes against Voltage Instability", IEEE Power Engineering Society Winter Meeting, 2000.

[Nielsen, 1988]   E. K. Nielsen, M. E. Coultes, D. L. Gold, J. R. Taylor, P. J. Traynor: „An Operations View of Special Protection Systems", IEEE Transactions on Power Systems, Vol. 3, No. 3, August 1988.

[Phadke, 1986]   A. G. Phadke, J. S. Thorp, K. J. Karimi: "State Estimation with Phasor Measurements", IEEE Transactions on Power Systems, Vol. PWRS-1, No. 1, February 1986.

[Rehtanz, 2001]   C. Rehtanz: "Wide Area Protection and Online Stability Assessment based on Phasor Measurements", Bulk Power System Dynamics and Control V, August 26th – 31st, Onomichi, Japan, 2001.

[Rehtanz, 2002]   C. Rehtanz, M. Larsson, M. Zima, M. Kaba, J. Bertsch: „System for Wide Area Protection, Control and Optimisation based on Phasor Measurements", to appear at Conference Power Systems and Communication Systems Infrastructures for the Future, Beijing, September 2002.

[Shim, 2000]   K. S. Shim, H. K. Nam, S. G. Song, Y. G. Kim, K. Y. Lee: "Application Results of the Eigen-sensitivity Theory of Augmented Matrix to Small Signal Stability Analysis of Large Power Systems", IEEE Power Engineering Society Summer Meeting, 2000.

[Snyder, 2000]   A. F. Snyder, D. Ivanescu, N. HadjSaid, D. Georges, T. Margotin: "Delayed-Input Wide-Area Stability Control with Synchronized Phasor Measurements and Linear Matrix Inequalities, IEEE Power Engineering Society Summer Meeting, 2000.

[Taylor, 1994]   C. W. Taylor: "Power System Voltage Stability", McGraw-Hill, 1994.

[Taylor, 2000]   L. Y. Taylor, S. M. Hsu: "Transmission Voltage Recovery Following a Fault Event in the Metro Atlanta Area", IEEE Power Engineering Society Summer Meeting, 2000.

[Trudel, 1999]   G. Trudel, S. Bernard, G. Scott: "Hydro-Québec's defence plan against extreme contingencies", IEEE Transactions on Power Systems, Vol. 14, No. 3, August 1999.

[Uhlen, 2001]   K. Uhlen, M. Palsson, T. R. Time, O. Kirkeluten, J. O. Gjerde: „Raising Stability Limits in the Nordic Power Transmission System", submitted to IEEE Transactions on Power Systems.

[Van Cutsem, 1997]   T. Van Cutsem, R. Mailhot: "Validation of a Fast Voltage Stability Analysis Method on the Hydro-Québec System", IEEE Transactions on Power Systems, Vol. 12, No. 1, February 1997.

[Van Cutsem, 2002]   T. Van Cutsem, C. Moors, D. Lefevbre: "Design of Load Shedding Schemes against Voltage Instability using Combinatorial Optimisation", IEEE Power Engineering Society Winter Meeting, New York, January 2002.

[Vargas, 1999]   L. Vargas, V. H. Quintana, R. Miranda: "Voltage Collapse Scenario in the Chilean Interconnected System", IEEE Transactions on Power Systems, Vol. 14, No. 4, November 1999.

[Vu, 1999]   K. Vu, M. M. Begovic, D. Novosel, M. M. Saha: „Use of Local Measurements to Estimate Voltage-Stability Margin", IEEE Transactions on Power Systems, Vol. 14, No. 3, August 1999.

[Wang, 1996]   L. Wang, A. A. Girgis: „On-Line Detection of Power System Small Disturbance Voltage Instability", IEEE Transactions on Power Systems, Vol. 11, No. 3, August 1996.

[Wang, 2000]   Y. J. Wang, C. W. Liu, L. D. Sue, W. K. Liu: „A Remedial Control Scheme Protects Against Transient Instabilities Based on Phasor Measurement Units (PMUs) – A Case Study", IEEE Power Engineering Society Summer Meeting, 2000.