SPECIAL PROTECTION SCHEMES IN ELECTRIC POWER SYSTEMS

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SUMMARY

The report represents the initial study that aims at designing SPS (System Protection Scheme) having following characteristics: 1.) wide area approach; 2.) capability of mitigation one or more dangerous phenomena having a system wide nature (e.g. voltage instability, frequency instability etc.); 3.) emergency protection function (preventive protection can be sufficiently provided by SCADA/EMS systems); 4.) 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.); 5.) 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 introduction. In the second chapter definition of the problem and some fundamental questions are shortly outlined. The third 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. The fourth chapter is conclusion.

Keywords: *instability, protection, fault, schemes.*

1. INTRODUCTION

In this article 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.

2. WIDE AREA SYSTEMS

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.

3. 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.

3.1. 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 [1]:

- 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. 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.

Using of Neural Network to estimate the dynamic response of the power system to the under-frequency load shedding is proposed in [2]. This information is then used to calculate an optimal amount of load to be disconnected.

Advanced algorithm applying predictive control is described in [1]. 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.

3.2. 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.

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 [3]. 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.

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 [4].

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 [5].

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. 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 [6].

A step forward is QSS (Quasi Steady-State) approximation proposed in . 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 [1] 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 [7]. 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.

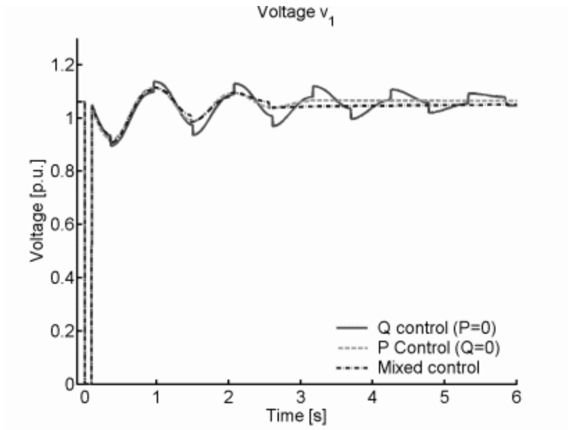

Fig. 1 The voltages in fault point.

3.3. 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 [8] 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 [9], 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.

[10] 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 [8]. CEPCO (Chubu Electric Power Co.). 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

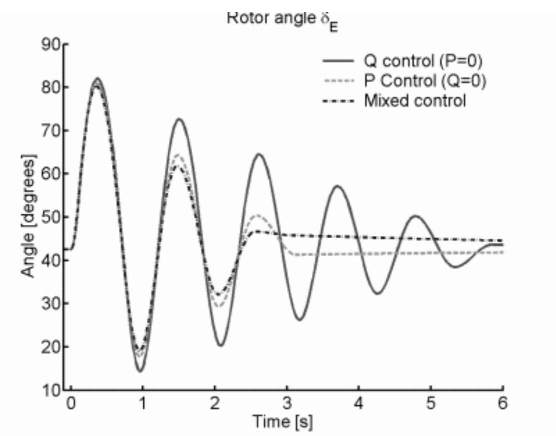

Fig. 2 The angle between the generator rotor and the strong grid.

3.4. 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 [9] if no measures increasing the damping were introduced. 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 [8]. 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 [6], 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 [8]. 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 [9].

The analysis of active power flow for a purpose of the oscillation modes identification is described in [10]. 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.

A Remote Feedback Controller (RFC) design methodology using PMU measurements is presented in [9]. 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 [10] 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).

4. CONCLUSION

This report briefly summarizes the information about SPSs. 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.

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BIOGRAPHIES

Michal Vargončík was born on 25.06.1981. In 2005 he graduated (MSc.) with distinction at the department of Electric Power Engineering of the Faculty of Electrical Engineering and Informatics at Technical University in Košice. His thesis title was "Impedance phenomena by the asynchronnous state and swinging network ". His scientific research is focusing on stability analyses of power systems and solutioning of asynchronnous operation of generators.

Michal Kolcun was born in 1954. He graduated (MSc.) at the Faculty of Power Engineering at the Moscow Power Engineering Institute in 1979, where he received a PhD in 1989. He became an Associate Professor of Electric Power Engineering at the Faculty of Electrical Engineering and Informatics at the Technical University of Košice. He was promoted as a professor of power and electric engineering in 2000. Since 1979 he has been working at the Faculty of Electrical Engineering and Informatics at the Technical University of Košice.

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