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Power Flow Studies for Assessment the Security of Steady States in Zone Inside the Large Interconnected Power System

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Abstract

This paper aims to introduce an effective method of making allowance for the potential impact of other transmission system operators (TSOs) or market players on the operation mode of a specific TSO in estimations referring to the full grid model based on the amount of real-time data sufficient to simulate a limited the interconnected power system (IPS) zone, yet not enough to update the full grid model. The preparation procedure of simulation of the equipotential grid model (EG) within the IPS based on the up-to-date computer technology is disclosed. The results of the EG-based emergency disturbance simulation in reference to the power system state estimation (SE) in real-time are more reliable in comparison with the results of other models. The EG application is more efficient in the procedure of analyzing the IPS tolerability against a specific number of potential faults and outages of individual components empowered by the most relevant calculations due to well-known software support.

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Keywords: TSO; Power flow study; Superposition principle; Equipotential grid model; Compensating injections

1. Introduction

The present-day progress of power engineering is specified by IPS setups combining an array of individual disconnectedly operating electric power systems (EPS).

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A specific IPS supports more efficient use of available power-generating capacity, improves power supply reliability and provides higher quality of electricity for consumers[1,2-7]. The increasing element loading of transmission grids (transmission lines, transformers etc.) gives rise to higher potential of emergency states due to operational breakdowns (both nodal and linear). Therefore, each random IPS state is checked for electrical operation mode tolerability with the help of the reliability analysis (RA). An operation mode is considered to be acceptable in cases where Ohm's and Kirchhoff's laws and operation constraints are observed. An operation tolerability check is feasible after its calculation performed on the basis of the IPS mathematical model taking into account its interconnection with a number of EPS located in different target areas. In addition, it should be noted that up-to-date IPS are controlled by many operators either according to decentralized or hierarchic principle where the upper level of hierarchy provides inter-regional coordination. Thus, both every single TSO and every single distribution system operator (DSO) address the challenge to provide reliable and sustainable power delivery to consumers localized in a relatively small area within the IPS network. The complexity and high dimensionality of the IPS control tasks necessitate the mandatory support of advanced computer technologies. One of the options to enhance the IPS control efficiency is a shift from individual software to complex software solutions designed to address the interrelated tasks of operation analysis in aid of dispatch management decision-making. In this context, the compatibility of calculation is determined not only by a targeted purpose but also by the integrated data-base support.

Since the maximum significant number of element outages of the IPS is not known a priori the RA seeks to focus on the analysis of systems having the utmost combination of dead elements. To implement a huge sequence of calculation regarding the IPS multi-zone operation modes in order to determine their RA in reference to each possible combination of dead elements is absolutely unfeasible without reliable support of advanced computer technology. The efficiency of calculation largely depends on the software package in service.

A range of industrial software packages designated to solve various power grid problems is available. For example, such as: PPS/E, PowerFactory, EUROSTAG, Mustang, RastrWin and others[8-12]. Although the software packages differ in some specific features, they share some common features as well. A typical performance function of the packages deals with the ability to calculate an electrical operating mode.

In order to make allowance for the influence of other interconnected participants on the operation mode of a specific TSO it is required to estimate the operating mode of the full IPS model and to obtain real-time information regarding the external grid to the extent sufficient to update the common grid model (CGM) of the entire IPS. Since the TSO lacks sufficient data to update the IPS detailed model the simulation problem is generally solved in one of two ways. The first method involves the substitution of an external part of the grid for an electric equivalent: Ward (Norton) Equivalent Circuits[13], Dimo REI (Radial Equivalent Injections) method[14] or other techniques[15-16]. This method is often chosen in the event of availability of rather limited amount of real-time information referring to the external grid. After the substitution of external grid for an equivalent the TSO is capable to analyze only the modes of its own EPS. Besides, the TSO has no chance to simulate accidents in the equivalent part of the grid. The second method involves the scaling of the external grid represented in full[15]. This method is often chosen in the event of availability of a large amount of real-time information referring to the external grid. However, the bulk transmission grid responds poorly to scale. Therefore, the TSO may encounter difficulties in achieving a high-quality operation mode of the controlled power system. The inability to control the external grid operation mode quality remains a problem for both methods of simulation. Thus, due to real-time data problem a TSO either abandons the external grid analysis and scales the CGM back into the equivalent or seeks to obtain the required amount of real-time data in order to extend simulation zone.

The developed the equipotential grid model (EG) - based method enables to update the EG within the IPS in order to explore it without regard to the power system operation mode employing only the source data accessible for the TSO. The impact of accidents on the IPS operation parameters can be determined subject to the EG, which is extremely important for the reliability study of the IPS operation. This is especially relevant in reliability analysis (RA) which considers a full totality of the anticipated emergency states within the IPS, analyzes post-contingency electric modes and decides on the efficient control actions (CA) to be taken in order to provide maximum power delivery to consumers[2-7]. Major system accidents within 70-80s of the twentieth century and recent years have proved that the most crucial cause of accidents involves multiple failures of the IPS elements (more than 2). The facts confirm the need to address operation modes in the event of failure of two or more IPS elements. The proposed method of development the CGM-based EG contributes to the efficiency of emergency mode analysis as compared to other familiar approaches. The paper consists of six sections. The first section highlights the problem topicality and its present state specifying some modern software systems applicable for calculating electric power system modes. The second section summarizes the use of modern computer technologies in the field of operational dispatch management. The third section describes the common IPS model development procedure. The fourth section describes simulation of emergency disturbances. The Experimental procedure is covered in the fifth section. The conclusions of the work done are stated in the sixth section.

The localized electric system control solves more effectively such problems as repair and service of electric equipment or quality voltage maintenance at the consumers' substations. On the whole, this management structure is more acceptable for DSO, as well as interconnected TSO. Most TSOs work in meshed systems engaged in power delivery to consumers and transit power flow service. The transit power flows supported by the IPS operation modes can reach significant values which are hardly predictable with sufficient accuracy for the TSO. In order to make allowance for the impact of other parallel operated participants on the TSO operation mode, it is required to estimate the full model of the interconnected power system, and to obtain information on the external grid to the extent sufficient to update the model.

The SCADA systems (Supervisory Control And Data Acquisition) are used in the TSO operational management practice. These systems are designed to support the supervisory staff actions during the EPS operational and emergency control. SCADA include: remote telecontrol devices installed in the IPS substations for tracking TV signals on switching equipment state and remote metering of mode parameters, communication channels; database; real-time mode parameter display systems. The SCADA systems typically include additional functions known as Energy Management systems (EMS)[17]. State Estimator (SE) of the EPS is one of the main functions of the EMS. SE offers the EPS steady-state mode estimation technique based on measurement data obtained from SCADA system. SE enables to track errors in the telemetry information from the "observable area", which includes a control area of the given TSO, and a small portion of the external network. Everything that is beyond the "observable area" is not available for SE estimation. SE adjust the source data in the "unobservable area" and rejecting "bad data" in the "observable area" by ad-hoc algorithms[20]. Due to the function service any telemetry data vector elements transferred to the SE are marked with the quality characters. Data quality character serves as a ground for further analysis of telemetry data reliability. The EMS software enables to process telemetry results, generate control commands for dispatch control objects and automatically create individual grid models (IGM) based on SCADA data. "Individual" here means that each TSO creates and provides data for the mathematical model of its controlled zone within the interconnected power system. The IGM data is sufficient to provide estimation of a steady-state mode of the IPS part respective to the operational zone of one TSO or DSO. In order to carry out the IGM–referred variants calculations, the IGM model needs to be included into the common grid model (CGM).

2. Common IPS model development process

The CGM is created with a level of detail IGM of the TSO. Effective load flow calculation methods[18], as well as modern computer technology capabilities allow working with the IPS models consisting of ten-thousand nodes[1]. Therefore the IGM of some DSO can be integrated into the CGM. However, even on the TSO level, several dozens of which may enter the IPS, the combination of the CGM out of separate fragments is a complex process which is hardly applicable in real-time. A more practical seems to be a mixed-level approach where the CGM is re-combined with a certain frequency, for example once a month, for the rest of time the CGM operates according to the IGM principle, i.e. receives variable model parameters in real time. The issue of accessibility of required for the CGM operational data can be solved technically. For example, it is possible to arrange a centralized operational data store for the CGM, where the real-time source data respective its own zone model to be entered by every TSO. In the IPS context the task of the CGM updating could be potentially solved by the Power Grid Operators (PGO - TSO with above 20 GW maximum demand)[19], however, the process of operational management decentralization of the common power grid presents the problem of data accessibility in order to update the CGM. The problem is that certain data includes commercially (sensitive) information without subject to be legally transferred to third parties by the TSO. Therefore, the problem of the CGM updating must be resolved legally before it can be solved technically.

In the process of the equivalent development by help of known methods[15] not only the nodalization structure is to be transformed but the original grid mode as well. In this respect, the transformation of nodalization structure is carried out nearly precise. The basic inaccuracies of equivalents are related to operating parameter variation and grid configuration in the model equivalent part. Namely, errors spring when the transformed unknown data are changed. The proposed method for EG development makes the assumption on implementation of the principle of superposition in the nonlinear grid model. Obviously, the principle of superposition in nonlinear systems is not implemented; however, we can assume that it is "almost" implemented. In other words, the principle is to be satisfied with a minor error incapable to provide a quality impact on the results of further analysis.

Thus, to make the CGM appropriate for the analysis of the external grid, it is proposed to refuse equivalent development on the basis of the initial mode but to separate the grid model from the energy system initial mode. The EG is considered, regardless to the power system mode, employing only available source data. As a result, the modes with new parameters are to be received in the form of deviations of the estimated operational parameters from the measured parameters of the initial mode in question. Thus, any initial mode supported by known data can be estimated in terms of the reliability of steady-state operation of the energy system, namely, the impact of accidents i on parameters can be determined on the basis of the grid model.

The CGM-based algorithm of the EG creation takes place in several stages. At the first stage any reactive power sources used to maintain voltage in the grid nodes are recorded in the CGM, namely, all generators, except for the swing bus, are converted from the PU mode to the PQ mode[21]. Further, the reactive power regulation available margin is corrected by taking away the current reactive power of compensating units from the upper and lower limits.

At the second stage any injections are eliminated from the mode, namely, active and reactive powers of loads, generators, shunt resistors and shunt admittance branches. Shunt admittance branches represented according to π-models of the equivalent-Pi or transformer magnetizing admittances can be transferred to the adjacent nodes without change of the results of electric mode calculation.

At the third stage the transformation ratios of transformers are normalized. This means that voltage phase slues are reset to zero and transformation ratio modules are set relatively equal to each other. The transformation ratios of transformers, feeding the radial system, do not affect the distribution of power flows in the case of EG. In order to minimize errors it is recommended to take any transformation ratios of transformers as equal to one relative unit value. Thus, according to the reference units transformation ratios to be equal to the voltage type ratio of the nodes connected with this transformer.

At the fourth stage, the control mode calculation is carried out. Once any transformations have been performed correctly, the in the swing bus, regardless of the source voltage, there should be zero generating power. In addition, the voltage at all nodes of each voltage class should be equal to each other, and the active and reactive power in all branches of the model should become infinitesimal approximately equal to zero.

At the fifth stage the generators, as well as other reactive power sources, capable to maintain node voltages are reverted back to the mode PU[21]. Generators and reactive power sources should continuously maintain those voltages which have been obtained by calculation on the fourth stage. Generators and reactive power sources are required in order to bring the emergency response of the equipotential model to the respective response of the original CGM. The passive model without generator nodes fails to provide support to the voltage required for the active power transmission over long distances. The active power of each generator must be zero. Reactive power range of each generator provides for that reactive power generation zero to be found within the range. In other words, the minimum reactive power is to be negative, and the maximum - positive. Once every transformation has been performed correctly, then under re-calculated mode any node injections and power flows via branches remain zero. Therefore, the equipotential model has been created.

Being the equipotential model EG features the following relevant properties:

- Power flows via EG branches are not varied when the grid configuration is changed.
- EG node voltages remain constant as long as become disconnected from the power supply.
- EG is loss-free, i.e. equipotential model is globally optimal in terms of losses in the grid. Therefore, any changes of network injections contribute to grid loss.

3. Simulation of emergency disturbances

For the best result of calculation is necessary to know the status of all transmission lines, transformers and circuit breakers that may affect the operation of the power system under study. In the analysis of potential emergency situations it is desirable to have information on the actual or perceived load of network elements and generators, which as a result of accidents can be disconnected, and the amount and placement of reserves that can be put into operation to eliminate the consequences of accidents. Any EG-supported calculations can be performed on the grid model in cases of lack or total absence of operational information. At the same time, it is feasible to specify the maximum continues admissible value of a mode parameter, its planned value, expectation value at a certain time interval or hypothetical value of the parameter in question. Thus, any entity performing calculations on the grid model may not have access to confidential information. Moreover, the EG-based calculation results practically are independent from the software used.

EG-addressed emergency disturbances are simulated by way of compensating injections, which are applied to the nodes of disturbance at a scale 1: 1 followed by simultaneous shutdown of the network elements. For example, under increasing the power generator by 100 MW the respective EG node is added with 100 MW generation or -100 MW load, and then the resulting mode is calculated. In the event of a power transmission line disconnection, the respective EG branch is disconnected, and the beginning and end of the branch nodes are subject to injection, fully compensating source power flows across the line, which can no longer go to the disconnected branch and turn back in the direction of the grid. For example, if under a source mode the power flow via power transmission line “A-B” is X MW from “A” to “B”, then node “A” is added with “-X” MW load and node “B” with “X - ΔX “MW load where ΔX - value of active power losses in the line under the source mode. In case of a large volume of operational data the measured active and reactive power across the line are added to the load of nodes «A» and «B» with the opposite sign. In general number of disturbances i, added to the EG model, it corresponds to potential emergencies i that hypothetically occur in the target time interval. In case of emergencies i applied to the EG the model mode deviates from equilibrium. Therewith, the result of the mode calculation is determined by the vector of mode parameter deviations from the vector of source parameters. As the source mode parameters the measured power values (current) and voltage values may be accepted. These EG-calculated values of mode parameters, as well as compensating injections applied to elements, are added to the initial values of measured parameters. For example, the active power flow through the branch is added to the actual measured power across the controlled transmission line. If the branch is interruptible, the sum of measured values and applied compensating injection is zero. The result is the expected controllable mode parameters values after accidents i. Thus, the EG-based calculation gives assessment of the impact of accidents i on each of the elements of the grid model. As a result, the expected values of measured parameters of the electric power system mode can be predicted prior to a probability event to be studied, if they are included in the EG model.

4. Experimental procedure

To exemplify the EG efficient workability let us consider the calculation of emergency operation of the electric system circuit shown in Fig. 1. Each quadrant of Fig. 1 cropped from the IEEE 118 Bus Test Case represents a portion of the American Electric Power System (in the Midwestern US) as of December, 1961[22]. The data was manually entered from a copy of a copy of a copy, etc., of the AEP 118 Bus Test System document dated December, 1962 and “made available to the electric utility industry as a standard test case”. It was entered in PECO PSAP format and later in IEEE Common Data Format by Rich Christie at the University of Washington, Seattle, Washington, USA in 1993. The source modes are shown on the left (see Fig. 1a and Fig. 1c). The modes after simultaneous outage of three elements are shown on the right (see Fig. 1b and Fig. 1d): the simultaneous outage of autotransformer 345/138 kV at substation Olive and two 345 kV overhead lines from substation Muskingum to Eastlima and to Kammer. Autotransformer at substation Olive is marked by a flag in Fig. 1. Transmission lines 345 kV are located outside of the tested segment, so not shown in Fig. 1. Mode calculations (see Fig. 1b) are made on the full model and Fig. 1d - on the equipotential model. It is easy to see that the result of the full model-based calculation (see Fig. 1c) can be achieved if the source mode is added with the relevant parameters deviation obtained under accident simulation on the balanced equipotential model (see Fig. 1d).

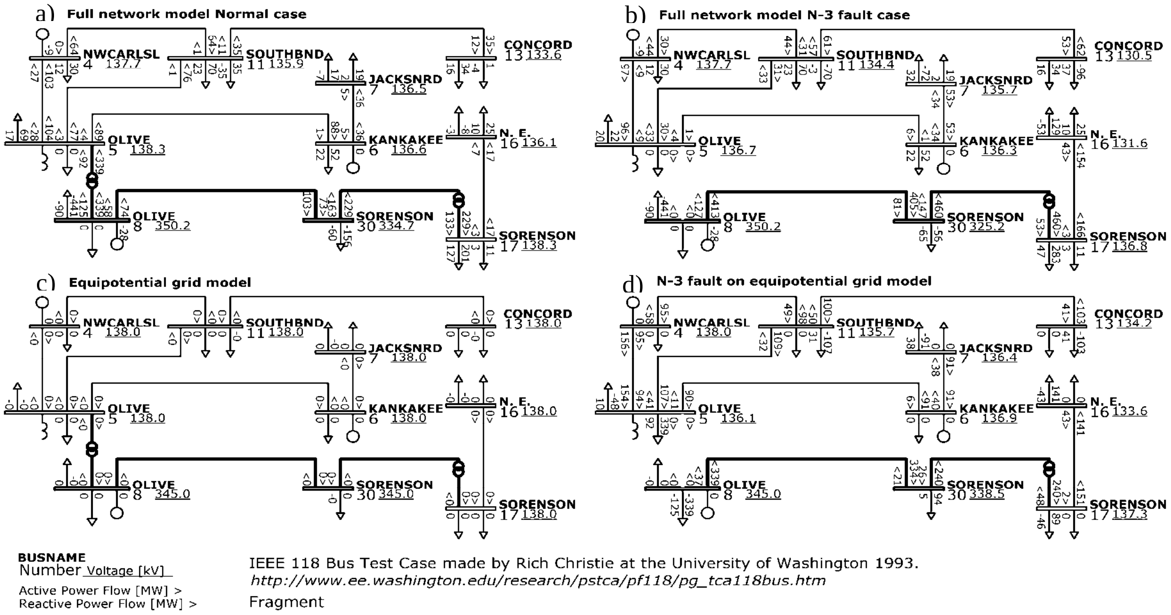

Fig. 1a-d. N-i fault study by traditional method vs. by superposition method.

For example, the expected active power flow via 138 kV line from JACKSNRD (7) to KANKAEE (6) $P_{l\_76} = -36+91 = 55$ MW (53 MW in original case). In case study of accident severity it is general to calculate the deviation of mode parameters from the initial parameters on the basis of the current estimated mode, i. e. by finding: $dP_{l\_76} = 53-(-36) = 89$ MW. In case of EG calculations the value of the active power flow deviations are obtained as a result of the mode calculation and additional calculations are not required. The deviations of post-emergency power flows via 212 branches of IEEE 118 Bus Test Case in the mode calculated according to EG method against the mode calculated on the basis of the full model are displayed in Fig. 2.

EG-based calculations can be compared with X-ray study of interconnected power system by Wilhelm Conrad Roentgen's method. Obviously, the method has additional errors as compared with the calculation based on the current mode in the full IPS model. However, in terms of accuracy the method may take an intermediate rank between the calculation based on the full CGM and calculation based on PTDF / LODF (Power Transfer Distribution Factors / Line Outage Distribution Factors), which is widely used in power systems for emergency operation calculations[23]. The EG-based calculation method eliminates errors which are inevitable under assessing the state of the power system based on the mathematical model of power grid and tend to arise significantly if the actual mode is close to the critical operation mode.

EG is unable to withstand the emergency disturbances by load variation according to the static response. For this reason, the original range of emergency disturbances subject to calculation on the full CGM is rather wide. Nevertheless, the ability to scale the disturbance vector, which is realized in EG by a simple multiplication of compensating injections by the constant k less than unity and following division by k deviations obtained, which considerably enhances the reliability of EG-based solutions compared with the reliability of the result achievement based on full CGM model. Furthermore, the accuracy of the EG-based calculation fails to decrease.

The example of EG-based calculation workability while analyzing N-i of the operation tolerability in case of potential faults and outages i in the power system allows arriving at two reasonable conclusions referring to the SE application in emergency accident estimation. First, the external grid elements that may influence the TSO mode must not be ruled out from the calculated model in the process of equivalent development even though there is a lack of load operational data. Second, in order to model disturbances it is not enough to make a list of elements to be disconnected. The deviation of the calculated load values of disconnected elements from their actual (or hypothetical) values by adding deviations in the form of compensating injections to the terminals of disconnected elements should also be taken into account while simulating emergency disturbances.

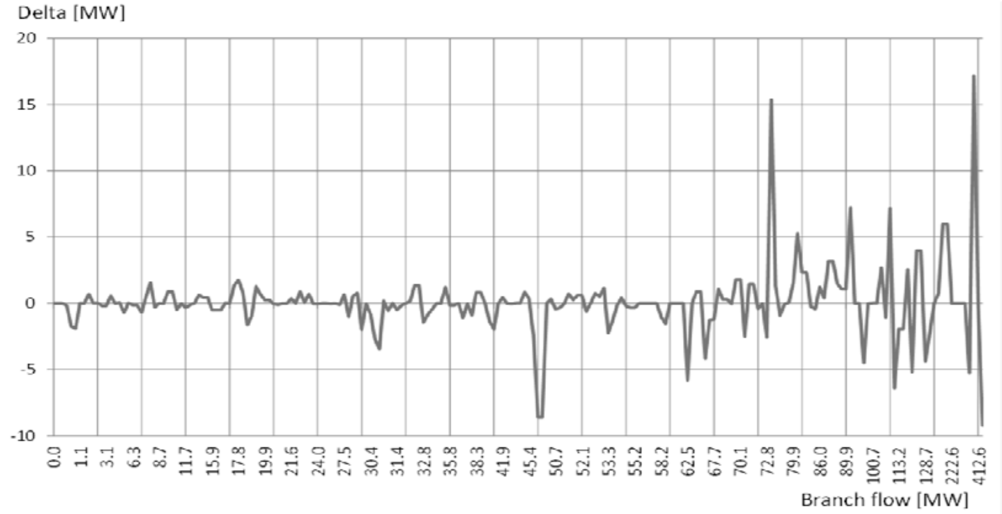

Fig. 2. N-i fault study difference between traditional method and superposition method.

5. Conclusion

The proposed method of the equipotential IPS model development for the analysis of N-i accidents allows for calculation under simultaneous disconnection of several elements of the electric grid without simulating (forming) of the current source mode. Instead, the actual measurement data can be used. The application of the method allows improving the reliability of the results by way of scaling of disturbances found unfeasible in the course of conventional analysis.

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