



Developing Scalable Smart Grid Infrastructure to Enable Secure Transmission

System Control

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Abstract	This document is mainly focused on the novel methods for risk assessment and identification of risk-relevant components. To implement stability awareness and risk assessment for smart grid, researches on transient stability, small-signal stability and cascading outages have been carried out in this EPSRC-NSFC joint project. In this document, novel analysis methods for transient stability, small-signal stability and cascading outages will be presented respectively. Methods proposed by the participants of this project will be presented and the advantages and disadvantages of all the methods will be discussed in detail.			
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Content

1 Introduction	4
2 Transient Stability Analysis	5
2.1 Stochastic Time Domain Simulation	5
2.2 Transient Stability Analysis Based on Energy Function Methods.....	5
2.2.1 Energy Function Methods with Reduced Order Model	6
2.2.1.1 Generator Pair-Wise Potential Energy Function for Online Stability Analysis	6
2.2.1.2 Discussion on Reduced Order Models.....	6
2.2.2 Energy Function Methods with Structure Preserving Model.....	6
2.2.2.1 Structure Preserving Energy Functions for AC/DC systems	6
2.2.2.2 Complexity Analysis of Branch Potential Energy	6
2.2.2.3 Stochastic Energy Function for Risk Assessment of Transient Instability	7
2.2.2.4 Discussion on Structure Preserving Models	7
2.3 Transient Stability Analysis Based on Data Mining Technologies.....	7
2.3.1 Decision Tree	7
2.3.2 Support Vector Machine	8
2.3.3 Artificial Neural Network.....	8
2.3.4 Nonparametric Regression Method	8
2.3.5 Discussion on Data Mining Technologies	8
3 Small-Signal Stability Analysis.....	9
3.1 Model-Based Small-Signal Stability Analysis.....	9
3.2 Measurement-Based Small-Signal Oscillation Monitoring	9
3.3 Risk Assessment of Small-Signal Stability	9
3.4 Discussion on Methods for Small-Signal Stability Analysis	10
4 Risk Assessment of Cascading Outages and Blackouts.....	10
4.1 Short-Term Risk Assessment of Cascading Outages.....	10
4.1.1 Cascading Event Searching Based on Fault Chain Theory	10
4.1.2 Risk Assessment of Cascading Outages Considering Protection System Reliability	10
4.1.3 Risk Assessment of Cascading Outages Considering Substation Interior.....	11
4.1.4 Cascading Event Searching Based on Dynamic Simulation	11
4.2 Long-Term Risk Assessment of Cascading Outages.....	11
4.2.1 Long-Term Risk Assessment Method with Slow Processes	11
4.2.2 Long-Term Risk Assessment Method Considering Voltage Collapse	12
4.2.3 Discussion on Long-Term Risk Assessment Methods.....	12
5 Conclusion	12
References	13

Abbreviations

ANN	Artificial Neural Network
BPNN	Back-Propagation Neural Network
CART	Classification And Regression Tree
DT	Decision Tree
EAC	Equal Area Criterion
SDE	Stochastic Differential Equation
SMIB	Single-Machine-Infinite-Bus
SOC	Self Organised Criticality
SVM	Support Vector Machine
TDS	Time Domain Simulation
TSA	Transient Stability Analysis
TSJD	Two-Sided Jacobi-Davidson

1. Introduction

Transient stability, small-signal stability, and cascading outages are three research themes employed for implementing risk assessment and identification of risk-relevant components in smart grids in this project. In this report, novel analysis methods for these research topics will be presented. Firstly, methods for transient stability analysis including stochastic time domain simulation, Lyapunov-based energy function methods, and data mining-based pattern recognition methods will be reviewed in Section 2. Secondly, both model-based and measurement-based methods for small-signal stability analysis will be reviewed in Section 3. Finally, methods for cascading outage prediction and blackout risk assessment under different time frame will be reviewed in Section 4. Methods proposed by participants of this project will be presented and the advantages and disadvantages of all the methods will be discussed in detail.

2. Transient Stability Analysis

Transient stability is the ability of power systems to maintain synchronism when subjected to severe disturbances. Transient Stability Analysis (TSA) is essential to system operation since it can assess the risk of insecurity thereby control schemes can be designed for the timely prevention of blackouts. Methods for TSA include Time Domain Simulation (TDS), Lyapunov-based energy function methods and data mining-based pattern recognition methods. In this section, enhanced methods based on TDS, energy function and pattern recognition will be presented.

2.1 Stochastic Time Domain Simulation

Time domain simulation is the most reliable method for transient stability analysis since post-disturbance response can be obtained by solving a set of differential equations. Considering that traditional deterministic TDS and probabilistic TDS are not able to address the time-varying feature of uncertain wind generation, stochastic TDS is proposed in [1] during this project. By introducing the time-varying wind generation as a Wiener process into the dynamic model for deterministic TDS, Stochastic Differential Equations (SDEs) are thus obtained to study the impact of stochastic wind generation. Monte Carlo simulations are then performed to assess the risk of transient instability of wind-integrated power systems.

Time domain simulation, however, is too computationally intensive for online application. Thus heuristic methods such as Lyapunov-based energy function methods and data-mining-based pattern recognition methods currently attract more widespread attention.

2.2 Transient Stability Analysis Based on Energy Function Methods

Energy function methods were firstly applied to transient stability analysis in the 1980s. The classical model, reduced order model and structure preserving model are three different kinds of system model utilised in energy function methods. Energy function methods with the reduced order model and

structure preserving model have been studied in this project.

2.2.1 Energy Function Methods with Reduced Order Model

The reduced order model is also known as the system equivalent model. Two sets of coherent generators should be firstly identified and then be separately aggregated into an equivalent critical generator and an equivalent stable generator. After that, Single-Machine-Infinite-Bus (SMIB) equivalence is performed and Equal Area Criterion (EAC) is further adopted to assess transient stability.

2.2.1.1 Generator Pair-Wise Potential Energy Function for Online Stability Analysis

During this project, the generator pair-wise potential energy function [2] is proposed to estimate the critical generators and then a quantitative SMIB equivalent energy function is utilised to evaluate the transient stability of a disturbed system. The proposed generator pair-wise potential energy function method can be applied for online stability analysis by utilizing only PMU measurement since it do not rely on a detailed representation of the network model.

2.2.1.2 Discussion on Reduced Order Models

The reduced order model has the advantage of reflecting the physical characteristics of rotor angle stability with compact models, thus the analysis complexity is significantly reduced. However, network structure is lost and load impedance is absorbed into the equivalent reduced network, which results in two shortcomings: 1) it precludes the consideration of reactive power demand and voltage variation at load buses; 2) it reduces the impedance network leading to a loss of system topology and hence precludes the study of how the transient energy varied among different network components.

2.2.2 Energy Function Methods with Structure Preserving Model

To accommodate the drawbacks of reduced order models, the structure preserving model is proposed to consider the detailed models of different system components.

2.2.2.1 Structure Preserving Energy Functions for AC/DC systems

Considering the increasing application of HVDC power transmission, energy function methods are developed for AC/DC systems with a more reliable DC model in [3]. Each DC line is represented as two terminal buses with dynamic loads depending on AC bus voltages and DC line current. Then the energy function for AC/DC systems consists of the kinetic energy of generators' rotors, the potential energy related to the generators' power angles, the potential energy related to the AC transmission system as well as the loads, and the potential energy related to the HVDC system.

2.2.2.2 Complexity Analysis of Branch Potential Energy

During this project, complexity analysis of transient potential energy flow is conducted to study the

dynamic behaviour of power system fault propagation [4]. With the structure preserving model, transient energy of transmission lines is represented by the branch potential energy function. The complexity of potential energy distribution is then analysed based on the multi-scale entropy method. Numerical studies show that unstable fault contingencies result in higher complexities than stable contingencies, thus the complexity of potential energy can be used as an important feature to distinguish the stable contingencies and the unstable contingencies.

2.2.2.3 Stochastic Energy Function for Risk Assessment of Transient Instability

Integration of flexible loads and intermittent renewable generation has led to greater uncertainties in system operation. The stochastic energy function method is also introduced to perform a risk assessment of transient instability in [5]. Considering the random variation of loads as a standard Wiener process, the power system dynamic model can be represented by a set of stochastic differential equations. The structure preserving energy function is then constructed under stochastic Lyapunov stability conditions. Using Monte Carlo simulations, the risk of transient instability can be assessed.

2.2.2.4 Discussion on Structure Preserving Models

Post-disturbance response in the fault phase is only needed for energy function methods to infer stability by comparing the transient energy at fault clearance and the critical energy. However, there are two disadvantages: 1) construction of energy functions should satisfy the necessary conditions for Lyapunov stability, which is not always easy to achieve; 2) the dominant unstable equilibrium point should be identified accurately for computing the critical energy and obtaining an accurate result.

2.3 Transient Stability Analysis Based on Data Mining Technologies

Data mining technologies are able to extract the mapping relationship of a predictive object against critical attributes with massive amount of sample data. These technologies are more attractive when the acquisition of the predictive object requires enormous computation while the critical attributes are measurable. This advantage of data mining technologies provides a real-time stability inference by applying pre-determined mapping rules. Decision Tree (DT), Support Vector Machine (SVM), Artificial Neural Network (ANN) and Statistics Regression Methods are utilised for online transient stability analysis.

2.3.1 Decision Tree

A decision tree is a decision support tool which uses a binary structured tree graph or model to predict their possible consequences. It is grown by recursive splits of the learning cases at its nodes. The fundamental idea of selecting each split is such that the learning cases in each descendant node are purer than the parent node. Different kinds of enhanced DT-based data mining technologies, such as Classification and Regression Trees (CART) [6] and Ensemble Decision Trees [7], have been utilised for

online transient stability analysis.

2.3.2 Support Vector Machine

Support Vector Machine is a general method to solve classification, regression, and estimation problems. Training of a SVM classifier involves constructing a hyperplane that separates the data with the maximum margin of separability and finding an optimal decision function that accurately predicts unseen data into different classes. In [8], post-fault values of generator voltages, speeds, and rotor angles measured by PMU are used as input features for a SVM-based classifier for transient stability status prediction.

2.3.3 Artificial Neural Network

Artificial Neural Network is a kind of data mining technology that mimics the projection procedure of biological neural networks. Consisting of one input layer, one or multi hidden layers and one output layer, ANN is able to deal with nonlinear projections. Since power systems are nonlinear dynamic systems, Artificial Neural Network has shown its great potential for online awareness of power systems. In [9], the initial condition of each generator, load demand, and disturbance ID are selected as inputs for ANN-based transient stability prediction.

During this project, a MapReduce-based high performance Back-Propagation Neural Network (BPNN) is utilised for online transient stability awareness. With this proposed method, data preparation and pattern training can be performed in parallel computing environments, which results in higher efficiency in online computation and analysis.

2.3.4 Nonparametric Regression Method

A composite method which combines nonparametric feature selection and group Lasso regression algorithm is also utilised to extract the mapping relationship of transient stability margin and multiple stability indicators [10] during this project. This method provides an explicit functional mapping relationship between the transient stability margin and multiple stability indicators while DT, SVM, and ANN only provide complex implicit projection structures.

2.3.5 Discussion on Data Mining Technologies

In general, either pre-disturbance conditions or post-disturbance measurements are used as inputs for data mining technologies in transient stability analysis. Regarding the former, inaccurate prediction may be induced by system topology changing and unforeseen disturbances; however, the recognition rules can be easily integrated into preventive control schemes. The latter usually provides a more reliable prediction under any contingencies; nevertheless, it is not able to offer any control strategies.

3. Small-Signal Stability Analysis

Low frequency oscillations have occurred in power systems and led to great blackouts in recent years. Model-based and measurement-based analysis methods are two primary methods for small-signal stability analysis. In this section, both of these methods will be reviewed and discussed. Risk-based assessment methods for small-signal stability will be also reviewed.

3.1 Model-Based Small-Signal Stability Analysis

Eigenvalue analysis is a traditional model-based method for small-signal stability analysis. By linearizing the differential equation at an equilibrium point, a state matrix can be obtained and then oscillation modes can be identified by computing eigenvalues. With the interconnection of large-scale power systems, the order of state matrix increases significantly, which leads to inefficiency for traditional methods such as the QR method. A Two-Sided Jacobi-Davidson (TSJD) method is proposed to address this problem by [11]. Active power deviation in transmission lines is firstly used to determine whether each mode is an inter-area oscillation mode and then the TSJD method is applied to compute the modes that are most-correlated to the chosen system output. The participation ratio is used to separate the electromechanical modes. This method has been successfully applied to practical large-scale transmission systems in China.

3.2 Measurement-Based Small-Signal Oscillation Monitoring

With the deregulation of electricity market, system operators may not be able to access the precise model of generators and transmission facilities. Time-varying operating scenarios may also differ from the one used for offline analysis. These two issues will result in inaccurate estimation of small-signal oscillation. Novel monitoring methods based on PMU measurements and signal processing methods thus provide an alternative.

A two-level oscillation monitoring framework is proposed by [12]. PMU data is firstly used for modal estimations at the substation level based on decentralised frequency domain decomposition and then the estimations are sent to control centre for further analysis to extract system modal properties of local and inter-area modes. Since PMU data are analysed in a decentralised manner, the computation burden for the control centre and the information flow in the communication system are both reduced.

During this project, an identification method for critical oscillation modes based on inter-area oscillation relevant generator contribution factor is proposed [13]. The oscillation contribution factor, which considers the damping properties and the relevant generators of each mode, is firstly defined to rank all the modes; then the modes with higher contribution factors are identified as critical modes. This method has been successfully applied to the Sichuan provincial transmission system.

3.3 Risk Assessment of Small-Signal Stability

Risk-based assessment methods for small-signal stability analysis are proposed in [14,15]. In general, Monte Carlo simulation is firstly performed to generate numerous operating scenarios according to pre-defined probability distribution of uncertainties such as load at buses, power flow through HVDC lines, and power output of renewable sources. Deterministic analysis is carried out to calculate the eigenvalue of critical system oscillations with all the samples. Probability density function for the critical mode damping is determined by statistical analysis. Finally, the risk of small-signal instability can be obtained by combining the severity evaluation and its corresponding probability.

3.4 Discussion on Methods for Small-Signal Stability Analysis

Model-based eigenvalue analysis provides a reliable evaluation of oscillation modes; however, interconnection of large-scale power systems has led to a higher order of state matrix and greater difficulty in eigenvalue analysis. Moreover, offline analysis may not provide consistent mode evaluation because of operating uncertainties. Although measurement-based methods are capable for online oscillation monitoring, measurement noise may induce estimation error as signal processing methods are usually sensitive to noise.

4. Risk Assessment of Cascading Outages and Blackouts

Cascading outages have played a vital role in several blackouts occurred in recent years. Although cascading outages are rare events, the massive loss caused both to the economy and society has attracted the attention of researchers to investigate the risk of cascading outages and blackouts. Depending on time frame, methods for risk assessment of cascading outages can be sorted into two categories: 1) short-term risk assessment based on event searching and 2) long-term risk assessment based on the multi-layer interaction model. In this section, both of these methods will be presented.

4.1 Short-Term Risk Assessment of Cascading Outages

Short-term risk assessment methods focus on searching for cascading events with high probability and evaluating the risk of load loss.

4.1.1 Cascading Event Searching Based on Fault Chain Theory

Fault chain theory of security science has been used to identify the vulnerable transmission sections and search the cascading events of high probability in [16]. A vulnerability index which considers power flow change and overload tolerance of transmission devices is proposed to identify the critical device in each stage of the cascading event and evaluate the outage risk of the critical device. By iteratively searching and tripping the critical devices, the consequence of cascading events can be assessed.

4.1.2 Risk Assessment of Cascading Outages Considering Protection System Reliability

Reliability of protection systems has a great impact on the risk of cascading outages. A risk assessment

method considering detailed reliability models of protection system components is proposed by [17]. Firstly, the reliability of circuit breakers is expressed by a Poisson process of shock magnitude with a common distribution and non-homogenous degradation rate. Secondly, dynamic fault tree based models are established for evaluating the failure risk of each component and then calculating the overall reliability of protective relays. After that, cascading events searching based on interactions of protection systems and load curtailment computation are performed iteratively and finally the risk of load loss is assessed.

4.1.3 Risk Assessment of Cascading Outages Considering Substation Interior

The impact of substation interior is seldom considered in blackout risk assessment. During this project, a hierarchical power system model consisting of equipment level, substation level and power system level is established and then utilised for blackout risk assessment [18]. Thus, the assessment error caused by the terminal substation as an equivalent bus is modified by considering the substation interior configuration, relay protection failure and substation interior equipment failure as a whole. Numerical studies show that blackout risk arises to some degree when the impact of the substation interior and relay protection is taken into account.

4.1.4 Cascading Event Searching Based on Dynamic Simulation

In [17,18], quasi-steady analysis is adopted to search cascading events and assess the risk of blackouts; however, these methods are not able to identify transient events such as generator tripping by out-of-step relays and load curtailment by under-voltage or under-frequency shedding. Thus, the cascading analysis model which involves time domain simulation and event checkers is proposed by [19]. This model overcomes the weakness of quasi-steady analysis but it sacrifices the analysis efficiency because of employing time domain simulations.

4.2 Long-Term Risk Assessment of Cascading Outages

Long-term risk assessment methods focus on computing the occurrence probability of blackouts of different scale and investigating the factors that increase blackout risk.

4.2.1 Long-Term Risk Assessment Method with Slow Processes

Models for long-term risk assessment methods usually consist of two layers of system processes: 1) fast processes for cascading failure simulations, and 2) slow processes for transmission expansion simulations. These models are able to reflect the long-term processes of power systems and verify the Self Organised Criticality (SOC) of power systems. Another benefit of these methods is that they provide a probability estimation of blackouts of different scales and thus the impact on blackout risk of important factors such as transmission expansion strategy and reliability of transmission devices can be studied. Since tree-caused outages have contributed to '8.14' US-Canada Blackout in 2003, the growth of

trees under transmission lines is considered in slow process by [20]. In [21], the impact on blackout risk of renewable energy integration is also studied.

4.2.2 Long-Term Risk Assessment Method Considering Voltage Collapse

To reduce the computation burden, the DC-OPF model is usually utilised in fast processes while the impact of voltage collapse on system blackouts cannot be studied. During this project, a novel simulation framework embedded with AC power flow is proposed [22]. Cascading failure evolution, operating condition variation and systematic upgrade are considered in the cascade trigger layer, operational status layer, and infrastructure upgrade layer, respectively. This method highlights the closely related factors impacting blackout occurrence among operation, scheduling, and expansion perspective and meanwhile identify the vulnerable sections of power systems.

4.2.3 Discussion on Long-Term Risk Assessment Methods

All of these two-layer models are based on quasi-steady analysis and the transient phase is not considered. The influence of this simplification on risk assessment should be further studied and more detailed models should be developed.

5. Conclusion

This document presented a detailed report of some state-of-the-art methodologies for power system stability analysis and risk assessment. Novel methods for transient stability analysis, small-signal stability analysis and risk assessment of cascading outages and blackouts are presented. Meanwhile, some methods proposed by participants of this project are reviewed. The advantages and shortcomings of these methods are discussed.

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