学位論文全文の要約

題　目　Robust Method For Transient Stability Assessment Of Power Systems Based On Energy Functions

(エネルギー関数に基づくロバストな電力系統過渡安定度評価法)

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Recently, transient stability studies target at different problems, such as renewable energy issues and uncertainty treatment, modeling, high speed computation for real-time assessment of system condition, improvement of energy function method, optimal power flow, real-time control of transient stability, etc.

The objective of this thesis is to develop a fast computation method suitable for online detection of the power system state after large disturbances. A preliminary study has shown that the detailed numerical simulation method is useful but very time consuming and therefore not suitable for real time stability assessment. Thus, development of an effective screening method is a crucial task for power system stability analysis.

This thesis presents a solution founded on energy function methods that satisfies both requirements: efficient computation time and sufficient accuracy. It is obtained from a minimization problem and computed as a trajectory that starts from an exit point and reaches a place that is sufficiently close to the Controlling Unstable Equilibrium Point (CUEP). Using this formulation, CUEP is reliably computed by the Newton-Raphson (NR) method as a least square solution. The accurate detection CUEP is a crucial task for estimation of Critical Clearing Time (CCT).　CCT refers to the maximum time that the power system remains stable under fault condition.

The conventional power system model is relevant for the expected circumstance in the next ten years. In Japan, renewable energy penetration is mostly photovoltaic generation, which can be dealt with the conventional power system model. According to the current situation and requirements of power systems, the energy function methods are suitable for these issues.

Thesis features:

1. Overview of Energy function Methods.
2. Modified trapezoidal formula method for power system stability analysis
3. Formulation of critical conditions for the ordinary differential equations for transient stability.
4. Application of Critical trajectory method to the BCU method for “approximated” CCT as a transient energy function method.

5. Improved method for detection of CUEP for power systems transient stability analysis.

6. Critical conditions for transient stability analysis.

7. Application of Critical trajectory method for "exact" CCT.

This thesis consist eight chapters. The content of each chapter is outlined as follows:

Chapter 1 Introduction

In Chapter 1 is given a brief classification of power system stability and the current problems related to this subject. It is described the development of a new computational method for online detection of power system state after large disturbances. The new method is based on energy functions and critical trajectory method. The improvements are summarized and the study objectives are explained. The following outline of all chapters provides navigation to the thesis content.

Chapter 2 Power system transient stability

This chapter describes basic concepts and definitions in relation to power system transient stability analysis. This includes the purpose of the Swing Equation, the concept of Equal-Area Criterion, Numerical Integration methods and Direct methods. The challenges and limitations of the present methods for evaluation of the power system conditions are highlighted and taken into account for the establishment of the new method. Furthermore, the power system model is defined as well as the common assumptions that are used to study transient stability.

Chapter 3 Formulation of Critical Trajectory method

In Chapter 3 is presented the formulation of critical trajectory method and modified trapezoidal formula. Firstly, a basic concept of dynamic behaviors of power system is outlined. It is explained the mechanics and superiority behind the modified trapezoidal formula for the transient stability analysis. In addition, it is termed the boundary conditions under which the critical trajectory obtains solution. Finally, a complete mathematical interpretation is presented in a form of a least square minimization problem for obtaining the critical trajectory.

Chapter 4 An Application of Critical Trajectory Method to BCU Problem for Transient Stability Studies

It is described a new method for obtaining Controlling Unstable Equilibrium Point (CUEP) for transient stability analysis in electric power systems. A minimization problem is formulated to attain CUEP by applying the critical trajectory method to the boundary controlling unstable equilibrium point (BCU) method. The new method computes critical condition for the ordinary differential equation for the transient stability formulated as a boundary value problem. The Proposed method simultaneously computes a trajectory on the stability boundary starting from the exit point reaching CUEP. This trajectory is denoted as critical trajectory in this thesis and the CUEP characteristics are formulated as an end point condition. The effectiveness of the method is demonstrated through simulations for various systems. The performance is judged is in terms of accuracy of the critical clearing times and computational time effectiveness.

Chapter 5 An Robust method for detection of CUEP in Power Systems

It is described a new formulation for detecting CUEP. This is an improvement of the already established method in Chapter 4. The solution is obtained on basis of a minimization problem. The critical trajectory method is applied to the BCU method. The method is combined with new criterion characterized by the potential energy boundary surface (PEBS) property. The new condition improves the robustness of the method by reassuring the situation of the trajectory to lie exactly on the ridge of PEBS. The results show the improved CUEP determination for number of contingencies in which the former approaches fail. It is shown the improved performance for ill-conditioning fault locations and reasonable computational times. The performance of the proposed method is compared with other well-known method which is Shadowing method. The proposed method has almost the same performance as the Shadowing method for usual cases and superior for some big power system models.

Chapter 6 Direct transient stability assessment of stressed power systems

This chapter discusses the performance of Critical trajectory method for power system transient stability analysis under various loading settings and heavy fault condition. This is an evaluation of the established method in Chapter 5. The method obtains CUEP which is essential for estimation of power system stability margins. The robustness and effectiveness of the method are demonstrated via six power system models and five loading conditions. As benchmark is used conventional simulation method whereas the performance is compared with and BCU Shadowing method. This assessment is mainly focused examination of the robustness, accuracy and conservativeness of the stability judgment. Graphical representations are used to summarize the accurateness of the CCTs computation whereas more detailed data provide information in regards to the conservativeness of the method. The results confirmed the robustness and superiority of our method under all conditions as well as the adequacy of the estimated CCTs.

Chapter 7 Critical conditions for transient stability analysis

In this chapter is presented analysis of various end point conditions in order to improve the accuracy of CCT determination. Two new end point conditions are proposed and the evaluation delivered promising results. They describe physical features of the critical trajectory. The condition maximizes the length of the trajectory; the examination showed that critical point (end condition) might be too far from the initial condition therefore such a criterion is included to conditions describing the critical point. The second condition is concerned with the distance within the trajectory in the domain of critical point. We found out that distance is minimum and this characteristic was also added to the boundary value problem. Here the critical trajectory method is applied to the complete power system model whereas in the previous two chapters it use used for an approximate CCT determination of reduced power system model. The minimizing problem is formulated for obtaining the exact Critical Clearing Time without any approximations. It is confirmed that the proposed method can provide the exact CCTs, adequate with the results from the conventional numerical simulations. This application of Critical Trajectory method is more accurate than direct techniques proposed in the previous two chapters whereas the computation times are higher. Nevertheless, the new critical conditions provide valuable progress in regards to predicting the dynamic behavior of power systems.

Chapter 8 Conclusion

The study is summarized and indicated the major achievements. Further, recommendations for future research are discussed in relation to the current study.