



Reliability Evaluation of Renewable Generation Integrated Power Grid including Adequacy and Dynamic Security Assessment

Final Project Report

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Power Systems Engineering Research Center
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Executive Summary

The goal of this project is to investigate a reliability evaluation approach for power systems that are undergoing changes including increased penetration of renewable resources and the associated impact on system dynamic performance. These changes have brought complexities to reliability studies both for resource adequacy assessment and dynamic security assessment (DSA). Adequacy and dynamic security, the two fundamental functions of bulk power system reliability, have been analyzed separately in the system planning practice. With increasing proportion of converter-interfaced generation, the reliability evaluation methodology needs to be revisited to incorporate the evaluation of the resource adequacy as well as the adequacy of stability control capability. It is also recognized that traditional deterministic methods are not capable of addressing the increased sources of uncertainty. Alternatively, probabilistic methodology is inherently more suited to represent stochasticity and therefore is the analysis method of choice for reliability evaluation in this project.

A probabilistic reliability evaluation approach with adequacy and DSA integrated in a single framework is developed in this research. The research investigates the techniques for adequacy assessment and DSA, developing the quantification metrics for the assessment results that provide a solution to integrate adequacy assessment and DSA in an integrated framework. The sequential Monte Carlo Simulation (MCS) is selected as the analysis method as it is well suited for the analysis of large systems and is capable of considering time-vary characteristics in systems. The use of MCS for the assessment of a large number of cases can be time consuming, therefore, acceleration methods for the integrated reliability evaluation process are investigated to improve the practical application of the approach.

This report consists of three parts. Part 1 studies the assessment methods of resource adequacy and dynamic security, as well as the MCS framework to integrate the resource adequacy assessment and DSA. To improve the computational efficiency, an acceleration method for MCS and a contingency pruning process for DSA, are developed and implemented as part of the integrated reliability evaluation approach. As a proof-of-concept, the proposed approach is demonstrated on a synthetic test system and the simulation results illustrate the efficacy of an integrated reliability evaluation approach. Part 2 is focused on improving the speed of computation by using machine learning. A time-consuming operation in the adequacy assessment is the use of OPF to evaluate if in a given state the load can be satisfied. It is shown that machine learning can successfully replace OPF for this purpose. Part 3 is a study on the characteristics of the Importance Sampling. This part provides a compact reference to Cross Entropy based Importance Sampling and studies the sensitivity of computational efficiency provided by it under various situations. This can provide some guidance under which conditions it is advantageous to use this variance reduction technique.

Part I: Integrated Reliability Evaluation including Adequacy and Dynamic Security Assessment

Power system reliability assessment includes two aspects: adequacy and security. The purpose of adequacy assessment of a power system is to ensure that there are enough generation and transmission resources to supply the aggregate electric power and energy requirements of the electricity consumers while taking into consideration scheduled and reasonably expected,

unscheduled outages of system components. Security assessment, on the other hand, focuses on the ability of the electric system to withstand sudden disturbances or unanticipated loss of system components. Both system adequacy and security are considered essential to provide the desired level of reliability of power systems but the two aspects are traditionally treated separately in practice.

In this part of the report, an integrated reliability evaluation combining both adequacy and dynamic security using a probabilistic approach is formulated and tested. With an integrated reliability evaluation, not only is the reliability of the post-contingency stable equilibrium point (SEP) assessed but also addresses the DSA related issue of whether a stable transition to a post-fault SEP can be achieved. The approach evaluates the system response for each selected contingency, examines transient stability in the transition from the pre-contingency to the post-contingency period, and finally evaluates the post-contingency steady-state equilibrium to ascertain that all flow limits and voltage limits are satisfied. Stochastic characteristics including renewable resources, component failures, and load variations are taken into consideration in probabilistic sampling and dynamic performance modeling. System adequacy and dynamic security are quantified in terms of MW load curtailment from the respective assessment processes and are incorporated into the calculation of the integrated reliability indices. The outcome of the integrated reliability evaluation provides the probability, frequency, and magnitude of system loss of load.

There are two important steps in the integrated reliability assessment; 1) the methodology for system state generation and 2) the technique used for state evaluation to determine the reliability indices. MCS provides a framework of probabilistic analysis based on modeling the stochastic characteristics in the system. Each system state sampled from MCS consists of generator and transmission contingency information and the system pre-contingency steady-state operating condition. The impacts of a contingency on system adequacy and dynamic security are assessed using optimal power flow (OPF) analysis of the post-contingency steady-state condition and time-domain simulation for examining the dynamic behavior, respectively. The procedure for each step is as follows:

- In each iteration of the sequential MCS, the system states are generated and incorporated with an annual 8760-hour load curve and wind speed curve. State evaluation is then conducted for each state to determine both the adequacy and the dynamic security. Dynamic security is first evaluated. When dynamic security evaluation indicates that there is a stable transition to a post-fault stable equilibrium point (SEP), the adequacy assessment is then conducted to evaluate the post-fault steady-state condition. A state is seen as a successful state only if it is steady-state stable and transiently stable. The duration time and load curtailment of all failure states are then utilized in the calculation of integrated reliability indices. Loss of load probability (LOLP), expected power not supplied (EPNS), and loss of load frequency (LOLF) are used to quantify the integrated reliability. After each iteration of the SMCS, reliability indices are updated. The coefficient of variance (COV) is calculated after each SMCS iteration to determine the convergence. The final reliability indices are obtained after the MCS converges.
- The adequacy assessment addresses the steady-state system condition after a contingency. Power flow analysis is used to assess system steady-state conditions. Considering realistic power system operating limits, AC power flow is used as the steady-state analysis technique in this work to take into consideration both bus voltage magnitude and thermal limits of transmission components. When the AC power flow results show that there is a violation of

operating limits, an AC optimal power flow (ACOPF) with remedial actions including generation rescheduling and load curtailment is deployed to optimally correct the abnormal system conditions. The remedial actions, first prioritize generation rescheduling, without curtailing any load. If the operating constraint violations still exist, remedial actions with load shedding capability are then applied. The minimum amount of load shedding that is needed to alleviate operating constraint violations is determined from the AC OPF study. In this work, the OPF package in PSS/E is utilized to solve this optimization problem.

- While adequacy studies evaluate post-contingency steady-state conditions, the DSA estimates whether the system can transition to an acceptable stable equilibrium point after a contingency. Time-domain simulation (TDS) is widely recognized as the most accurate method to describe power system transient behavior and therefore is the method of choice to perform the DSA in this work. As a result of the enhanced component modeling capabilities in TDS, critical protection systems can be modeled and their resulting actions can be simulated in the TDS. The protection systems that activate generator tripping and load shedding are represented such that following a contingency the action of these critical protections systems renders the power system to be transiently stable. Considering the requirements from the North American Electric Reliability Corporation (NERC) Protection and Control (PRC) standards, to stabilize the system, the protection systems include under-frequency load shedding, over frequency and under frequency generator tripping, over voltage and under voltage generator tripping are considered, and dynamic security is quantified by the MW load shedding due to security preserving corrective protection action.

The proposed integrated reliability evaluation procedure has been tested on a synthetic power system, which is generated to represent the realistic test system comprising of Ontario and upstate New York. The test system consists of major features of a realistic power system for transient stability and reliability studies for system planning. Compared to the traditional reliability evaluation which evaluates the adequacy and dynamic security separately, the proposed method provides the reliability indices reflecting both adequacy and dynamic security based on the quantification of the two aspects of reliability in terms of load curtailments. The quantification of the impact of dynamic security is included by the load curtailment from protection action to maintain system stability after contingencies. By including the value of load curtailment into the calculation of reliability indices, the integrated system reliability can be represented using the well-recognized reliability indices which are LOLP, EPNS, and LOLF. The results from case studies show the importance of considering the two reliability aspects together since both the steady-state and transient system performance need to be analyzed in reliability studies. Also, the two acceleration methods are verified with significant improvement of the computational efficiency. In practical applications, further methods can be explored to further reduce the computational burden.

As an outcome of this project, a research-grade software has been developed to implement and demonstrate the proposed approach.

Part II: Deep Learning and Multi-Label Learning Based MCS Methods for Composite System Reliability Evaluation

The preferred technique for composite power system reliability evaluation has emerged to be the Monte Carlo Simulation. However, this method can be quite computation intensive especially for

high reliability systems. This is because for high reliability systems it takes longer time to collect enough samples with loss of load to calculate the reliability indices. This part of the report is focused on exploring the use of machine learning to improve the computational efficiency of the composite system reliability evaluation.

The reliability evaluation is performed in three phases. In the first phase samples are generated, in the second phase the samples are evaluated to determine if a problem exists and then this information is used in the third phase to find estimates of reliability indices. Most of the computation effort comes from the first two phases.

The computational effort coming from the first phase has been addressed by the use of Importance Sampling which appears to be a good tool for sampling from a distorted distributed with lower variance. In the second phase for adequacy evaluation, the time-consuming part is the optimal Power Flow whether DC or AC Power flow is used. This report is focused on exploring the use of machine learning to replace the OPF. The following results have been obtained.

- A novel method to evaluate reliability indices for composite power systems is introduced with a combination of MLL and MCS. The proposed method is implemented for MLKNN and MLRBF classifiers to identify status of buses. The case studies show that the method significantly reduces the computational burden of MCS without sacrificing accuracy. Additionally, this method advances the state of the art of using machine learning in power system reliability evaluation from the previous methods by including computation of bus indices and the transmission line failures. Moreover, the work done shows that the proposed method can be combined with the well-known variance reduction technique of IS. The outcomes for this approach show this methodology improves time efficiency of MCS even further.
- Deep learning structures are investigated to evaluate composite system reliability evaluation through MCS. A well-known deep learning topology, CNN, is implemented to characterize sampled system states for both AC and DC flow models. The results show that computational efficiency for classification using AC flow model is much higher than DC flow model since AC flow equations require nonlinear programming techniques while DC flow equations can be solved with linear techniques. The results obtained show that the proposed architecture performs state characterization with a high accuracy with COV equal or less than .01. The computation time is dramatically reduced.
- This study demonstrates that the application of the proposed machine learning methods on composite power system reliability evaluation accurately determines the system status with a substantial speed up compared with OPF based Monte Carlo Simulation methods. At the same time the accuracy is not sacrificed.
- Using machine learning to enhance the process of dynamic security assessment as well as the OPF should be investigated further. Then perhaps the Time Domain Simulation could be used to train CNN to replace this time consuming operation. This could make the inclusion of security assessment in composite reliability assessment computationally efficient and attractive to users.

Part III: Using Importance Sampling in Monte Carlo Simulation - Computation Time Sensitivity Studies

The results obtained by Monte Carlo are only estimates of true values and not the true values. Therefore the estimates have a variance. The estimates approach the true values as the variance of estimates is reduced by increasing the sample size. Importance sampling helps further by reducing the variance of the estimator and thus a smaller sample size is needed to get the same coefficient of variation. The coefficient of variation determines the gap between the upper and lower bounds with a given level of confidence. The smaller the coefficient of variation, the tighter are the bounds around the true values. The main advantage of using variance reduction technique of Importance sampling is the reduction in computational time. This section explores the conditions under which the computation time is reduced more favorably by implementation of Importance Sampling and thus it becomes advantageous to use this variance reduction approach. It is shown that in general, the conditions which lead to higher computation time for the straight MCS tend to favor the use of Importance Sampling for relatively higher reduction of computation time by reducing the variance of estimates. The conditions which lead to higher computation time are either the ones that lead to higher reliability, i.e., lower loss of load probability or the ones where tighter bounds on estimates are needed to have higher confidence in the estimated results.

Project Publications:

- [1] Y. Wang, V. Vittal, M. Khorsand, C. Singh. (2019). Probabilistic Reliability Evaluation Including Adequacy and Dynamic Security Assessment. IEEE Transactions on Power Systems. PP. 1-1. 10.1109/TPWRS.2019.2923844.
- [2] U. Dogan, C. Singh and V. Vittal “Importance Sampling using Multi Label Radial Basis Classification for Composite Power System Reliability Evaluation.” IEEE Systems Journal (Under Publication).
- [3] U. Dogan, C. Singh “LSTM Networks to Evaluate Composite Power System Reliability Evaluation with Injected Wind Power” 2019 IEEE Power & Energy Society (PES) General Meeting.
- [4] U., Dogan, and C. Singh. “Power System Reliability Evaluation using Monte Carlo Simulation and Multi Label Classifier” National Power Systems Conference (NPSC). 2018.
- [5] S.K. Bavajigari, C. Singh, “Investigation of Computational Advantage of using Importance sampling in Monte Carlo Simulation”, NAPS 2019.

Student Theses:

- [1] Yingying Wang. Integrated Reliability Evaluation including Adequacy and Dynamic Security Assessment. PhD Dissertation, Arizona State University, Expected: August 2021.
- [2] Dogan Urgun. An Investigation on Deep Learning and Multi-Label Learning for Composite System Reliability Evaluation. PhD Dissertation, Texas A&M University, February, 2019.