Abstract

Reliability Assessment of Protective Relays in Harmonic-Polluted Power Systems

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In a great majority of bulk power system reliability studies, protection systems are assumed to be perfect. Substations are generally simplified to buses, and different transmission lines converge at those buses to connect generators or to serve loads. Most system interruptions are attributable to equipment outages or security problems in transmission and distribution systems. Reliability software tools deal with equipment outages only and on a very rare occasion, security issues related to operation of a protection equipment form a part of the analysis. When this happens, system models are very much simplified, mostly due to lack of appropriate data.

Stochastic Markov chains need transition rates which are usually obtained from statistical studies on a particular object, through observation of its performance. In an ideal case, such approach demands a supervisory software, tracking the actual states of power system components. It often happens, though, that the information about exact cause of a device failure is missing or the software itself is not recording all the data, needed in the process of reliability evaluation. In the past, the reliability-driven computer programs were not even implemented. Reliability of protective systems has been provided by careful design, based on sound judgement of experienced engineers. In most cases, this method served very well and low failure rates of power systems show that the protection automation has been carefully designed, commissioned and controlled. On top of that, advanced mathematical tools have been recently applied as an extension of a descriptive reliability evaluation for protective system engineers. Today, the use of fully automated, central database with the capability of making decisions or reliability evaluation is gaining in importance.

Usually the residence intervals in various states of power equipment are known, yet information about the number of transitions from one state to another is either missing or incomplete. This is mainly caused by a difficulty in recording of the state changes in the protection equipment or poor data acquisition and recording by power utilities. The transition rates are key parameters in all power system reliability models. Partial information on protection systems poses a challenge to construct or complete a transition rate matrix for reliability assessment. The dissertation addresses the issue of reliability evaluation of protective relays, operating in harmonic-polluted environment. It presents a solution

to the problem of finding transition rate matrix for a Markov chain of a simplified digital distance relay model. In this approach, the power system network and its associated protection is designed in a graphical preprocessor to Alternative Transients Program (ATPDraw). Parametric simulations of different circuit topologies during nominal and fault conditions are executed, processed, and analyzed automatically through batch and MATLAB scripts. Statistical calculations are implemented to obtain reliability parameters. An example is used to demonstrate the interactive protection system simulation, developed using the new approach.

Proliferation of distributed generations (DGs) and power electronics-based loads is bringing about more harmonic-polluted power signals. While some failures may occur as a consequence of non-sinusoidal current or voltage waveforms, existing reliability models of protection relays have not taken the harmonic-related failures into consideration. This thesis develops a comprehensive Markov reliability model to categorize the possible functional states of a component, say a transmission line, protected by a relay, operating in harmonic-polluted environment. In order to make the proposed model practically tractable, it is further simplified in two ways, through merging the states of the same consequence. The first simplified model focuses on the power component reliability assessment; while, the other is built for reliability analysis of a protection system. Calculation of the transition rates and how the resultant model is mathematically evaluated are then discussed. Numerical analyses and outcomes are based on the real-world data taken from Canadian substations. Accordingly, the results and conclusions drawn in this dissertation would be interesting to both academia and industry. Moreover, the proposed reliability assessment methodology is readily applicable in scrutinizing the impacts of harmonic pollution on the protection devices of other power components.

The main aspect of the dissertation has been to show, how the simplified Markov models with harmonic contents can be used in the small area reliability studies. The effect of harmonics-polluted signals on system reliability indices has been investigated. Moreover, simple steps have been proposed to facilitate the calculation process of harmonic-related transition rates. Therefore, the emphasis has been on modeling aspect with an interesting real life system example, but with artificially increased component failure rates. It should be remarked that the proposed models are general and can be readily applied to real-life systems, if the required data is available.

Bulk power system reliability depends on the reliability of all components: sources, junctions, feeders, transformers, protection equipment, circuit breakers, etc. Although, the majority of these elements have been evaluated in terms of dependability and security, the protection system assessment, as a whole, has not been well developed. Complex mathematical models, available in a literature are difficult to apply in power system reliability studies, due to the lack of data required to determine all model transition rates. This thesis proposes a simple solution, first to address the basic states of a protective relay operation, second to find the missing transition rates for the steady-state probability calculations and then to address the problem of harmonic components in distribution and transmission systems. Harmonics, as demonstrated in this dissertation, decrease the reliability of power system automation and indirectly affect the reliability of a bulk electric power system. The expansion of the proposed generic protection model and the use of the aforementioned

technique for evaluation of Markov models with incomplete data, provides a new solution for the reliability evaluation of protective relays. An emphasis has been put on the need to simplify complex Markov models of the protection systems, in order to apply them effectively in power system reliability studies.

The reliability evaluation of a transmission system, in terms of delivery point interruptions, caused by component outages, is the leading topic of the dissertation. The analysis is conducted, taking into account relaying system failures and harmonics. Moreover, the experimental and industrial relays are tested and simulated to assess hardware and software vulnerabilities to higher harmonic contents. Based on those studies, the stochastic reliability Markov models are developed and used in the sensitivity evaluation of the practical power systems. The solution to the missing transition rates of the stochastic chains is proposed and the custom-made software, utilizing the EMTP computation engine, is demonstrated.

Although, there are several very comprehensive models for protection system reliability evaluation, the focus of this dissertation is on practicality of their application in the small area reliability studies. To the best knowledge of the author, this is the first attempt to use simple Markov models with harmonic aspect in conjunction with small area reliability studies. It is also the first time such models are coupled with simulations which give reliability indices for particular components.

There are two major scientific novelties presented in this dissertation. The first, aforementioned, is the new paradigm in reliability analysis which combines the performance of a protection equipment, subjected to polluted signals, and small-area reliability concepts into a single application. By far, each aspect of the system operation has been analyzed separately. The second is an EMTP-ATP- and MATLAB-based software tool, developed to evaluate a protective relay status. The computer program (RelWare) utilizes Markov state transition models. The thesis deals with the issue of incomplete data that many engineers and scientists found a frequent problem while consulting with the industry. The dissertation provides a review of the state-of-the-art work, and proposes its own contributions.

Conducted research enabled the formulation of the following theses:

I. It is possible to determine the reliability of power system protection relays by tracking their performance and calculating the probability of relay maloperation under fault conditions and during normal operation in a harmonic-polluted environment.

II. It is possible to combine the results of the experimental research on protective relays with the reliability analysis of a fragment or bulk electric power system.

Results, presented in this dissertation, rely on the accuracy and completeness of the compiled data. In terms of the developed Markov models for the evaluation of protective relays in harmonic-polluted environment, it is assumed that harmonic production pattern of non-linear loads is stationary and does not change over time. This is a reasonable assumption and does not pose serious limitations on the applicability of the proposed model. Therefore, it is inferred that the harmonic-related failures of the protective relays are also stationary and they can be analyzed using stochastic Markov chains. If this criterion has not been met, the basic Markov modeling approach would not be applicable anymore and alternative methods appropriate for systems with non-exponential distributions should be employed in this regard.

The dissertation is organized as follows. Chapter 1 is the introduction and the abstract of the present thesis. Chapters 2 and 3 give basic information about the state-of-the-art protections and the reliability analysis. Chapter 4 is a comprehensive literature review of the topic of harmonics in distribution and transmission systems, with details, concerning the typical distortions and imposed standard limits, in the Appendix. Chapter 5 covers the analysis of the effects of harmonics on the electromechanical and microprocessor-based relays. The information about the utilized custom-build device of the M.Sc. thesis in electronics is available in the Annex. Chapters 6 and 7 concentrate on the practical aspects of the work: the stochastic Markov models and the acquisition of the reliability indices for protective devices, respectively. The program and the models' codes, developed for the purpose of the dissertation are attached to the document.

Keywords: electromechanical relay, EMTP-ATP, failure analysis, failure rates, frequency balance approach, harmonics, MATLAB, minimal cut sets, overcurrent protection, phasor estimation, power system reliability, protective digital distance relay, PSCAD, reliability analysis, RMT, series and parallel resonance, stochastic Markov model, transition rates, WinAREP.