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REVIEW ARTICLE

STEADY STATE SECURITY OF A POWER SYSTEM AS A SURVEY BY CONTINGENCY ANALYSIS

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ABSTRACT

The robustness of power systems can be ensured by steady state security regarding power grid contingencies based on a steady state model. An overview of contingency analysis methods which consider steady state security of power system with stability margin index is provided in this paper. Traditional methodologies of contingency analysis for power systems, steady state security include full AC power flow analysis, approximate methods and contingency ranking. Methods are investigated to speed up the full AC power flow algorithm and improve the accuracy of approximate techniques. The indices for contingency ranking, such as performance index and voltage stability margin, are discussed in detail.

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INTRODUCTION

With the increase of power grid interconnections and the penetration of intermittent energy resources, modern power systems have become increasingly more complex and dynamic. Moreover, because of economic benefits and widespread transmission expansion, power systems have been forced to operate closer to their stability limit. If localized outages in one or more items of equipment violate the stability limit, the system may respond by a cascade of outages and even a system blackout. Therefore, security analysis has become an important tool to assess the stability of a power system under component outages and topological changes. The dominant approaches that can be categorized in terms of failure lasting time, are steady state and dynamic security analyses. Contingency analysis is included in both categories of power system security analyses. This paper focuses on contingency analysis in the context of only the steady state security category. In 1978, Dy Liacco adopted a deterministic framework for power system security analysis based on a steady state model. In Dy Liacco's framework, the power system security in the presence of contingencies is determined using optimum power flow (Liacco, 1978). In 1987, Stott *et al.* considered steady state security assessment as a violation detection process under actual operating states and contingencies (Stott *et al.*, 1987). In 1992, Balu *et al.* proposed that the main purpose of security assessment is to determine the security of the power system with respect to contingencies (Balu *et al.*, 1992). In 2004, IEEE/CIGRE defined power system security as the degree of risk to survive contingencies without interruption of customer service (Kundur *et al.*, 2004). The prior research establishes that historically contingency has been considered as an essential part of security analysis. It is therefore of value to undertake a review of contingency analysis studies regarding power system security. For succinctness of exposition, the scope of this work is constrained to the steady state security analysis. The ensuing sections present a comprehensive review of the literature on contingency analysis since 2000, covering various methods and techniques which are of great interest to researchers and engineers. In Section II, the definition and research history of contingency analysis are presented. Special approaches for contingency analysis in the security planning stageare reviewed in Section III. Traditional approaches to contingency analysis for steady state security of power systems are discussed in Sections IV, including full AC (alternating current) power flow methods, approximate methods, and contingency ranking methods. Section V presents conclusions and discusses future research needs.

Contingency analysis

Contingency is an operational outage in one or more devices, such as transmission lines, generators, and transformers. Contingency analysis is the process to anticipate what might happen to a power system in the event of unplanned component outages or topological changes.

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A. Historical Methods for Contingency Analysis

The simplest form of contingency analysis consists of a full AC power flow computation for each considered outage. This method, which could calculate a power system's MW flows, MVA flows, and bus voltage magnitudes after outages, is time-consuming because hundreds of branches need to be considered in practice even for a small power grid. However, contingency analysis should preferably be executed in real-time, because corrective control operations must be taken as soon as possible after a contingency occurs. Hence, several methods have been proposed involving a compromise between calculation speed and accuracy. The Power Flow Decoupled Method (Wood and Wollenberg, 2012) is sometimes adopted to resolve this conflict, but this technique is only slightly faster than the full AC power flow approach with similar accuracy outcomes. The search for faster solutions has been a significant preoccupation in the literature. Approximate contingency analysis methodologies have been used over many years. These methods implement approximate but quicker algorithms. Examples include the DC (direct current) load flow or the sensitivity based method. DC load flow can improve computational efficiency by only calculating branch MW flows, but there are large computational errors which are realized under reactive power flow or bus voltage magnitude violations. The sensitivity based voltage security analysis methods are proposed to solve this problem. In some cases, some form of full AC power flow should be used to ensure high accuracy. For the purpose of avoiding checking all possible cases, only critical cases are selected and calculated. These methods are offered under various names, such as "contingency selection", "contingency screening", "contingency clustering" or "contingency ranking". Besides this, the development of high performance parallel computing and faster processors makes it possible to run thousands of contingency power flows in parallel. Finally, the application of artificial intelligence (AI), such as neural networks, fuzzy theory, and intelligent algorithms, makes it conceivable to obtain faster solutions without requiring a specific model of the power grid. AI has proven to be particularly popular in contingency analysis area during recent years. Due to space constraints, these approaches are excluded from this article.

Contingency analysis in planning stage

The steady state security of a power system should be considered in both planning and operation stages. The planning stage includes construction and operation planning. Contingency analysis is widely adopted in both stages to ensure power system security. In the construction planning stage, the power grid is designed to withstand contingencies by means of a proper grid structure. In the operation planning stage, contingency lists should be selected as pre-knowledge for operators to inform them about the situations that will ensue after foreseeable power grid outages.

A. Contingency Analysis in Construction Planning Stage

Whenplanningandconstructingapowergrid, contingency analysis becomes critical to modeling success and risk quantification of the network. The deployment of power system components, such as generator deployment and optimal installation of flexible AC transmission systems devices etc., is fundamental to power system modeling. A risk based contingency analysis that takes into consideration event probability for transmission and substation planning, is developed in (Song *et al.*, 2009). The risk evaluation of contingency can be represented by an inverse curve that uses the probability of contingency as the x-axis and event consequence as the y-axis. The authors in (Chen *et al.*, 2014) develop the expansion of transmissions and generations in an electrical network at a minimum cost, considering contingency constraints. One algorithm based on Bender Decomposition (Benders, 1962) has been applied to solve the exponential increase of the number of constraints with rising problem size. Another algorithm based on implicit contingency screening has been employed to avoid combinatorial explosion. The proposed method is promising in contingency-aware transmission and generation expansion. The study of network reconfiguration under N-1 contingencies, including wind power and energy storages is presented in (Meneses de Quevedo *et al.*, 2015).

B. Contingency List in Operation Planning Stage

During operationplanning orpre-dispatchoutage assessment, contingency analysis is required for assessing power system behavior in the presence of disturbances to help initiate necessary control operations intended to maintain power system security.Traditional contingency analysis which calculates all possible failures in a power grid, is highly time-consuming. In (Echavarren *et al.*, 2005), a continuation and optimization based algorithm is adopted to detect static power flow infeasibility under a given contingency hypothesis. The proposed algorithm chooses the maximum contingency convergence margin as infeasibility index to detect the feasibility of a given contingency hypothesis. The proposed algorithm has potential for contingency planning under highly-loaded scenarios.

Contingency analysis on steady state security

It is clear that a power grid is a complex network consisting of numerous elements. Failure of any of these components may lead to power grid insecurity. Contingency analysis allows an electrical system to be operated defensively. It could help an operator act fast enough after contingencies in order to prevent cascading failures. Traditional contingency analysis methods for steady state security include full AC power flow methods, approximate methodologies, and contingency ranking. Some researchers consider and evaluate only a specific type of outage, for example, branch outages. Others merely evaluate post- contingency voltage, and are not interested in a ranking list. A number of publications focus on contingency ranking, but contingency evaluation is not included. Other papers merge all these concerns into one process.

A. Full AC Power Flow Methods

The goal of a full AC power flow study is to obtain the angle and magnitude information for the voltage of each bus in a power system for a specified load, generator power and voltage conditions. Gauss-Seidel and Newton-Rhapson (N-R) algorithms are commonly employed to obtain complete voltage information for each bus on digital computers with an acceptable error tolerance (Wood and Wollenberg, 2012). The Newton power flow is the most robust algorithm used in practice. Fast decoupled load flow (FDLF), which only considers the relationships between reactive power and voltage, and between active power and voltage angle, is an efficient method to calculate power flow. However, it is obvious that

FDLF is not the same as full AC power flow in terms of high accuracy (Vijayvargia *et al*., 2016). A decoupled power flow analysis is carried out by Hazarika *et al*. (2006) to determine line outage contingency, taking into account system islanding. An FDLF based topology processor is applied to determine the status of each island. This paper gives referable information on line tripping contingency analysis including the effect of islanding.

B. Approximate Methods

Instead of using full methods, approximate techniques with a compromise on accuracy and conceivably with speed gains have been proposed to find solutions in a faster fashion. There are several efficient ways to approximate full power flow with less calculation time. A simple approach to approximate active power is DC load flow. Other methods, such as sensitivity based method/ distribution factor method or linear active power flow method were widely adopted at the end of the nineteenth century. However, with the increasing complexity of power grids, active power flow methods alone are no longer effective nor accurate for contingency analysis. The reasons for their shortcomings are that they do not consider the QV components, which can result in considerable errors, due to both the non-linear relationships among the variables and the fact that the operation reaches the generator limits. Since power systems are being required to operate dangerously close to their stability limits, voltage stability problems deserve special attention. The linearized reactive power flow equation is the simplest method for voltage magnitude and reactive power flow calculation. Nevertheless, it suffers from relatively low accuracy because of the use of a linear model as well as linearized inter-variable relationships. Aydogan *et al*. (2003) combine a reactive power linear model with a bounded-network technique to solve branch outage problems. The bounded network solution concentrates only on the sending and receiving ends of the outage branch. Load bus voltage magnitudes calculated from linear models are later improved by minimizing all reactive power mismatches between the sending and receiving buses. The accuracy of this method is relatively better compared to the simple linear reactive power model. The application of linearized power flow equations does not require excessive computation time. This makes the proposed method hold great potential to be applied on-line.

C. Contingency Selection Methods

Contingency selection is an effective approach for identifying the most severe outages in an electrical network while incurring low computational costs. All the traditional approaches, such as N-R power flow or the approximate methods, are widely adopted in contingency selection. In addition, varying performance indices and voltage stability margin-based methods have developed rapidly in recent decades with a focus on contingency ranking.

1) Performance Index

The performance index (PI), which describes how much the parameter deviates from steady state, is a conventional way to estimate the effects of various contingencies on system security. In (Sekhar and Mohanty, 2013), Sekhar and Mohanty studied power system contingency ranking using a performance index based on N-R power flow. The contingencies are ranked by both active power performance index and voltage performance index (PIv). In this scenario, the inclusion of reactive power limitation when calculating PIv is particularly helpful on improving ranking accuracy. The calculation of performance index using the N-R load flow method yields a criterion for measuring the severity of possible contingencies in a power system. Additional contingency evaluation should be developed based on selected contingencies. The PI is adopted to analyze the effect of line outages on voltage stability and maximum loadability in power system (Naik *et al*., 2015). Both the active power performance index (PIP) and the reactive power performance index (PIV) are computed to identify severe line contingencies. Static voltage stability is studied by increasing the load on the load bus to the maximum loadability limit, accompanied with the most severe line contingency. The authors offer the observation that the maintenance of voltage stability under the most severe line contingencies requires additional reactive power compensation. However, different ranking lists based on separately calculated PIV and PIP values make it difficult to decide which one is the superior choice. An adaptive evaluation criterion is required to determine which PI performs better under specific conditions.

2) Voltage Stability Margin

A contingency event is a major concern in power system voltage stability analyses, as unexpected outages may lead to voltage instability and even to voltage collapse. However, it is unnecessary and impractical to analyze all possible contingencies. Therefore, appropriate voltage stability criteria should be adopted to identify the most critical outages in terms of voltage stability. The margin between the current operating point and the voltage collapse point is the most commonly used indicator for this purpose. Most of the proposed contingency analysis methods in the literature are based on this indicator. The tangent vector norm is an effective technique for contingency ranking under a voltage stability point of view, as the norm tends to infinity when the operating point approaches a bifurcation point. De Souza *et al*. (2003) monitor the tangent vector norm associated with each contingency. Contingencies with the largest norms are identified as the most critical. This method may be applied for on-line voltage security assessment because the tangent vector norm is calculated in a numerically inexpensive fashion. The disadvantages of this method are that a single index may lead to erroneous conclusions and that reactive power reserve has not been considered. In (Zambroni de Souza *et al*., 2011), a combined index is proposed for contingency ranking based on mixing QV and PV curves. First, the tangent vector and QV curve are applied to identify critical buses. Then, the reactive power margin and a post-contingency load margin are calculated using a continuation power flow (CPF) and a QV curve separately. A constrained reactive implicit-coupling method is used to accelerate the calculation speed. Finally, system reinforcement is done considering both the load margin and the reactive power reserve. With the proposed mixing method, the critical buses of the system can be determined, the most serious contingencies can be ranked, and the most important reinforcements can be implemented. However, to avoid non-convergence problems, particular attention should be paid to the parameter chosen when calculating the post-contingency load margin using CPF. The continuation parameter chosen problem is the subject in (Matarucco *et al*., 2014), which presents a branch outage contingency analysis under steady state conditions using the continuation method. This novel method calculates the post-contingency loading margin starting from base case with maximum loading point. The voltage magnitude of the bus that presents the largest voltage magnitude variation rate during P-V curve change is selected as continuation parameter. A criterion for parameter change is used in this method to ensure the convergence of CPF when analyzing transmission lines or transformer outages. The application of the proposed method on IEEE test systems shows a significant reduction in the number of iterations. The main advantage of the proposed method is that the contingencies are efficiently analyzed after straightforward modifications of the continuation method. Besides the continuation power flow method, some other methodologies have been applied for voltage stability ranking. An improved method derived from a generalized curve fit (GCF) approach is proposed by Jia and Jayasurya (2000) for estimating the voltage stability margin for each contingency. The GCF method is modified through the selection of fitting points.

The proposed combination of performance indices has five PI functions in total. Two are traditional performance indices. Another three PI functions are defined in terms of a voltage stability index and associated weighting factors based on exhaustive tests. The voltage stability index is derived from the root discriminant analysis of quadratic equations of branch power flow. The final ranking list is the union of the five ordered PI lists. Post-contingency voltage stability margins are calculated by CPF as a reference. The merit of this approach is each PI favors certain severe contingencies, and the union of PIs may successfully identify all severe contingencies. In (Akorede *et al.*, 2009), a voltage collapse proximity indicator (VCPI) method that considers voltage security is employed to accomplish the screening and ranking of critical load buses and system branches.

3) Sensitivity Analysis

Sensitivity analysis is not only proper for power flow calculation, but also available for contingency ranking. A new λ/MVA sensitivity ranking algorithm of branch contingencies is presented in (Flueck *et al.*, 2002) for voltage collapse analysis. Instead of ranking contingencies based on voltage deviations, the proposed method directly ranks saddle-node bifurcations to solve the problem. The new λ /MVA sensitivity ranking algorithm is efficient and accurate in estimating all single- branch contingencies. Amjady and Esmaili (2005) develop a new sensitivity-based method for voltage contingency ranking. Sensitivity of the load stability margin with respect to contingency is considered as a severity index for voltage contingency ranking. The proposed severity index calculation is applied to diverse types of voltage contingencies, including islandingandnon-islanding,unstableand generator contingencies. The proposed method can save calculation time while preserving accuracy.

4) High Computing Environment

Following the development and commercial availability of GPUs (Graphics Processing Units), parallel computing has been successfully applied to accelerate the calculation speed of static contingency analysis. The approach can be used to enhance the computation efficiency of various power flow methods, such as full AC power flow, fast decoupled load flow, DC power flow, and continuation power flow technique. Ezhilarasi and Swarup (2009) employ a parallel processing approach for PI calculations for each contingency based on full AC power flow. Task allocations with a parent and child process are used to implement parallel contingency analysis. Data communication is performed through the Message Passing Interface (MPI). This enhances the real-time simulation environment by making it simple, fast and accurate. Tests show appreciable performance gains in terms of speedup and efficiency for large systems. A parallel computation approach for contingency analysis purposes using a microcomputer network based on FDLF is implemented by Balduino *et al.* (2004). This method involves three steps.

First, the steady state load flow is calculated for a base case using the Newton method. Second, FDLF is applied forcontingency ranking. Finally, selected severe contingencies are evaluated by means of exact load flow calculation. A master/slave model is applied to implement the three-step procedure in both synchronous and asynchronous modes. Both PVM (Parallel Virtual Machine) and MPI are used for parallel execution. The test results reveal that the PVM method under a synchronous mode delivers the best results in most of the tests for this type of application. Coincidentally, a combined architecture of FDLF and master/slave parallel computing for contingency analysis has been applied to a large-scale power system (Yang *et al.*,). Compared with the method of Balduino *et al.*, the proposed approach employs a three-layered master/slave hierarchical structure along with a dynamic task schedule system to achieve fine scalability levels.

Conclusion

This paper outlines a number of the most relevant current methodologies for contingency analysis presented in the literature to address the topic power system steady state security. In practice, the state-of-the-art contingency analysis approaches rely heavily on traditional methods. However, full power flow methods are limited by their high computation burden, while approximate methods lack high accuracy. Contingency ranking methods, on the other hand, attempt to strike a compromise between accuracy and computational speed. The development of artificial intelligence and parallel computing in recent years appears to pave the way for potentially overcoming all the technical shortcomings identified in this paper. In addition, all indications suggest that on-line security analysis is likely to become an increasingly popular focus topic for future research activities in this area.

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