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A flexible framework of line power flow estimation for high-order contingency analysis

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ABSTRACT

Traditionally, power system contingency analysis involves massive power flow calculations, which are usually based on linear approximation methods, such as *dc* load flow model or distribution factors based method, for fast speed but with compromised accuracy. Particularly, the accuracy of power flow results can deteriorate with the increase of *k* given *N–k* contingency analysis. Consequently, the obtained results may provide misleading information by under estimating the impact of some severe contingencies. In order to effectively implement online *N–k* contingency analysis, we propose a flexible framework of power flow estimation, where generalized line outage distribution factors (*GLODFs*) and *ac* power flow model are integrated together to formulate a two-stage scheme. At first stage, the Monte Carlo sampling technique is used to generate tables of computing errors for the hybrid *ac*-(*GLODFs*/*ac*) method. The achieved error information can then provide useful references in the second stage to select either *ac-GLODFs* based method or *ac* power flow model for *N–k* contingency analysis. Theoretically, the framework can provide significantly enhanced accuracy as well as satisfied efficiency. Finally, comprehensive case studies with the *IEEE*-118 bus system are given to validate the proposed framework.

Introduction

In the past decade, there have been some large-scale blackouts across the world. The recent studies reveal that cascading failures may be the most critical factor causing these blackouts [1–3]. Cascading failures can be defined as that the malfunction of one or only a few components (initial disturbance) of a system can trigger a cascaded effect and cause the failure of successive components, and finally may lead to the breakdown of the whole system [4]. In the modern electric power industry, inter-area connections have become a main tendency because of immense economic, social and environmental benefits. However, a regional system that used to be isolated now may be vulnerable to those disturbances occurred in neighbouring systems due to interconnections and cascading effects. Traditionally, the $N-1$ security criterion is a common industry standard for the security of power system for many years. This criterion requires that a planned power system should have enough security margins and be able to withstand the failure of any single component. For example, the failure of a transmission line should not violate the system due to redundancy (security margins) [5]. However, this security criterion may not be adequate to assess new scenarios where multiple-component failures occur simultaneously or successively in a very short time. The recent serious blackouts have highlighted the necessity of higher order (*N–k*) contingency analysis. That is to say, a planned system should be able to withstand the failure of any *k* components [5]. However, this is very challenging due to the fact that the total number of contingencies to be analysed is $N!/[k!(N-k)]$. For a medium size power grid with $N = 1000$, there are over 166 million contingencies for $k = 3$, and around 41 billion for $k = 4$ [14]. A blackout usually involves more than 6–10 cascading events depending on the scale of a power system. Assume that each contingency analysis takes about 1–2 ms on an ordinary computer. It is clear that exhaustively checking all possible combinations of contingencies for online analyses is computationally

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infeasible. Fortunately, most contingencies have low probabilities of occurrence, and therefore deserving no attentions at all. Accordingly, some recent works [1–3,6,7,22,23] attempted to model and analyse the cascading process so as to identify only high risk chains of related events that may lead to blackouts. Then add these chains of events into a presumed $N-1$ contingency set to form a new *N–k* (where *k*>=2 is implicit) contingency set prepared for online analysis. After the initial *N–k* contingency set is defined, operators can implement online contingency analysis so as to identify critical contingencies in advance. The challenge of online contingency analysis comes from numerous repetitions of power flow computations given a huge contingency set in order to obtain post-contingency states. Generally, *ac* power flow model can obtain an accurate solution. However, its speed is quite slow and not suitable for online contingency analysis with large scale initial contingency set. Instead, *dc* power flow model has been widely used to screen through initial contingency set in the first step and find out those cases that might result in violations of operation constraints. Subsequently, full *ac* load flow analysis is only needed for very limited cases in the second step [11]. Besides *dc* model, linear sensitivity factors, especially line outage distribution factors (*LODF*s) can be used to estimate the change of power flow on monitored transmission lines caused by a single line outage [11]. The main demerit of the two linear approximation based methods is their inaccurate contingency screening. It is well known that the average errors of linear approximation models are around 5% and 10% depending on systems [11,21,27]. Moreover, when *N–k* contingencies are considered, the accuracy and speed of these methods would degenerate due to the topological variation of post-contingency grids. The poor accuracy may result in some important contingencies omitted in the screening stage. Therefore, new methods of power flow estimation for contingency analysis are needed to enhance the computational accuracy.

Recently, the *LODFs* were generalized (*GLODFs*) to estimate possible overload under multiple-line outages, presenting a promising way for rapid analysis of high-order contingencies [8,10]. However the *GLODF*s based method which is derived from *dc* power flow model, still suffers from poor computational accuracy. In order to address this issue, a flexible framework is proposed in this paper to properly deal with the accuracy and efficiency in *N–k* contingency analysis. The main contributions of this paper include three aspects. Firstly, we propose an *ac-GLODFs* method that provides better computational accuracy and speed than existing linear approximation methods. Secondly, a new hybrid method given the integration of *ac-GLODFs* and *ac* power flow is developed to further enhance computing accuracy with satisfied speed so as to tackle some system environments where the *ac-GLODFs* method cannot obtain required accuracy. Furthermore, an offline computing approach to compare and quantify the computing errors of the hybrid approach has been presented. Thirdly, an online contingency analysis algorithm is proposed based on rational trade-offs between computing accuracy and speed. Theoretically, the accuracies of the *ac* power flow model and the *ac-GLODFs* method are formed as two extreme points. The framework can provide different online analysis schemes with adjustable accuracies between the two points.

The remaining parts of the paper are organized as follows: Section 'Contingency analysis methodology' reviews the contingency analysis methodology and the *ac*, *dc* and distributed factors based power flow models. Section 'Accuracy analyses of GLODFs' makes an accuracy analysis of the *GLODF*s based method. Section 'Proposed flexible framework for N–k contingency analysis'. Numerical simulations on the *IEEE*-118 bus system are given in Sections 'Simulation results' and 'Conclusion and future work' concludes the whole paper.

Contingency analysis methodology

Traditional contingency analysis

Many problems that happen on power systems can result in severe trouble within a short duration that operators could not take action fast enough [11]. Contingency Analysis (*CA*) programs, as part of Energy Management Systems (*EMS*) simulate possible contingencies to assess system security. The results can alarm operators of any potential violations of operating constraints in advance. Formulation of initial contingency set is the first step in contingency analysis. Traditionally, the set is formulated by $N-1$ criterion, since it is not common to have random outages of multiple important components simultaneously. In the second step, operators acquire current states reported by *SCADA* to make online contingency analysis. The procedures study all contingency cases one by one based on the initial contingency set to compute post-contingency states via repetitive of power flow calculations. If no violation of operating constraints is identified, the power system is regarded as "$N-1$ secure". Otherwise, operators should take corresponding actions before (preventive) or after (corrective) the occurrence of a contingency [9]. An important and difficult issue in contingency analysis is the computing speed of power flow since online contingency analysis running at an operations centre must be executed very quickly and accurately. When the contingency set is small, applying *ac* power flow is possible to quickly achieve precise solutions. This is not the case for modern power grid, where the initial contingency set is usually huge. Consequently, it is infeasible to employ *ac* load flow for online analysis due to the excessive computing burden. Fortunately, *ac* information is not required as most contingency cases do not involve *MVA* flow or voltage limit violations [11]. Thus, the common industry practice is to apply a mixed scheme. In the first stage approximate techniques are used, like *dc* power flow model or linear sensitivity factors (distribution factors), to rapidly estimate post-contingency system stages; in the second stage the cases with operating constraints violations identified by preceding step should be further checked by using full *ac* power flow. The flowchart of online contingency screening (the first stage) is displayed in Fig. 1. *dc* power flow model or distribution factors based methods are implemented in the component of post-contingency estimation because of their rapid speed.

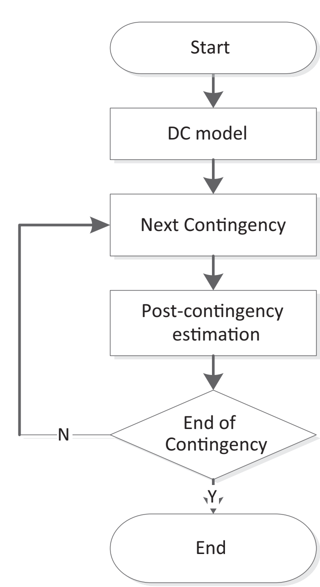

Fig. 1. Flowchart of contingency screening analysis.