Electric Power Systems Research 163 (2018) 365–374

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A hybrid method for reliability evaluation of line switching operations

Shijia Zhao, Chanan Singh*

Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA

A R T I C L E I N F O

Keywords:
Contingency ranking
Reliability evaluation
Line switching operations
Performance index

A B S T R A C T

In this paper, a hybrid method is proposed for reliability evaluation of line switching operations in power systems. A contingency ranking (CR) method is introduced as a pre-selection method to speed up the simulation and to provide analytical analysis of state space. The differences between event-based and yearly-based indices are analyzed to better understand and utilize the results of the proposed method. Two case studies are conducted separately on IEEE RTS and IEEE 118-bus system. The analysis of results from using the hybrid methodology for both case studies shows reasonable accuracy in identifying critical lines with a significant improvement of calculation speed.

1. Introduction

Line switching operation in power systems is an important part of network topology and flow control. It utilizes novel transmission technology to improve the transmission usage. The idea was first proposed in Ref. [1] to consider transmission line as controllable assets. With the increase of renewable penetration [2–6] in power systems, using line switching in power system operations can not only reduce overflows in transmission lines but also improve system security. However, with line switching operations, additional complexity and uncertainty are introduced into power system analysis [7–13] and protection functions [14–18]. There is no doubt that integration of topology and flow controls can affect the reliability performance of power systems [19–24]. To avoid degradation of reliability and effectively utilize line switching in power system operations, comprehensive reliability evaluation is essential. To achieve this objective, a hybrid reliability evaluation method for line switching operations is proposed in this paper.

The research interest in line switching operations has been increasing over the recent years. Refs. [18,21,22,24,25] discussed the economic benefits of incorporating line switching operations, N-1 reliability is studied in Ref. [26] considering the co-optimization of generation unit commitment and transmission switching, Refs. [9,17,27,28] illustrated the possible improvement of stability with topology control. However, there are limited research efforts on the reliability evaluation of line switching operations. It is pointed out in Ref. [29] that most studies strongly prune the cases evaluated, instead of analysis on the overall state space of line switching, only selected scenarios were evaluated to make the case. A reliability evaluation method based on Monte Carlo Simulation (MCS) is proposed in Refs. [30,31]. The method provides insights into the overall state space of line switching operations. However, the method is based on sweeping through transmission lines without analytical guidance so the computation speed is rather slow.

Traditional approach to contingency ranking (CR) is based on using a performance index (PI) to provide a measure of system performance [32]. It has been widely used in power system analysis [33–36], some innovative usage of CR method has been proposed in recent years. A bi-level optimization model was introduced in Ref. [37] for the risk assessment of transmission systems, Neural network and data environment analysis was combined with contingency ranking in Ref. [38]. A margin-based framework for contingency selection was proposed in Ref. [39] for unbalanced systems. However, there have been limited research efforts on using CR method in reliability evaluation of line switching operations.

In this paper, a contingency ranking (CR) method is introduced into the reliability evaluation of line switching operations as a pre-selection method. The hybrid of CR and traditional MCS method is designed not only to speed up the simulation, but also provide analytical analysis of state space of line switching operations. To further improve the proposed hybrid method, analysis of results is updated to distinguish between event-based and yearly-based indices. Results analysis is designed to be clearer and emphasizes the observed patterns.

Following are the contributions of this paper:

1) A novel CR method with improvements to accommodate reliability evaluation is introduced as a pre-selection step of the proposed hybrid method. It not only reduces the computation time of this

* Corresponding author.
E-mail addresses: zsjjames@tamu.edu (S. Zhao), singh@ece.tamu.edu (C. Singh).

https://doi.org/10.1016/j.epsr.2018.07.001
Received 19 January 2018; Received in revised form 5 June 2018; Accepted 2 July 2018

Nomenclature

CR	Contingency ranking
EPNSP	Expected Power Not Supplied Percentage

method, but also provides analytical understanding of state space contrary to the inherent randomness of traditional reliability evaluation based on MCS alone.

2) A new performance index (PI), based on Expected Power Not Supplied Percentage (EPNSP) is proposed in this paper to be used as an indicator in the CR pre-selection method. Its performance is superior to the traditional PI and its direct connection to load loss ensures the accurate pick-up rates of pre-selection method.
3) Two outputs are obtained from CR method: the ranking list and the newly introduced dictionary. Both are utilized in the MCS afterwards. The ranking list generated is used to guide the sequence of line removal tests and significantly reduce the number of tests required while still picking up most of the target transmission lines with non-trivial difference from benchmark case. The dictionary is used to speed up simulation and provide map of PIs for analytical analysis of state space.
4) The difference between event-based and yearly-based indices is discussed in this paper to provide guidance on analysis of results. Instead of showing all the recorded results, only important results are shown to emphasize patterns observed.
5) Contrary to intuition, removal of some transmission lines is found to be beneficial to the reliability of power system. The reasons are further analyzed in Section 3.

The paper is organized as following: Section 2 illustrates the foundation and new features of the proposed hybrid reliability evaluation method. Two case studies were conducted using the proposed method and results are presented and analyzed in Section 3. The conclusions are summarized in Section 4.

2. Hybrid reliability evaluation method

2.1. Foundation of the proposed method

The foundation of the proposed hybrid method before the introduction of CR method is illustrated in this section. Four reliability indices are used in this paper to record the reliability performance in transmission line removal tests [30]. The first two are traditional reliability indices, yearly-based HLOLE and EENS, the mean values of these indices are traditionally used to evaluate reliability of power systems. Different from yearly-based indices, event-based HLOLE and EENS are introduced to capture information of each failure event subsequent to line removal and are defined in Eqs. (1) and (2).

$$Event\_based\ HLOLE = \frac{\sum_{i=1}^{N} HLOL_i}{N} \tag{1}$$

where

$HLOL_i$ is loss of load hours of *ith* load loss event.

N is number of load loss events.

$$Event\_based\ EENS = \frac{\sum_{i=1}^{N} ENS_i}{N} \tag{2}$$

where

ENS_i is energy not supplied during *ith* load loss event.

N is number of load loss events.

In traditional MCS analysis, only one mean value is saved for each recorded reliability index and the distribution information is not captured and is lost. Therefore, event-based indexes and worst-case comparison are introduced in the proposed method. Event-based index treats each failure event separately and equally which makes impact analysis possible and worst-case comparison is based on the reconstruction of index distribution and maximum value is taken at 99.7% of Cumulative Distribution Function (CDF) as the worst-case scenario.

Many distributions like Gaussian Mixture Method (GMM) or a combination of exponentials or gamma or Weibull are quite versatile in approximating the distributions. To reconstruct the distribution of reliability index, Weibull distribution is selected to process recorded data obtained from MCS because it can represent a wide range of distributions by appropriate choice of shape and scale parameters. To provide more details on the Weibull distribution reconstruction, actual results of sequential MCS are used to validate its accuracy and effectiveness. It is observed in Fig. 1 that the results of sequential MCS failure events follow "truncated" distribution due to its non-negative characteristic and Weibull distribution fitting the data closely and captures the distribution information of recorded reliability indices. The Root Mean Square Error (RMSE) of fitting these distributions is presented in Table 1 to further validate its accuracy and effectiveness in distribution reconstruction. It should be noted that extra processing is needed for yearly-based indices which is illustrated in Section 2.7.

In order to cope with inherent randomness of MCS, the bounds of recorded indices are obtained according to Ref. [31]. They are then used in comparison of indices to emphasize non-trivial difference compared with the benchmark case. The definition of trivial/non-trivial difference is given as following: If bounds of indices of certain test and benchmark case have overlapping regions, then the test's indices are assumed to have trivial difference compared with benchmark case. Otherwise, the bounds have no overlapping regions, and the test is denoted as having non-trivial difference compared with benchmark case.

Based on the comparison of reliability indices, transmission lines are categorized into 3 categories.

1) Recommended lines: their removal improves system reliability in at least one of the four reliability indexes
2) Safe lines: their removal causes none or trivial impact to system reliability, thus they are "safe" to be considered in line switching operations.

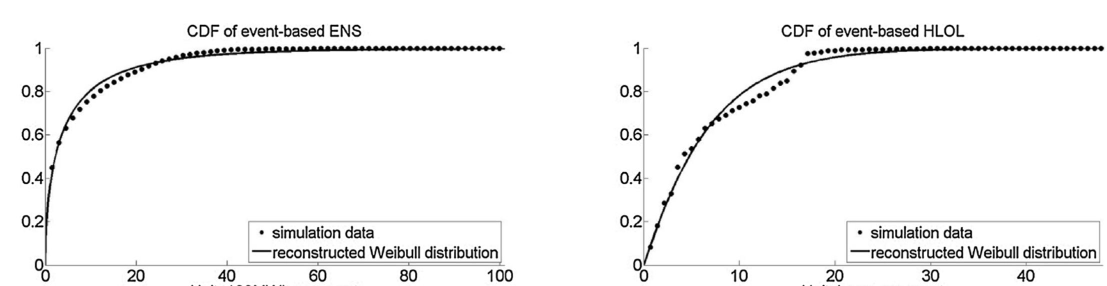

Fig. 1. Reconstructed Weibull distribution based on sequential MCS reliability indices.