Multi-state system reliability analysis of HVDC transmission systems using matrix-based system reliability method

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A B S T R A C T

This paper presents a new reliability analysis method for High Voltage Direct Current (HVDC) transmission systems based on the Matrix-Based System Reliability method. The proposed method can compute the failure probability of HVDC transmission systems by use of efficient matrix-based procedures. Unlike conventional system reliability methods whose practicability strongly depends on the system size and the complexity of its multiple states, the proposed method can describe any general system event in a simple matrix form and therefore provides a straightforward way of handling the system events and estimating their probabilities. The main qualities of the proposed method are demonstrated by the reliability assessment of two multi-terminal HVDC (MTDC) transmission systems with multiple derated states. The performance of the proposed method and the results obtained were compared with two traditional assessment methods: Capacity Outage Probability Table (COPT) and Monte Carlo simulation. In this comparative analysis it is shown that the proposed method is a competitive alternative for reliability analysis of MTDC systems in terms of simplicity and efficiency.

1. Introduction

The demand for reliable supply of electricity is growing, increasing the need for a higher level of power system reliability. However, electricity customers around the world are experiencing more blackouts and brownouts [1]. One of the most recent blackout occurred on June 2016 in Kenya, where 4.7 million households and businesses went without power for over 4 h [2]. High Voltage Direct Current (HVDC) transmission systems can help to reduce the spread of such large-scale disturbances by acting as a "firewall" [3,4]. Additionally, HVDC transmission systems have well-known advantages in long-distance bulk-power delivery, asynchronous interconnections, and long submarine cable crossings. Between 1972 and today, the installed capacity of HVDC has reached over 200,000 megawatts and continues to grow, with ratings of 7500 megawatts and ± 800 kV on a single bipolar system [5]. The increase of applications of HVDC transmission systems is because this technology can provide the necessary features to avoid technical problems in the power systems, enhance the transmission capacity and system stability very efficiently, and assist in prevention of cascading disturbances [6].

In the light of the above, reliability evaluation of HVDC transmission systems is an important and integral feature of the planning, design and operation of power systems with HVDC links [7]. For example, the profitability of power systems can be affected by some reliability figures in HVDC systems, causing a major impact on potential investors as well as the operation of power grids. Also, to build a converter station is much more expensive than an ordinary AC substation of similar rating because a better technical performance of an HVDC system needs many more components. Several organizations, such as CIGRE and EPRI [8,9], have initiated multiple research activities through their study committees to design HVDC systems for optimal reliability and availability performance [10]. Thus, it can be said that reliability analysis of HVDC systems is a subject that attracts a lot of interest from scientific and technological research groups since it has relevance for many areas of planning and operation of power systems.

Conventionally, most of the researchers working on reliability evaluation of HVDC transmission systems have employed traditional methods, which can be categorized as analytical [11–17] and simulation methods [18–21]. Each method has advantages and disadvantages, so the appropriate method is determined by the type of evaluation desired as well as the nature of the problem. Analytical methods calculate the reliability indices from mathematical models using direct numerical solutions. For example, fault tree methods are graphical techniques that model how failures propagate through the system [22]. These methods can be divided into qualitative and quantitative techniques. Qualitative techniques provide insight into the structure of the

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fault tree, and are used to detect system vulnerabilities and common cause failures, whereas quantitative techniques computes values such as failure probabilities [23]. The main disadvantage of fault tree methods is that the number of paths increases dramatically as the components are increased, e. g., the number of paths is 2^n for an n-component system in which each component can reside in one of two states. The number of paths is even greater if some or all the components can reside in more than two states.

Other examples are the Markov process methods. These methods are used in reliability assessments to model the stochastic processes of systems [24]. Markov modeling implies two main assumptions: (1) the future states for the system are independent of all past states except the immediately preceding one, and (2) the probability of making a transition between two specific states is constant at all times in the model. Markov modeling is quite useful when modeling systems with dependent failure and repair modes as well as when components behave in a statistically-independent manner [25]. However, in most of these methods it can be very difficult to construct the state-space diagram for multi-state systems (MSS) since it is not a normalized process where all the states and transitions must be identified correctly, which may lead to numerous mistakes even for a relatively small MSS. Additionally, with these methods the number of differential equations in the system that must be solved is equal to the total number of MSS states (product of number of states of all the system components). This number can be very large even for a relatively small MSS.

Finally, in the case of simulation methods, which are often known as Monte Carlo simulation, these methods estimate reliability indices by simulating the actual process and random behavior of the system. These techniques can be divided into two categories: (1) non-sequential and (2) sequential. Non-sequential simulation considers each time interval independently and therefore cannot model time correlations or sequential events. The sequential approach, on the other hand, takes each interval in chronological order. Sequential simulation is very useful in assessing HVDC systems considering time varying power generation and load demand [26]. Also, simulation approaches are generally used for special purposes in order to determine, for instance, the probability distributions of reliability indices. The main disadvantage of simulation methods compared with analytical approaches is the time and expense involved in the development and execution of simulations. To obtain accurate and understandable results, a large number of simulation trials are usually required, especially when the component availabilities are high.

A special mention has to be made for an analytical method that consists of obtaining a capacity outage probability table (COPT), which is an array of capacity levels and the associated probabilities of existence. This analytical method is becoming increasingly popular in analyzing the different applications of HVDC systems [11,27]. This is because the COPT can be generated quickly by combining the components using basic probability concepts and a unit addition procedure, as long as the number of system components is not large and each component can reside in only two states (up and down). However, if the system components are in huge numbers with multiple states, due to the inclusion of more fault scenarios, then the generation of the COPT will be complicated since it might be required to deduce very long equations for estimating some capacity output state probabilities, which can lead to long and tedious tasks with lots of manual efforts and potential mistakes.

Despite disadvantages of these traditional methods, they are still being considered for assessing the reliability of HVDC transmission systems because they have proved to be valuable tools. However, the complexity of HVDC systems is continuously increasing and other problems are emerging such as complex system events and large number of system/component states. For example, a multi-terminal HVDC (MTDC) transmission system has more components and complicated operation modes than a two-terminal HVDC transmission system. Therefore, there is an increasing demand for the development

of new efficient and accurate methods to facilitate reliability assessment of HVDC transmission systems.

In this paper, a reliability analysis method for HVDC transmission systems is proposed, which is based on the matrix-based system reliability (MSR) method [28–30]. The proposed method can compute the probability of each capacity outage state that is possible for HVDC transmission systems by use of efficient matrix-based procedures. Unlike the traditional reliability methods, the proposed method is uniformly applicable to general systems and the complexity of the computations is not affected by the system event (failure condition) definition, since the system reliability is computed by simple matrix calculations. Also, this feature allows the analysis of parameter sensitivities to obtain additional information that could be used by researchers and developers of HVDC systems during the decision-making processes to improve the reliability of the components of HVDC systems.

The main qualities of the proposed method are demonstrated by the reliability assessment of two MTDC transmission systems with multiple derated states. In order to prove the superiority of the proposed method on conventional approaches in terms of simplicity and flexibility, the equations for estimating system state probabilities were deduced by using the conventional procedure for COPT and the proposed method. Also, the equations obtained by the conventional procedure were programmed for computer solution and a non-sequential Monte Carlo algorithm was applied in order to demonstrate the advantage of the proposed method in terms of computational efficiency. Additionally, a sensitivity analysis of one of the MTDC systems was considered in order to observe the flexibility of the proposed method for routine studies.

The rest of the paper is structured as follows. Section 2 introduces two types of MTDC systems. In Section 3, the proposed matrix-based method is described in detail. In Section 4, the proposed method is applied to the two MTDC systems and its performance is compared with an analytical technique and a Monte Carlo simulation. Section 5 summarizes the concluding remarks.

2. Two multi-terminal HVDC transmission systems for reliability analysis

2.1. HVDC system with a VSC tapping station

The MTDC system analyzed in [11] (see Fig. 1) is used here as an illustrative application example of the proposed method for reliability analysis of HVDC systems. This is a transmission system with a voltage-source converter tapping station. In general, HVDC systems are divided into segments in order to facilitate its analysis; for example, the system represented in Fig. 1 is divided into three main segments: the sending end, the receiving end, and the tapping station. The first two segments form the main transmission line, while the tapping station has two purposes: supplying power along the transmission route to areas with comparatively little consumption and; transferring renewable energy resources such as wind power generation.

According to [11], the main transmission line is a conventional bipolar HVDC system, where its main components are: AC filters (ACFs), shunt capacitor banks or other reactive-compensation equipment (Caps), AC breakers (Brks), converter transformers (Trns), valves (Vlvs), smoothing reactors (SRs), DC filters (DCFs), and DC transmission lines (DCTLs). The bipolar configuration can be seen as two monopolar configurations in parallel. If an outage occurs in one pole, it is still possible to run the HVDC system in a derated state with the remaining pole and an earth return current. The tapping station involves almost the same components as the sending end, except that the converter is a VSC employing IGBT power semiconductor, and a DC switch (DCSW) is used to disconnect the tapping station from the HVDC system.

In practice, for reliability analysis purposes, an engineering system is frequently represented as a block diagram in which the system components are connected together either in series, parallel, meshed or