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Optimal transmission conversion from alternating current to high voltage direct current transmission systems for limiting short circuit currents

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ABSTRACT

The excess of short circuit currents (SCC) has threatened the security of electrical energy transmission and become one of the most critical problems in power grid operations. At present, high voltage direct current (HVDC) transmission technology is a practical and applicable option to limit short circuit currents by separating a synchronous power grid into several asynchronous power grids. During the transmission expansion planning, the short circuit currents can be effectively limited by strategically converting alternating current to high voltage direct current transmission systems, improving transmission capacity as well. Due to the high construction cost of high voltage direct current transmission systems, improper conversion would influence the economy of power system planning and the effect of short circuit currents reduction. Therefore, an approach of optimal transmission conversion (OTC) for limiting short circuit currents is proposed in this paper. To solve the problem with the strong nonlinearity of short circuit currents, a novel linearization method based on direct current power flow is developed. The case study based on a 22-bus power system and IEEE 118-bus system are performed for illustration and validation. The simulation results demonstrate that the short circuit currents are effectively reduced and the security of electrical energy transmission is guaranteed by applying the proposed approach and model. The major contribution of this paper is to provide a new method for limiting short circuit currents. Hopefully, the proposed approach can provide new insights for the planning and operations of large-scale hybrid power systems.

1. Introduction

Along with the growth of world energy consumption and the increase of renewable energy supply, the scale of power grids needs expanding and the structure of power networks needs strengthening. Although transmission capacity is improved and energy demand is satisfied by means of transmission network expansion, redundant and parallel transmission lines make synchronous interconnected AC power systems excessively compact. The compacter the power grid is, the greater the short circuit currents will be. This improper power system planning directly leads to the rapidly increasing short circuit currents, which threatens the security of electrical energy transmission and poses great challenges for power grid operations.

Currently, the excess of short circuit currents has been a critical problem that many regions across the world are faced with [1]. For instance, in China, the excess of short circuit currents is serious in the Guangdong power grid, due to 1) the scale of the Guangdong power grid is growing quickly; 2) the high-volume power transmission from the west to the east; 3) the small reactance of transmission lines due to the installation of series compensators [2]. In Iran, the short circuit current is expected to exceed the interrupting capacity of existing circuit breakers as a result of the commission of two new generating stations by 2015 [3]. In Japan, with the growth of the power grid scale, the Tokyo area is faced with the problem of excessive short circuit currents as well.

Large short circuit currents impose stricter requirements on electrical equipment in power systems, such as the insulation and interrupting capacity. If the interrupting capacity is insufficient for effectively clearing faults, the impact of the faults may spread to

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wider areas, jeopardizing the security of electric power systems. Therefore, how to limit the short circuit currents is an imperative task for the planning and operations of power grids.

High voltage direct current (HVDC) transmission technology is a practical and effective option to limiting short circuit currents. HVDC is one of the key solutions to transmit bulk power over large distances [4], gradually becoming a critical technology in the field of power grid planning [5]. HVDC transmission system has three aspects of advantages: 1) Since the power flow through HVDC can be controlled independently and rapidly, compared with pure AC power systems, the power grid with HVDC is able to be stabilized against larger disturbances. 2) HVDC allows connected power systems running at different frequencies, which improves the economy of each grid by optimizing power exchange. 3) What is concerned most in this paper is that HVDC transmission system can reduce the short circuit currents by separating a synchronous power grid into several asynchronous power grids. Therefore, the application of HVDC provides a new and promising means to limiting short circuit currents when conducting transmission planning of large-scale AC power systems.

The fault analysis of hybrid AC/DC systems and the planning of HVDC transmission systems have been widely investigated in the past decades [6]. Aghaei et al. [7] presented a multi-objective optimization algorithm for the MDEP (Multi-Stage Distribution Expansion Planning). The objective functions of the MDEP consist of various factors, including short circuit capacity. A modified PSO (Particle Swarm Optimization) method is used for solving the nonlinear model. Wasserrab and Balzer [8] analyzed both line-to-line and line-to-ground faults at different locations in a hybrid AC/DC system. Gilles [9] presented the formulation for solving the single-stage HVDC transmission expansion planning to reinforce AC networks. In this formulation, the detailed model of DC transmission systems is adopted instead of sensitivity coefficients. Kuruganty and Woodford [10] proposed a methodology for a reliability cost-benefit analysis of HVDC transmission expansion planning. Different factors such as forced outages of the generation and transmission are considered in the methodology. Chamorro et al. [11] studied transmission expansion planning from economics perspective. A valuation model combining optimization techniques is proposed and Monte Carlo simulation is utilized to assess the lifetime benefits of the expansion project. This model and approach is theoretically applied for Western HVDC subsea link between England/Wales and Scotland. Urquidez and Xie [12] proposed the concept of targeted conversion of AC lines to DC lines for improved economic dispatch. By incorporating the converted HVDC, transmission congestion is relieved and economic benefits for renewable energy integration are improved. Asad and Kazemi [13] presented a novel distributed optimal power sharing (ODCPS) method for planning radial dc microgrids. Seddighi and Ahmadi [14] addressed transmission expansion planning by a multistage stochastic programming model. The model incorporates uncertainties of energy demand, fuel prices, gas emissions and possible disruptions.

In existing literature, the emphasis is on the fault characteristics [15] and the operation planning of hybrid AC/DC power systems [16]. However, few publications have addressed the issue of reducing short circuit currents by converting AC lines to HVDC. For a power system, converting AC lines to HVDC can improve the network structure, thereby reducing short circuit currents. Moreover, with the help of HVDC, the transmission capacity is increased and power transmission corridors are saved. To this end, a new concept termed *optimal transmission conversion* (OTC) is proposed in this paper. In our proposed OTC model, AC lines are strategically converted to HVDC for limiting short circuit currents when conducting transmission expansion planning. The objective is to minimize the converting cost of HVDC and the constraints incorporate the short circuit currents limitation. Moreover, since the transmission capacity of HVDC is large, the electrical energy transmission of the power system is improved as well. To the best knowledge of the authors, the OTC model and the short circuit current linearization method are novel, distinguished from existing researches. In particular, this paper focuses on nodal three-phase short circuit currents.

The major contributions of this paper are as follows:

1) Based on DC power flow, the new concept OTC is presented and the OTC model is formulated. The objective of this model is to determine the best location and number of HVDCs in the hybrid power system, subject to short circuit currents limitation. In this model, the short circuit current constraints are explicitly incorporated.
2) A novel linearization method based on DC power flow is developed to solve the problem brought on by the strong nonlinearity of short circuit currents. Compared with the existing nonlinear planning models, the OTC model proposed in this paper is successfully transformed into a mixed-integer linear programming (MILP) problem. This model can be efficiently solved using off-the-shelf MIP solvers.
3) A compensation factor is proposed to reduce the error of short circuit currents brought on by linearization. With the help of compensation factors, the computation error of short circuit currents is greatly reduced, which further guarantees the effectiveness of the proposed model and approach and the feasibility of the power system planning results.

2. Framework

In this paper, optimal transmission conversion from AC lines to HVDC for limiting SCCs is proposed. The framework of this paper is shown in Fig. 1.

In the framework, the procedures of OTC are introduced. Firstly, the mathematical model of AC power flow for hybrid AC/DC systems is established incorporating the HVDC models. By this means, the ACPF results can be acquired. Secondly, based on the ACPF results, the short circuit currents can be calculated given the bus voltages as exogenous conditions. Finally, the optimal transmission conversion model is constructed with the SCC constraints. The optimization results, i.e., the conversion strategies from AC to HVDC, are iteratively delivered to the first module.

The rest of this paper is organized as follows: In Section 3, the model of HVDC for solving power flow of hybrid AC/DC systems is sketched. In Section 4, the calculation principle of short circuit currents is briefly introduced. In Section 5, the model and approach of optimal transmission conversion considering the constraints of short circuit currents are proposed. In Section 6, the linearization

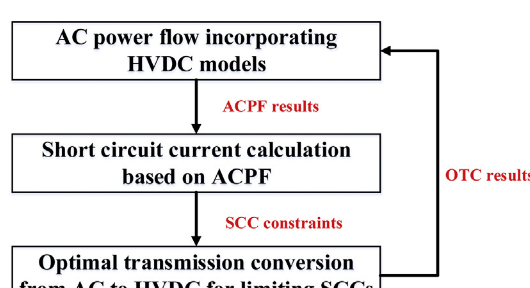

Fig. 1. The framework of optimal transmission conversion.

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