Abstract
論文の内容の要旨

Title of Dissertation
Evaluation of Multi-Terminal VSC HVDC Systems by Stability Constrained Optimal Power Flow in a Power System with Large-Scale Wind Power Plants
（大規模風力連系電力系統における安定性制約を考慮した最適潮流計算による多端子自励式直流送電システムの評価）

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Hierarchical optimal power flow analysis with power system stability constraints in mixed AC / multi-terminal VSC HVDC systems with large-scale wind power plants is formulated. This aims to solve two problems triggered by the wind power transmission. First of all, power system instability issue triggered by large-scale long-distance wind power transmission can be overcome. In addition, the capacity factor and the economic benefits obtained by the wind power transmission system can be increased by flexible multi-terminal VSC HVDC system operations.

Hierarchical optimal power flow approach is developed considering both MTDC reinforcements and operations. MTDC systems are evaluated from wind power hosting capacity and economic viewpoints. As for the wind power hosting capacity analysis, the MTDC system which allows the largest wind power plant installations is found where small-signal stability constraints are considered. Given the hosting capacity results, MTDC reinforcement decisions and operations are calculated. The following economic benefits of MTDC systems are analyzed. The hosting capacity of the same MTDC system with transient stability constraints are investigated. Time-domain simulation results with AC and DC faults are discussed to understand the transient behaviors of mixed AC / multi-terminal VSC HVDC systems with wind power plants. The influences of the transient stability constraints on the investment costs and fuel costs have been examined.

In Chapter 1, the necessity of HVDC transmission systems has been suggested for the aim of massive wind energy utilizations in Japan. LCC and VSC based HVDC technologies are compared each other. The basic multi-terminal topologies and converter configurations for VSC HVDC systems are explained. Previous works related to the transmission expansion planning and operation of VSC HVDC systems for the transmission of renewable energy source outputs are investigated to emphasize the distintive

contributions of this dissertation from the works. The objectives and structure of this dissertation are summarized.

In Chapter 2, the synchronous generator model of AC system is described. The synchronous generator model can be modified for time-domain simulation based on feasible assumptions. Each synchronous generator model is equipped with AVR and GOV systems. These systems are modeled as simple first order lag transfer functions. Voltage and frequency dependencies of AC system loads are explained. In this dissertation, all AC system loads are modeled as static constant impedance characteristic loads. The aggregated wind power plant models are considered as static loads. The FRT requirement of the wind power plants is considered as well.

Among many types of VSC HVDC system models, the average value model with control system is adopted and explained. Symmetrical bi-pole behaviors can be simulated with this model. Regarding the DC voltage control cooperation of multi-terminal VSC HVDC systems, voltage margin method and DC voltage droop control are explained. The modified cooperation control which adopts the characteristics of both methods is suggested. The FRT requirement of VSC HVDC systems is also taken into account.

The protection strategy of mixed AC / multi-terminal VSC HVDC systems is explained. Hybrid-type DC circuit breakers are utilized for the clearance of DC faulted sections quickly and selectively. After a DC fault clearance, DC voltage recovery process is required to prevent large DC transmission line current flows.

A Japanese power system model with aggregated wind power plant models is adopted for the analysis. Power system reinforcements with either new AC transmission systems or a MTDC system have been considered for the installations of large-scale wind power plants.

In Chapter 3, a simplified annual analysis is suggested for economic benefit analysis. One year is classified into different section numbers depending on seasons, load patterns, and wind power outputs conditions.

Hierarchical optimal power flow with power system stability constraints is developed to determine the reinforcements and operations of MTDC systems. Power system small-signal stability constraints, transient fluctuations of generators' rotor-angles, PCC bus voltages, DC voltages, and DC transmission line current flows are included as additional inequality constraints in the optimization process. As a result, the OPF solutions are stable from all these stability viewpoints even large-scale wind power plants are installed.

Differential evolution algorithm is used to solve the optimization problem. In evolutionary algorithms, the stability constraints can be dealt with using fitness functions and penalty values.

In Chapter 4, the wind power hosting capacities of power system models considering the small-signal stability constraints are calculated. Unlike pure AC systems which suffer from the small-signal instability problem, the system model with a MTDC system is free from such phenomenon.

Several different multi-terminal configurations are discussed. The corresponding wind power hosting capacities of the MTDC systems are calculated. The critical factor which determines different hosting capacities is AC transmission line capacities nearby the inverter-mode VSCs. The MTDC system allowing the largest wind power hosting capacity is revealed that AC transmission lines nearby the inverter-mode VSCs have sufficient AC transmission line capacities.

A novel economic benefit analysis is proposed to evaluate the economic benefits produced by the hierarchical OPF analysis. The fuel cost reduction effects and increased wheeling charge incomes of MTDC systems are included in cash inflow terms. As regards the fuel cost reduction effect, the contributions of wind power plants and the hierarchical OPF method are defined separately. This aims to exclude the effect by the wind power plants and focus only on the benefits of the proposed method. Net present values and profitability indices are calculated.

In the sensitivity analysis of wind power capacity, as the total capacity of the wind power plants increases, higher annual cash flow and NPV of the MTDC system are obtained. As for the MTDC investment efficiency, the wind power capacity which gives the maximum investment efficiency exists.

The sensitivity analysis of small-signal stability constraints is carried out. Different damping ratio constraints are considered in the analysis. The annual fuel cost result of the system without any MTDC systems is increased when a strict damping ratio constraint is considered. On the other hand, the annual fuel cost of the system with a MTDC system is not influenced by the same damping ratio constraint. This is due to the system stabilization effect of the MTDC system. As a result, the increased fuel cost reduction benefit of the MTDC system is obtained by the considerations of strict damping ratio constraints. The results of NPV and PI are increased as well.

In Chapter 5, the wind power hosting capacity is reduced by the consideration of the transient stability constraints. Hierarchical TSCOPF analysis is carried out to calculate the system reinforcement and operations. The hierarchical TSCOPF analysis is capable of producing stable solutions against critical AC and DC faults. Time-domain simulation results are explained to understand the transient behaviors of mixed AC / multi-terminal VSC HVDC systems with wind power plants.

The influences of the transient stability constraints on the reinforcement and fuel costs are discussed. More MTDC system reinforcement capacity is required compared to the case without the consideration of the transient stability constraints. As for the fuel costs, different influences of the transient stability constraints are observed depending on the wind power output conditions. In peak wind output conditions, the influences on the fuel costs are not considerable. In contrast, significant fuel cost increments are observed in low and average wind output conditions. A novel MTDC reinforcement method or an improved DC voltage control strategy is required to relieve these fuel cost increments.