論文の内容の要旨

論文題目 ：
Modeling and Simulation of Grid-connected Superconducting Wind Turbine Generators
(電力系統に連系された超電導風力発電機のモデリングとシミュレーション)

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Superconducting machines have been proposed to solve the problem of upscaling wind turbine generators. In order to design such machines, since prototyping would be very expensive, it is crucial to be able to simulate the interactions between them and the external mechanical and electrical systems. Within this framework, we address in this thesis the problem of modeling and simulating grid-connected superconducting wind turbine generators.

The adopted model is a multiscale simulation constituted by three sub-models with unidirectional couplings: the wind energy conversion system model, the machine model and the HTS tape model. The multiscale simulation allows us to obtain the desired level accuracy, while the unidirectional couplings bring high efficiency. The sub-models are implemented in a flexible way using only commercially available softwares (Matlab/Simulink and Comsol Multiphysics), a key to bringing development of superconducting machines from the laboratory scale to the industrial level.

In order to simulate the wind energy conversion systems, we use Matlab/Simulink/SimPowerSystem to model the wind turbine generator, the blades, the machine shaft, the power converter, the exciter, and the associated control strategies. First, we investigate the adapted configuration for the correct operation and optimal grid integration of superconducting wind turbine generators. We summarize special characteristics of superconducting machines, particular needs of offshore wind farms and grid regulations. From this, we adopt a full-scale 3-level NPC back-to-back converter and discuss its control strategy. Secondly, considering the need for a simple and systematic design method, we develop a step-by-step procedure for the systematic design and control of a back-to-back converter for direct-drive electrically-excited synchronous generator-based WECS. We use it to build a reference 2 MW wind energy conversion system model and to evaluate its performances for three worst case

scenarios: startup, sudden wind variations and low-voltage ride-through.

To model the superconducting machine in the time domain transients simulation, we use a nonlinear coupled finite element phase-domain model. On the one hand, the machine parameters are obtained from static nonlinear finite element analysis (Comsol Multiphysics). On the other hand, the machine is represented by a lumped-parameter phase-domain model (Matlab/Simulink/SimPowerSystem). This approach offers two main advantages. First, as opposed to the classical dq model, the phase-domain model can naturally include space harmonics and saturation, two important features of multi-MW superconducting wind turbine generators. Secondly, it provides a reasonable simulation speed with the same accuracy as a full finite element model. Previous implementations of the phase-domain model being rather complex because of the use of the inductance concept, we propose a novel general nonlinear phase-domain model using N-dimensional lookup tables. The lookup tables describe the winding currents as function of the rotor angle and the winding flux linkages. They are constructed by N-dimensional interpolation from the lookup tables which describe the winding flux linkages as function of the rotor angle and the winding currents. The flux linkage is calculated using the vector potential. We use another lookup table for the electromagnetic torque. It is directly calculated using the Maxwell stress tensor. We present a flexible implementation of this model. And we validate it through comparison with the dq model and the finite element model.

The HTS tape model is a finite element model with H-formulation and edge elements implemented with Comsol Multiphysics PDE mode application. It takes into consideration the properties and the real thickness of the tape.

Finally, we demonstrate the versatility of the adopted method by simulating a grid-connected superconducting 10 MW class wind turbine generator. The analysis focuses on estimating critical parameters for the design of the machine such as current margins, resulting torque, and steady-state AC losses. We show that the current variations in the superconducting coil can be kept very low with the adopted power electronics, and therefore that it can be protected from quench and thermal run away. We underline that the shaft of the machine can endure high resulting torque during transients, and therefore needs to be designed adequately. We calculate the steady-state AC losses in the superconducting windings, including effects linked to the exciter, the AC/DC/AC converter PWM and the control strategy. To solve the problem linked with the high number of tapes in the superconducting coil cross section, we consider that the AC losses calculated for several tapes only can be interpolated to the others. Finally, we discuss the other possible applications of such a method: damper design, advanced controller design, etc.