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Mass minimization and sensitivity analysis of high power modular multilevel converter

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ABSTRACT

Optimal design and selection of passive components has been known as a challenging issue in the field of MMC converter especially in high power applications. Global optimization is an integrated optimization loop consisted of several sub-models such as circuit model, electromagnetic and thermal model, constraints, goal function and nonlinear solver. Global optimization algorithm is utilized to minimize the total converter volume regarding to the technical and manufacturing constraints. The most important factor to achieve the reliable optimization results is to employ the precise models. In this paper, several optimization algorithm with different level of complexity are proposed and developed to minimize the total MMC volume. The first model is consisted of a time-domain steady-state circuit model that determines the circuit value of passive components. Unlike the conventional model, the proposed circuit model does not neglect the switching frequency and saturation effect of arm inductance. The second model employs the circuit model in combination with the dimension and thermal model of arm inductance. Finally, a hybrid optimization algorithm is proposed which is consisted of an internal correction loop using finite element method to enhance the model accuracy. Also, a comprehensive sensitivity analysis has done to evaluate the total converter mass sensitivity against the different converter parameters and constraints.

Contents

1. Introduction

The demand to high power converters is increasing more and more. Increasing the power of wind turbines, photovoltaic power

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plants and other renewable equipment have been accelerated [1–4]. Therefore, the tendency to utilize the medium and high power converters made the multilevel converters as an interesting subject in the field of power electronics [1–7]. Multilevel converters were emerged in response to the limits of semiconductor devices against the high voltage and current [8,9]. Researchers always try to propose the new multilevel topologies providing lower THD and higher efficiency [6,7,10]. MMC converter is a composition of series and parallel Commutation cells which provides the possibility to endure the high voltage and high current [11,4,7].By increasing the converter power, the components volume is strongly augments and make it very bulky and expensive. Arm inductance is known as one of the most important and sensitive part of MMC converter which plays a dominant role in converter operation. Also, the arm inductances are the bulkiest part of MMC converter which intensely affects the converter size and price. Researchers proposed various methods to optimal selection of passive components regarding to different criteria such as current ripple, short circuit current, capacitor energy variation and capacitor voltage ripple [12–15]. In some applications, other converter parameters such as THD, efficiency are more important [12,15]. Therefore, optimal selection of MMC passive components is always dependent on the desired outputs [16]. Global optimization is an advanced approach which is used to reduce the total converter size considering their technical, operational and manufacturing constraints. The number of series submodules per arm, submodule capacitor value and arm inductance value are the most variables taht are chosen as optimization goal [17,14,18,19]. The main parts of a conventional global optimization loop are analytical model, goal function, constraints and nonlinear solver. The weakness of conventional optimization loop is the low accuracy of analytical models especially in the case of electromagnetic and thermal modeling. Hence, the hybrid optimization algorithm has been proposed to increase the analytical model accuracy [20–22]. In this research, a novel verification procedure was proposed and developed in order to achieve the accurate and reliable results. Global optimization of MMC converter is realized in three steps with the different level of complexity. In the first step, the optimization has done to compute the optimal circuit value of the passive components utilizing an accurate steady-state circuit model. The optimization algorithm computes the the passive components values regardless to their volume and dimensions. In the next step, the dimension model of inductor and capacitor is added to the algorithm. The optimization algorithm calculates the dimension variables of the inductor and capacitor in order to minimize the total converter mass. Finally, a hybrid optimization loop was proposed in order to enhance the analytical model accuracy and result preciseness. In hybrid optimization loop, the mathematical model of the system is a combination of analytical model and an advanced software utilizing an advanced numeric solver such as finite element method. This combination increases the model accuracy while the optimization time is increasing [21,22]. in each step, The optimization algorithm employs the results of the previous step to initialize the optimization variables and narrow the variable bands. In other words, the optimization results will be verified by the next optimization results. In the case of MMC converter, the arm inductances are known as the most complex component to design. Utilization of coupled inductors and core saturation region are is known as an efficient solution in order to reduce the current ripple and inductor mass in power electronic design even though it increases the design complexity. Electromagnetic designers choose the maximum possible magnetic field density (B_{max}) of the inductor to remain in the linear region of B-H curve of electromagnetic core. Entering into saturation region is always avoided because of the complexity of analysis. Utilizing the saturation region helps to reduce the inductor mass and increase the energy density of the

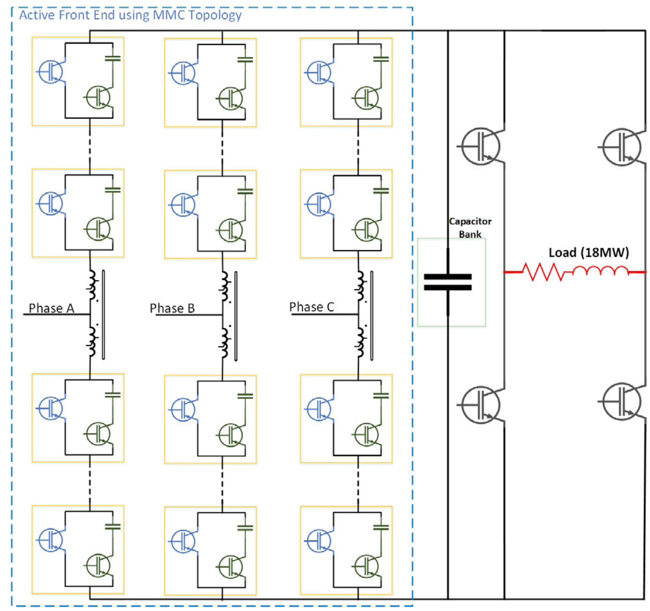

Fig. 1. High power MMC active front end using half-bridge submodules.

inductor, but it intensely affects the converter operation, stability and outputs such as THD, efficiency and etc. Hence it will be a trade off between the mass and converter performance. Given that a comprehensive analysis is needed to be done to design the inductors in the saturation region in order to ensure the converter stability. Fig. 1 shows the high power MMC Active Front-End (AFE) of Compact Linear Collider at the CERN Company. The Compact Linear Collider (CLIC) study is an international collaboration working on a concept for a machine to collide electrons and positrons (antielectrons) headon at energies up to several tera-electronvolts (TeV) [23]. As shown in Fig. 1, a high power multilevel active front end converter is connected to the grid via DY three phase transformer. Each arm of MMC converter is composed of number of series half bridge commutation cells which are connected to an arm inductance. Fig. 2 shows the desired output DC current of the load which is supplied by a full bridge converter. As shown, the current sharply goes up from 333 A to 6000 A in less than 0.3 s and then comes back to the previous value. This cycle is repeated every 0.9 s. There is no constant operation point, therefore all components should be

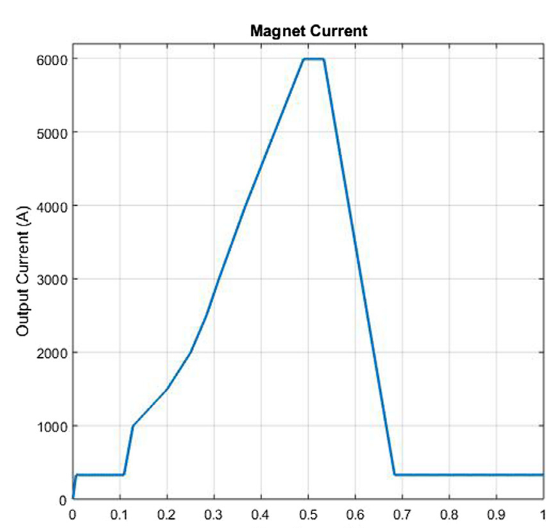

Fig. 2. The desired output DC current of accelerator magnet.