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Fast model predictive control algorithms for fast-switching modular multilevel converters

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ABSTRACT

For high-power/voltage systems, particularly for high-voltage direct current (HVDC), one of the most potential converter topologies is the modular mutlilevel converter (MMC). Model predictive control (MPC) is one of the switching methods studied in the literature for MMC to simultaneously achieve the three challenging objectives of (1) following the reference of the current waveform requested by upper-level control, (2) mitigating on circulating current, and (3) regulating capacitor voltages of submodules. Since the MPC models proposed in the literature suffer from high computation burdens making the algorithm not applicable to high-frequency switching MMCs, a binary integer programming based MPC has been proposed in this paper to optimize this multi-objective problem with minimum computing effort. The main contribution of the algorithms proposed in this paper is to significantly reduce the computation expenses by cutting the searching space from millions of feasible solutions to the incredibly low number of "4", while taking care of the three objectives of MMC control. The performance of the proposed method is evaluated via simulation in MATLAB SimPowerSystems.

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1. Introduction

Modular multilevel converter (MMC) is reported in the literature as the most promising topology proposed for voltage source converters (VSC) due to its salient characteristics such as scalability and modularity [1–7].

Simultaneous regulation of submodule capacitor voltages and elimination/minimization of the circulating current flowing through three phases of the converter is still one of the technical challenges associated with MMC application due to their mutual effects. Circulating current, in fact, not only is a function of the capacitor voltages of the submodules turned on at each time step, but also determines how the capacitor voltages of the same submodules change until the next switching time step arrives, which may lower the efficiency of the converter and cause more ripples in the capacitor voltages if it is not well suppressed. However, it should be noted that the circulating current is a useful mean to balance the energies between all six arms in situations where some energy unbalance are caused by asymmetric operations and fault situations and tolerances of the components [8].

The method proposed in [1] compares all possible switching combinations for the MMC switches in one bridge for their predicted performance one step ahead. This method requires significant computing effort. At each time step with the step size defined by the switching frequency, e.g. 100 μs for 10 kHz, the solution must be sought. For a 5-level MMC, there are 8 submodules in each bridge. Among the eight submodules, four submodules should be turned on to keep the dc-link voltage constant. Therefore, the number of the combination is $C_8^4 = 70$. The algorithm needs to check 70 possible on/off sequences and find the best one. For a 13-level MMC, C_{24}^{12}, or 2.7 million combinations should be checked. For a 16-level MMC, 155 million combinations should be checked.

In the authors' previous paper [9], a one-step model predictive control has been proposed. The proposed method aims to track the ac reference currents and eliminate the circulating currents. Based on the two objectives, the optimal upper-arm voltage and lower-arm voltage for a MMC bridge can be found. Based on the desired voltage level, capacitor voltages are sorted in order. When the arm current is positive, the capacitors with lowest voltages will be switched on to get charged. When the arm current is negative, the capacitors with the highest voltages will be switched off to get discharged. This method requires only sorting algorithms, which makes it efficient for MMCs with a large number of submodules.

The disadvantage of the above algorithm is its omission of the dc-voltage constraint. The number of submodules to be switched

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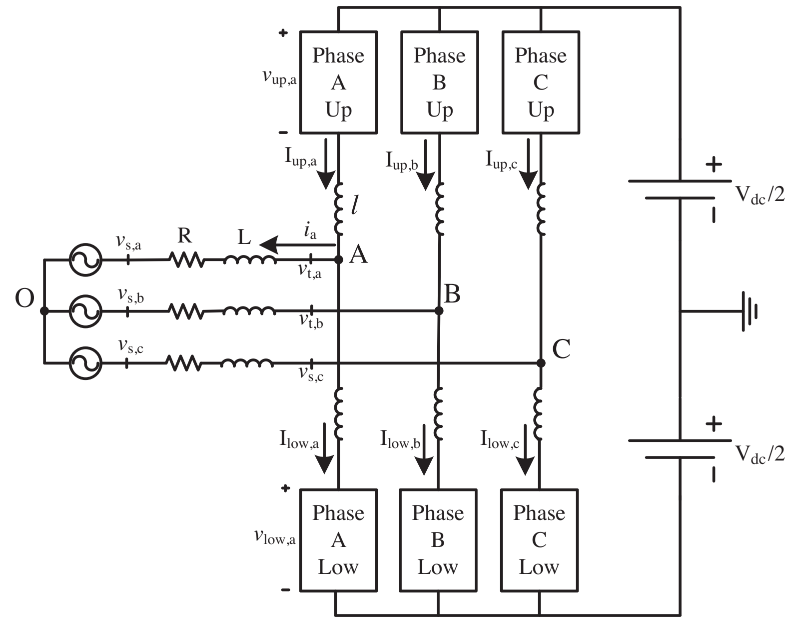

Fig. 1. Simplified scheme of a multilevel modular converter.

on is required to be fixed in PWM scheme and the MPC scheme proposed in [1]. In order to take this constraint into account, a mathematical programming problem is formulated and solved using heuristic way. In many papers, commercial solvers such as CPLEX are employed to solve MIP problems [10,11]. However, for this power electronics application, it is not feasible to employ a commercial solver. Firstly, the switching scheme will be programmed in a chip. It is not possible to have a commercial solver on a chip. Secondly, commercial solvers use general methods to solve optimization problems. In many cases, CPLEX has convergence issues due to its adoption of enumeration. For special optimization problems, a specific solving method will achieve much faster solving speed than a commercial solver.

In this paper, the mathematical model of MPC-based $(n+1)$-level MMC, which has n submodules at each arm, is proposed in order to track ac reference current, mitigate circulating current and to keep capacitor voltage nominal subject to selection of exactly n submodules to be trigged at each arm. The multi-objective optimization problem is then reformulated to a new model and the weighting sum method is employed to merge the objectives. To solve such problem, two algorithms are represented to seek the optimal solution for switching pattern. The first search algorithm design remarkably reduces the size of feasible solution to n instead of C_{2n}^{n}, but the simulation results shows that it has serious drawbacks

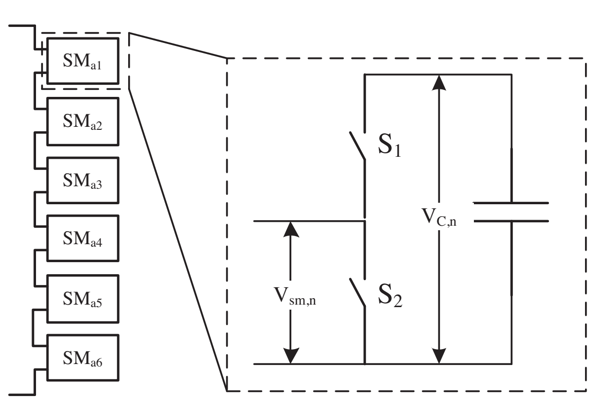

Fig. 2. The structure of MMC submodules.

in satisfying the objectives of MPC, which has led the authors to an alternative algorithm for better performance while maintaining the computation advantages. The second algorithm is developed by applying a relaxation on the constraint of number of switched-on submodules and increases the size of the feasible set to n^2, which introduces additional computation burden compared the first algorithm especially for high values of n. However, it is proved in this paper that this size can be cut down to 4 if appropriate weighting factors are selected and checking just 4 of the solutions is enough to find the optimal solution. This paper is focused on the lower-level switching control design where the upper-level control signals are assumed to be given as reference values. The efficiency of the algorithms are finally tested via simulations in MATLAB SimPowerSystems.

The following sections of the paper are organized as follows: Section 2 presents the MMC mathematical model. Section 3 presents the MPC strategy and the binary integer programming solving algorithms. Section 4 reports the simulation results of MPC based switching schemes. Section 5 concludes the paper.

2. Mathematical model of the MMC

2.1. System topology

Fig. 1 shows a simplified scheme for a three-phase MMC. At each phase of A, B, or C, there are two groups of switches on upper and lower arms. Fig. 2 shows the structure of each arm of a 7-level MMC. Each arm consists of 6 submodules (SM) each of which has two IGBT switches and a capacitor. There are two inductors in each phase in order to provide current control and limit the fault currents. The voltage of each submodule is either equal to its capacitor voltage $V_{C,i}$ or zero depending on the states of the two switches. Table 1 lists the submodule output voltage. The on/off states of the two switches of a submodule are always opposite to each other. The

Table 1
Submodule voltage.

State	$S1$	$S2$	V_{SM}
0(*inactive*)	OFF	ON	0
1(*active*)	ON	OFF	V_C

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