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A tuning-less model predictive control for modular multilevel converter capable of unbalanced grid fault

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ABSTRACT

This paper focuses on a tuning-less model predictive control (MPC) strategy with unbalanced fault-ride-through capability for a three-phase modular multilevel converter (MMC). Three individual control stages are designed to cater for the multiple control objectives in MMC without the need for any weighting factor tuning. A conceptually simple power regulation approach which requires neither synchronous coordinate transformation nor grid-voltage phase angle detection is introduced into the proposed MPC. Meanwhile, two alternatives are proposed to the power regulation stage to adapt to the special needs under unbalanced grid fault. Neither of the alternatives involves any tuning work. In addition, a modified sorting algorithm is presented to resolve the problem of unnecessary switching transitions, which is inherent in conventional sorting algorithm. The proposed tuning-less MPC is capable of direct active and reactive power control, circulating current minimization, submodule capacitor voltage balancing, switching frequency reduction, and great resilience under balanced and unbalanced grid conditions. The presented simulation results confirm the effectiveness and feasibility of the proposed control method.

1. Introduction

After the invention of modular multilevel converter (MMC) [1] in 2003, the literature on MMC is intensive, indicating its popularity in academia especially for high power and high voltage applications because of its advantages such as modularity, scalability, and lower losses. Similar to other power converter applications, the classical linear control and pulse width modulation (PWM) remain the predominantly used control strategies in the control of MMC [2–5].

Almost a decade ago, many scholarly works have rigorously researched on the model predictive control (MPC) in place of the linear control in the power electronics applications due to its simplicity, easy inclusion of nonlinearities, ease in digital implementation, and fast dynamic response [6]. A paramount property of MPC is that it is endowed with the capability of incorporating multiple control objectives in one controller, which is particularly suited for the complicated multilevel converter topologies, especially the MMC. As such, various principal control variables of MMC such as active and reactive power control, current control, circulating current mitigation, SM capacitor voltage balancing, and switching frequency reduction can be readily addressed in MPC simultaneously. Unlike the classical linear controllers, all the control variables in MPC are regulated without involving any tuning of proportional integral (PI) controller or designing of modulation stage. Nonetheless, the merit of control flexibility in MPC comes at the price of the inevitable heuristic tuning of weighting factors for each control variable [7]. Moreover, the coupling effects engendered from the various control variables further complicated the adjustment of the weighting factors, and thus incurring tedious and time-consuming control task.

Predictive current control (PCC) has recently emerged as a popular MPC technique which is seen gradually maturing in MMC applications since its first attempt in [8]. Since the real-time implementation of PCC in MMC becomes more challenging as the number of SMs increases, there is a surge of research works put emphasis on alleviating the computational burden such as switching states grouping [9], dual-stage MPC [10], fast MPC [11], grouping-sorting-optimized MPC [12], and voltage level based indirect MPC [13–15]. All the works in the mentioned literature involves weighting factors, with a notable exception of [15], in which the different control variables are independently controlled in their distinctly designed MPC strategies.

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Unbalanced grid voltage is one of the typically adverse grid condition in the modern power system. Similar to any grid-connected system, the MMC is also susceptible to unbalanced network. In this instance, according to the instantaneous *pq* theory, the controllers can choose to achieve either of the control targets [16,17], i.e.

(1) balanced and sinusoidal currents, oscillatory active power and reactive power,
(2) unbalanced but sinusoidal currents, active power oscillation elimination, oscillatory reactive power,
(3) unbalanced but sinusoidal currents, oscillatory active power, reactive power oscillation elimination.

In an effort to achieve the control targets, positive and negative sequence extraction of grid components are mandatory. However, the extraction methods in the current control strategies of MMC mainly involve properly designed PI controllers or proportional-resonant (PR) controllers which entail substantial tuning work [18–25].

On the other hand, being a viable alternative to the PCC, predictive direct power control (PDPC) is another type of MPC which remains relatively unexplored in the field of MMC, except in a recent literature [26]. The main characteristic which distinguish the PDPC scheme from PCC scheme is its decoupled active and reactive power control instead of current control loop [27]. In this regard, the PDPC is totally formulated in stationary $\alpha\beta$ frame, and thereby eliminates the use of phase-locked loop for current reference generation and avoiding rotary transformation. When addressing the unbalanced grid conditions, sequence extraction of grid components in $\alpha\beta$ frame is also relatively simple and not necessary involves PI or PR controllers [16,28]. Moreover, some recent works which advocate the use of a newly defined reactive power in PDPC has been proved useful in establishing certain control targets even without the need of sequence components extraction [29–31].

This paper aims to seek for a more straightforward and easy endeavor by designing a tuning-less MPC capable of unbalanced grid fault where individual control stage is designed for each control objective while getting rid of any heuristic tuning of weighting factors, PI controllers or PR controllers in MPC. The major contributions of the proposed tuning-less MPC are summarized as follows.

(1) The proposed MPC algorithm advocates separate control of power, circulating current and submodule capacitor voltages with each of them owns its dedicated control stage, thereby getting rid of the tuning procedure for weighting factors.
(2) The design of PI controller or PWM modulator is unnecessary as none of the control stages implements classical linear control techniques. In this instance, no tuning is involved in each control stage.
(3) Unlike the existing PCC in MMC, phase locked loop (PLL) is not mandatory for operation in the proposed power regulation loop since the deployment of PDPC enables the control problem to be formulated completely in $\alpha\beta$ reference frame. In this instance, phase detection inaccuracy incurred in PLL especially during non-ideal grid voltage conditions [32,33] is no more a potential risk.
(4) Two conceptually simple PDPC approaches with unbalanced fault-ride-through capability are proposed.
(5) The first PDPC strategy aims at balanced three-phase ac currents under unbalanced grid fault. Only the extractions of negative sequence grid voltages and positive sequence grid currents are needed to calculate the compensation items for power. The sequence extraction involves no PI tuning, but rather makes use of the instantaneous grid components together with their delayed counterparts.
(6) The second PDPC strategy aims at eliminating the double-frequency oscillations in both active and reactive power under unbalanced grid fault. Extension *pq* theory is directly incorporated into the controller without the need of sequence extraction. Similar to the first PDPC strategy, no tuning is needed.
(7) The proposed modified sorting, when comparing to conventional sorting, requires less computational effort by restricting the switching transitions, thereby achieving significantly less switching frequency.

The remainder of this paper is organized as follows. Section 2 discusses the topology and mathematical model for a three-phase grid-connected MMC. In Section 3, consideration is given to present the principle of the employed *pq* theories under unbalanced grid fault. Section 4 provides the detailed description of each control stage accompanied with a summarized comparison of the proposed tuning-less MPC with other MPC-based MMCs. The feasibility of the proposed control strategy is verified by simulation results in MATLAB/Simulink in Section 5. Finally, Section 6 draws the conclusions.

2. Mathematical model of MMC

The topology of a grid-connected three-phase modular multilevel converter (MMC) is shown in Fig. 1. The grid currents i_j, with $j \in \{a, b, c\}$ are modelled flowing from the utility grid to the converter through a series-connected inductor L_g and resistor R_g. Each phase unit comprises of an upper arm and a lower arm, with each arm comprises of N series-connected submodules (SMs). Each SM is composed of two active switches operate in a complementary manner to avoid short circuit of switches across the dc capacitor. The capacitor voltage of a SM is represented by v_c. As a SM has two operating modes, i.e. bypass and switched-in mode, the output voltage equals to either zero or v_c. In a $(N+1)$ MMC system, on the assumption that all the SM capacitor voltages are well balanced, the expressions for the upper arm voltage v_{uj} and lower arm voltage v_{lj} of phase j are estimated as follows [13]:

$$v_{uj} = n_{uj}\frac{v_{cuj}^{\Sigma}}{N},\; v_{lj} = n_{lj}\frac{v_{clj}^{\Sigma}}{N} = (N - n_{uj})\frac{v_{clj}^{\Sigma}}{N} \tag{1}$$

where v_{cuj}^{Σ} and v_{clj}^{Σ} correspond to the summation of upper SM capacitor voltages and SM lower capacitor voltages respectively, while n_{uj} and n_{lj} correspond to the number of switched-on SMs for upper arm and lower arm respectively. According to the Kirchoff's voltage law in Fig. 1, the model of the grid-connected MMC, when expressed in the three-phase stationary *abc* frame, are expressed as

$$\frac{V_{dc}}{2} = v_{uj} + R_{arm}i_{uj} + L_{arm}\frac{di_{uj}}{dt} - R_g i_j - L_g\frac{di_j}{dt} + e_j \tag{2a}$$

$$-\frac{V_{dc}}{2} = -v_{lj} - R_{arm}i_{lj} - L_{arm}\frac{di_{lj}}{dt} - R_g i_j - L_g\frac{di_j}{dt} + e_j \tag{2b}$$

where e denotes the grid voltage, V_{dc} denotes the dc side voltage, R_{arm} denotes the arm resistance, and L_{arm} denotes the arm inductance. By applying the Kirchoff's current law, the relationship between the grid currents and arm currents are

$$i_j = i_{lj} - i_{uj}. \tag{3}$$

To simplify the subsequent expressions for the proposed MPC, it is convenient to denote the difference of arm voltages as v_Δ, where $v_\Delta = v_l - v_u$.

Coupled with the relation outlined in (3), the dynamic equation of phase current i_j can be deduced by adding (2a) and (2b),

$$\frac{di_j}{dt} = \gamma_1 i_j - \gamma_2 v_{\Delta j} + 2\gamma_2 e_j \tag{4}$$