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Enhanced controller for grid-connected modular multilevel converters in distorted utility grids

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ABSTRACT

This paper is about the control of Modular multilevel converters, an innovative technology in the design of converters, which is beginning to be included in real installations. Papers about this topic include simulation models, circulating current reduction, voltage modulators, capacitor voltage balancing and control issues. The scheme for current source regulation used in this article includes all control loops, which are, from the outermost to innermost, DC bus voltage regulator, current regulator, voltage modulator, capacitor voltage balancing, and a PLL for the synchronization to the grid. Disposition-sinusoidal pulse width modulation is used as the voltage modulator, and an enhanced control strategy in the stationary reference frame for 3-phase MMCs is used for the inner current control loops. Very detailed simulations of the complete control system have been performed for both the enhanced control strategy in the stationary reference frame, and the well-known control in the synchronous reference frame, as well as some experiments using the hardware-in-the-loop simulation technique. The validation of these control strategies is made by a comparison of the capability of each one to compensate the harmonic distortions of the utility grid according to the grid code. The correct operation has been tested in the case of a strong/weak grid, unbalances and grid failures.

1. Introduction

The types of converters used for medium (MV) and high voltage (HV) AC/DC/AC conversion are line commutated converters (LCC) [1], voltage source converters (VSC) [2,3], and lately MMC, first used by Lesnicar and Marquardt [4]. LCC and VSC are the classical topologies used for converters, but VSC multilevel topologies have also been used [5]. The LCC topology is built with thyristors, while the VSC topology can use IGBTs, IGCTs or GTOs featuring two, three or more than three levels.

Modular multilevel converters (MMC) is a new topology that has acquired great interest for researchers [6] and which has begun to be implemented in actual installations. The base is a switching module (SM) composed by two bidirectional switches (IGBT + antiparallel diode) and a capacitor C (see Fig. 1). The converter is built using several SMs and an inductance per arm, two arms per phase, and containing three phases (see Fig. 1). The arm inductances L are used to couple the arm voltage to the DC bus voltage.

An MMC converter with n SMs per arm can generate a phase to midpoint of the DC voltage with n+ 1 levels. The number of AC output levels can be increased by increasing the number of SMs.

MMC has advantages and disadvantages regarding LCC and VSC [7]. The advantages include a reduction in the need for AC filtering, easy scalability, the distribution of the capacitive energy between several capacitors, and stress reduction in the semiconductor. The main disadvantage is the increased complexity: the number of modules and drivers, the number of signals to be handled, including module trigger and SM voltage feedback. Another disadvantage is the presence of the circulating three currents (one per phase) that circulate between each phase and the DC bus.

Studies about MMC tackle the analysis of semiconductor losses in comparison with other topologies, static and dynamic modeling, and

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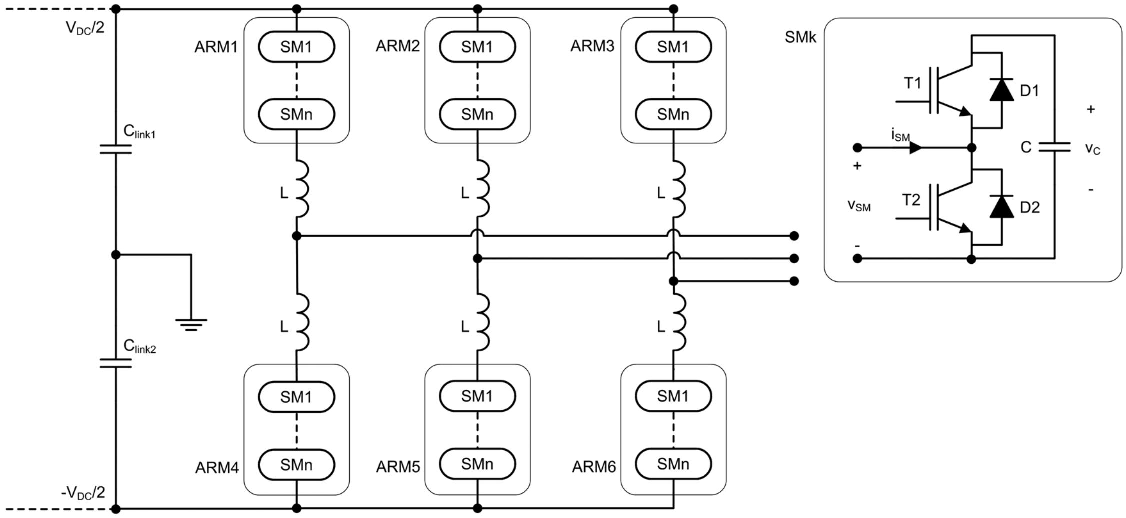

Fig. 1. MMC scheme and SM structure.

Table 1
Relations among elements and variables of the SM.

SM state	T_1 state	T_2 state	i_{SM}	Δv_C	i_{SM} flows through	v_{SM}
ON	ON	OFF	> 0	+	D_1	v_C
ON	ON	OFF	< 0	−	T_1	v_C
OFF	OFF	ON	> 0	0	T_2	0
OFF	OFF	ON	< 0	0	D_2	0

control in balanced and unbalanced grids [8]. The SM capacitor voltage changes when current flows through it, and several techniques can be used to keep those capacitor voltages balanced: sorting algorithms [7,8], averaged and balanced control [9], predictive control [10], methods which do not require the sign of the arm current to be known [11] and methods to decrease the switching frequency [12].

Moreover, if the semiconductor models are very accurate, the simulation of the MMC can be extremely slow because of the very high number of semiconductors. Therefore, less accurate models are studied to obtain simulation with a sufficient degree of accuracy through averaged and approximated models [13–16].

For the AC voltage modulator, several possibilities are described, such as PD-SPWM, multilevel PWM and current source predictive control. PD-SPWM is a type of PWM where the reference is compared with n carriers to obtain the gate signals of the SMs [8,17]. Multilevel PWM calculates the average value of the voltage over a commutation period and generates the duty cycle necessary to obtain it [7]. Predictive control evaluates a cost function that includes several parameters and selects the best combination of ON/OFF states of the SMs [10].

The upper and lower arms of a phase leg have current simultaneously; the consequence is the existence of undesired currents, the circulating currents. Their equations are calculated in Ref. [18], their suppression in Ref. [17], and their reduction in unbalanced systems in Ref. [19].

Other aspects of MMC studied are: models and control systems in unbalanced grids [20,21], influence of the commutation frequency and the number of SMs in the harmonic content [22], DC bus protection using thyristors included in the SMs [23] and current source control [24].

Regarding the 3-phase grid-connected renewable systems, several vector control strategies are studied in the scientific literature. Hysteresis control [25], dead-beat predictive control [26,27], and dq control [28,29], among others, have been widely used for several years with acceptable results. The linear dq control approach is the cheapest strategy and uses the well-known PI regulators in synchronous reference frame, which allow a zero steady-state error when DC variables are used, as well as an easy digital implementation in commercial microcontrollers; its main drawbacks are a lower dynamic response and a non-zero steady-state error when sinusoidal variables are used. On the contrary, the dead-beat predictive control has a higher dynamic response, but it is necessary to measure or estimate some variables, which increases the cost of the system, and is very sensitive to model mismatches and parameters uncertainties. The hysteresis control is a nonlinear strategy, having the fastest dynamic response, and being very easy to implement with analog devices, although enhanced more expensive signal conditioner circuits are needed due to the higher bandwidth of the measured line currents, which increases its overall cost; in addition, this strategy is almost insensitive to parameters uncertainties, and very robust to input and output disturbances, but a variable hysteresis band is mandatory [25] because its switching frequency is not constant, making the digital implementation very difficult.

The dq control strategy implemented in the synchronous reference frame [30] has been the preferable strategy for years and for this, the Park's transformation [31,32] is applied to the 3-phase line currents. However, a trade-off between the advantages and disadvantages can be noticed: although its digital implementation is very easy, its main drawbacks deal when it is used in 3-phase distorted grid-connected systems, where the low-order harmonic distortions of the grid voltages must be compensated because they will appear in the line currents instead, reducing the power quality and the power factor of the connection. The feedforward of the dq components of the grid voltages and the cross-coupling terms can solve the situation, but a high bandwidth is mandatory in the open loop transfer function of the line currents in order to decrease the effect of delays [33,34], which firstly, increases the switching frequency and, in consequence the losses, and last but not least, a programmable device such as an FPGA must be used.

The reduction of the power quality and the power factor can make impossible the connection of the renewable system to the utility grid if the magnitude of the individual harmonic distortions and/or the total harmonic distortion of the line currents are higher than the limits imposed by the grid code [35,36]. For the fundamental frequency ω_1 of the 3-phase utility grid voltages with positive-sequence, the implementation of a harmonic compensation scheme in the synchronous reference frame can be done as in [37], but the interpretation of the Park's transformation applied to the 5th, 7th, 11th, 13th, … harmonics must take into account the negative-sequence for the 5th and the 11th, as well as the positive-sequence of the 7th and 13th harmonics, and its transformation into the 6th and 12th harmonics, respectively, in the