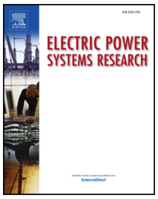
Electric Power Systems Research 163 (2018) 196–210

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



Modeling, control, and reduced-order representation of modular multilevel converters

Andres E. Leon[a,*], Santiago J. Amodeo[a,b]

[a] Instituto de Investigaciones en Ingeniería Eléctrica (IIIE) 'Alfredo Desages', Universidad Nacional del Sur (UNS)-CONICET, Avda. Alem 1253, Bahía Blanca 8000, Argentina
[b] ElectroAMSA Company, Mascarello 3560, Ingeniero White 8103, Argentina

ARTICLE INFO

Keywords:
Modular multilevel converter (MMC)
Power system simulations
Reduced-order model
Electromechanical transient analysis
Control systems

ABSTRACT

This paper presents a reduced-order model of the modular multilevel converter (MMC) for electromechanical transient simulations and small-signal analysis. The MMC model is firstly developed in detail; then, simplifications are introduced to reduce it to eleventh- and fourth-order models. The dynamic behaviors of the traditional voltage-source converter and the MMC are also compared. A thorough description of the MMC control system is presented including the inner current control loops, the outer voltage control loops, and the strategy to balance the floating capacitor voltages. Control systems in continuous- and discrete-time domains are given to enable their use in power system simulations and in practical implementations, respectively. Several tests are performed to compare the steady-state and transient response of the detailed and the reduced models. The results show that the fourth-order reduced model can properly capture the input-output dynamics of a complete MMC and significantly reduce the computational cost of large-scale power system simulations with multiple ac/dc converter stations.

1. Introduction

The first ac/dc converter stations based on voltage-source converters (VSCs) could not reach the high-power and high-voltage levels of the conventional line-commutated converters. VSC stations able to manage thousands of megawatts and to transmit at the highest voltage levels have recently become possible with the development of the modular multilevel converter (MMC) [1]. Many applications, such as multi-terminal dc systems, integration of offshore wind farms, and interconnection of asynchronous ac systems, are driven by these power converter developments [2–4]. To assess the impact of these installations on the system by means of small-signal and transient stability analyses, the converter stations are often represented by the traditional two- or three-level VSC [5–8], although multilevel converters such as the MMC are more appropriate for these power and voltage ranges. The characteristics of converter stations based on the MMC are not accurately described by the traditional VSC model. Both converter models have a similar representation on the ac side but a different one on the dc side, where the traditional VSC behaves like a voltage source and the MMC behaves like a current source [9].

Detailed models of the MMC with explicit representation of all submodule capacitors are not suitable for the stability analysis of large-scale power systems due to their high computational cost and the required small simulation time steps [2]. On the other hand, another issue should be considered in detailed models. Unlike to what happens in the traditional VSC, the alternating arm currents of the MMC cause ripples in the submodule capacitor voltages during normal steady-state operation [10]. The modeling of these ripples can be a drawback in power system stability analyses that require a constant equilibrium point to compute eigenvalues and small-signal properties [11]. To simplify the MMC representation, averaged or continuous models have been proposed in [12–15] but, as the arm capacitor voltage ripple is still modeled, these models do not have a constant equilibrium point; therefore, they cannot be used to perform small-signal (modal) analysis. To solve this issue, in [16–19], different rotating reference frames are defined and, after neglecting some terms, the oscillating variables are transformed to constant values. As in the averaged models, these approaches represent the individual arm voltages that require the inclusion of the circulating current control and the inter-arm voltage balancing algorithm in their control systems.

On the other hand, reduced models are usually considered in large-scale power systems where electromechanical transients are studied and the MMC is analyzed from an input-output point of view [20]. These models reduce the amount of state variables by assuming that the

---

[*] Corresponding author.
E-mail address: aleon@iiie-conicet.gob.ar (A.E. Leon).

https://doi.org/10.1016/j.epsr.2018.05.024
Received 10 November 2017; Received in revised form 16 February 2018; Accepted 23 May 2018

balancing of the submodule capacitor voltages is internally performed by the converter control system. In [21–26], reduced models have been proposed, but they do not model the MMC inductive behavior on the dc side, which was solved in [27–31] by adding a dc-side inductance. However, in these papers, the MMC representation is derived from a power balance equation, resulting in an RLC circuit that does not show the effect of the zero-sequence modulation index on the dc side. As shown in [32], the dc-side dynamics depends on the zero-sequence modulation index, and this has an impact on the accuracy of the transient response. This distinctive characteristic of the MMC also allows to independently control the total converter energy and the dc-bus voltage.

The contributions of this work can be summarized as follows: (1) the modeling and control of the MMC are described in detail –a step-by-step derivation is provided; (2) a reduced-order model of the MMC suitable for transient and small-signal stability studies is developed –this model allows to design the outer control loops in networks with multiple MMCs, as well as to speed up large-scale power system simulations; and (3) a comparison between the traditional VSC and the MMC is also performed to show their distinctive dc-side dynamics.

The paper is organized as follows. In Sections 2 and 3, a comprehensive model of the current and voltage dynamics is obtained directly from the MMC electrical circuit. The current control loops and the capacitor voltage balancing are described in Sections 4 and 5, respectively. The reduced MMC model is introduced in Section 6, where a comparison with the traditional VSC is also discussed. The inner and outer control loops of the reduced model are presented in Section 7. Section 8 evaluates the performance of the proposed control systems and compares the detailed and reduced models using the 401-level MMC of the France-Spain electrical interconnection (INELFE) project [33]. Finally, conclusions are drawn in Section 9.

2. MMC currents

2.1. Basic equations of the MMC electrical circuit

Applying the Kirchhoff's voltage law to the loops connecting the points *M–p–z–M* and *M–n–z–M* of the circuit shown in Fig. 1(b), the following equations are obtained, respectively

$$\frac{v_{\mathrm{dc}}}{2} - v_p^z + R_s i_p^z + L_s \dot{i}_p^z = v_{\mathrm{zM}} \tag{1}$$

$$-\frac{v_{\mathrm{dc}}}{2} + v_n^z - R_s i_n^z - L_s \dot{i}_n^z = v_{\mathrm{zM}} \tag{2}$$

where *M* is the fictitious dc-side midpoint, *p* and *n* are the positive and negative nodes, and the point $z = \{a, b, c\}$ is the midpoint of a generic converter phase-leg. The rest of the variables and parameters are defined in Fig. 1(b). Adding and subtracting (1) and (2) result in

$$v_n^z - v_p^z + R_s(i_p^z - i_n^z) + L_s(\dot{i}_p^z - \dot{i}_n^z) = 2v_{\mathrm{zM}} \tag{3}$$

$$v_{\mathrm{dc}} - v_p^z - v_n^z + R_s(i_p^z + i_n^z) + L_s(\dot{i}_p^z + \dot{i}_n^z) = 0. \tag{4}$$

Applying the Kirchhoff's voltage law to the loop *N–z–N* yields

$$v_g^z - R_e i_g^z - L_e \dot{i}_g^z = v_{\mathrm{zN}} \tag{5}$$

where *N* is the ac-side neutral point. On the other hand, applying the Kirchhoff's current law to the positive and negative nodes of the MMC gives

$$i_{\mathrm{dc}} = i_p^a + i_p^b + i_p^c = \sum_{w=a,b,c} i_p^w \tag{6}$$

$$i_{\mathrm{dc}} = i_n^a + i_n^b + i_n^c = \sum_{w=a,b,c} i_n^w \tag{7}$$

whereas applying the Kirchhoff's current law to the midpoint of a phase-leg gives

$$i_g^z = i_p^z - i_n^z. \tag{8}$$

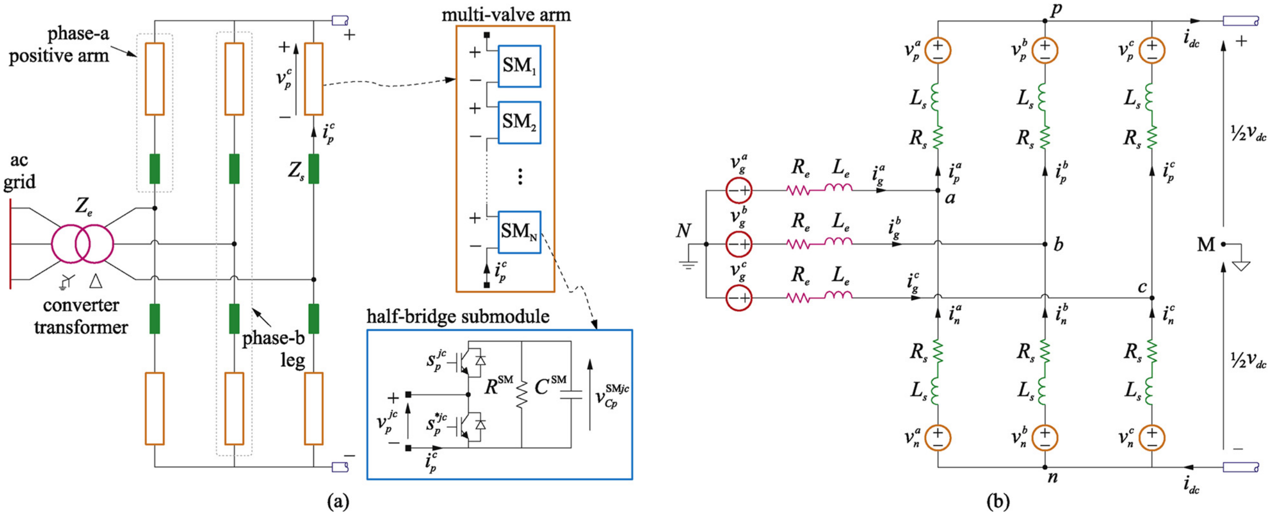
Unlike the traditional VSC, due to unequal voltages among the legs, the MMC has a current that can circulate within the three phases, in the following referred to as circulating current. This circulating current is independent of the ac and dc currents, and it is not seen in the output terminals of the converter. The arm currents can be written as a function of the above three currents as follows [34]

$$i_p^z = \frac{i_{\mathrm{dc}}}{3} + \frac{i_g^z}{2} + i_{\mathrm{cir}}^z \tag{9}$$

$$i_n^z = \frac{i_{\mathrm{dc}}}{3} - \frac{i_g^z}{2} + i_{\mathrm{cir}}^z \tag{10}$$

where it has been assumed that the dc current is equally divided among the three legs of the converter and that the ac current is equally divided between the two arms of a leg. This assumption is reasonable because, under normal operating conditions, the impedance of each arm is similar [35]. In (9) and (10), the circulating current is the same for both arms of a leg because, by definition, this current flows inside the converter, and it also verifies

$$i_{\mathrm{cir}}^a + i_{\mathrm{cir}}^b + i_{\mathrm{cir}}^c = 0. \tag{11}$$



(a) (b)

Fig. 1. Topology of the MMC. (a) Detail of the converter arm. (b) Equivalent electrical circuit.