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State-space model and PQ operating zone analysis of hybrid MMC

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ABSTRACT

A steady-state time-invariant (SSTI) state-space model is proposed in this paper for the hybrid modular multilevel converter (hybrid MMC). To analyze the internal dynamics of the hybrid MMC, the phasor modelling method is employed with considering three different frequency components in modulation signals. Originating from the state-space model, the steady-state model is obtained for analytically illustrating operating characteristics of the hybrid MMC. A 'scan and check' method is proposed to determine the feasible *PQ* operating zone of the hybrid MMC with considering multiple operating constraints, especially the requirement for successful voltage balancing of half-bridge sub-modules (HBSMs). The accuracy of the state-space model is verified by comparing the time-domain response with the equivalent electromagnetic model of a hybrid MMC in PSCAD/EMTDC. Feasible operating zones of the tested system under different DC terminal voltages are calculated. The effects of different operating constraints on limiting the *PQ* operating zone are analyzed. The impact of converter parameters such as the sub-module ratio, the arm reactance and the sub-module capacitance on the operating zone is presented in detail.

1. Introduction

The application of the modular multilevel converter (MMC) in practical voltage source converter based high voltage direct current (VSC-HVDC) transmission projects has drawn significant attention due to the various advantages of MMC in operation and control [1]. Comprehensive studies on design, modelling and application of the half-bridge sub-module (HBSM) based MMC (HB-MMC) have been reported [2–7]. But the HB-MMC lacks the ability to isolate the DC fault current. To enable overhead line transmission, the full-bridge sub-module (FBSM) based MMC (FB-MMC) can be employed, which has the capability to output both positive and negative voltages and actively interrupt the DC fault current. However, the high cost and power loss hamper the application of the FB-MMC. To achieve a trade-off between DC fault isolation ability and economic competitiveness, the MMC composed with mixed HBSMs and FBSMs (termed as the hybrid MMC) is considered as an effective approach [8–14].

Recently, there has been increasing attention on the topology, sub-module ratio design and the control strategy of the hybrid MMC [8–14]. To analytically describe operating characteristics and analyze the small signal stability of the hybrid MMC, a steady-state time-invariant (SSTI) state-space model should be developed [15]. There have been some researches on the SSTI modelling of the HB-MMC [15–17]. These models are primarily derived based on average dynamics of the MMC with well representing the internal dynamics of the HB-MMC [18]. However, compared with the HB-MMC, the hybrid MMC can output negative voltage and operate under the reduced DC terminal voltage, which brings about more control freedoms and state variables. As a result, the state-space model of the HB-MMC cannot be directly applied to the hybrid MMC.

To enable small-signal and steady-state studies, this paper presented a generic SSTI model of the hybrid MMC using the phasor modelling method. The internal dynamics of the hybrid MMC are modelled under rotating frames, such as the dynamics of capacitor voltages and circulating currents. The difference of the SSTI models between the HB-MMC and the hybrid MMC is analyzed. By setting the derivatives of the SSTI model to be zeroes, a steady-state model is obtained. Based on the steady-state model, *PQ* operating zones under different DC terminal voltages are portrayed using a 'scan and check' approach. A fast calculation method for approximately illustrating the *PQ* operating zone regarding the HBSM balancing constraint is disclosed. The accuracy of the state-space model is validated by time-domain simulation in contrast with electromagnetic simulation.

The remainder of this paper is as follows. Section 2 demonstrates derivation of the SSTI state-space model of the hybrid MMC. Section 3 presents the steady-state model and the solving process based on the operating principle of the hybrid MMC. Section 4 presents the proposed 'scan and check' calculation method as well as a fast calculation method

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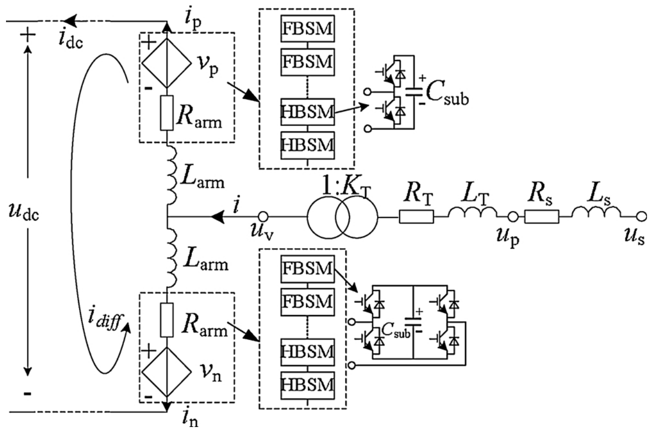

Fig. 1. Equivalent circuit for one phase leg of hybrid MMC.

for the hybrid MMC. Section 5 presents the simulation validation of the SSTI state-space model. Section 6 presents the analysis of operating zones under different DC terminal voltages and the impact of operating constraints and converter parameters on the *PQ* operating zone.

2. Steady-state time-invariant state-space model of the hybrid MMC

2.1. Basic operating principle of the hybrid MMC

The equivalent circuit for one phase leg of the hybrid MMC is shown in Fig. 1. Each phase leg of the hybrid MMC is composed of half HBSMs and half FBSMs. Two controlled voltage sources v_p and v_n represent output voltages of the upper and lower arm respectively. R_{arm} and L_{arm} represent the equivalent resistance and reactance of the phase arm. C_{sub} denotes the rated capacitance of the HBSM and FBSM. i_{diff}, i_p and i_n denote the circulating current, upper arm current and lower arm current respectively. Default positive directions of the currents are depicted as shown in Fig. 1. u_{dc} represents the DC terminal voltage. i represents the AC current. K_T, R_T and L_T are the ratio, equivalent resistance and equivalent reactance of the AC transformer. R_s and L_s are the equivalent resistance and reactance of the AC system. u_v, u_p, u_s are the voltages of the converter AC-side, the point of public coupling (PCC) and the AC system respectively.

The elementary control scheme of the hybrid MMC [10] is illustrated in Fig. 2. Three modulation signals with different frequencies are generated by the elementary control. m(t) generated by the inner AC current control loop is the modulation signal of fundamental frequency. The outer loop for d-axis regulates the average value $V_{c,avg}$ of total capacitor voltages in three phase arms to ensure the balance of arm energies. The outer loop for q-axis regulates the reactive power Q_{pu}. m_{dc}(t) is the DC modulation signal generated by the DC current control loop. The outer loop for the DC current control regulates the active power or the DC voltage and outputs the DC current reference value. m_{diff}(t) generated by circulating current suppression control (CCSC) is the modulation signal of double fundamental frequency. This paper focuses on the electric system modelling for the hybrid MMC, and the control dynamics are not involved. The effect of the controller is embodied in the modulation signals, which are regarded as parameters for the open-loop state-space model.

From the perspective of the phasor modelling, electric phasors for the electric system of the HB-MMC and hybrid MMC are similar. While according to Fig. 2, comparing the traditional double-loop control scheme of the HB-MMC with the elementary control scheme of the hybrid MMC, it can be found that the elementary control of the hybrid MMC introduces more control freedoms and constraints, which can be reflected in the composition of the arm modulation signals and the operating constraints.

Based on the analysis above, the difference of the phasor models for the HB-MMC and the hybrid MMC exists in the embodiment of the control system, i.e., the parameters of modulation signals. The modulation signals for the HB-MMC model in Ref. [16] need to be modified according to Fig. 2, while the rest parts in the HB-MMC model can be successively employed for the hybrid MMC model.

2.2. State-space model of the hybrid MMC

Suppose that the rated DC terminal voltage of the hybrid MMC is u_{dcN}, and the rated capacitor voltage of the HBSM and FBSM is u_{cN}. Then the total number N_{sm} of sub-modules per arm can be calculated (neglecting redundancy) by

$$N_{sm} = u_{dcN}/u_{cN} \tag{1}$$

Referring to the elementary control of the hybrid MMC, the modulation signals for the upper and lower arm m_p and m_n can be represented as

$$\begin{aligned} m_p(t) &= \tfrac{1}{2}m_{dc}(t) - \tfrac{1}{2}m(t) - \tfrac{1}{2}m_{diff}(t) \\ m_n(t) &= \tfrac{1}{2}m_{dc}(t) + \tfrac{1}{2}m(t) - \tfrac{1}{2}m_{diff}(t) \end{aligned} \tag{2}$$

As can be seen, compared with the HB-MMC, each arm modulation signal of the hybrid MMC contains a DC component m_{dc}(t) to regulate the DC voltage in order to match the reduced DC terminal voltage.

The output voltages of the upper and lower arm v_p(t) and v_n(t) can be expressed as [16]

$$v_p = m_p v_p^{\Sigma},\ v_n = m_n v_n^{\Sigma} \tag{3}$$

where v_p^{Σ} and v_n^{Σ} denote the total capacitor voltage of the upper and lower arm respectively.

The circulating current i_{diff} can be represented by arm currents as

$$i_{diff} = (i_p - i_n)/2 \tag{4}$$

Since the electric dynamics of the HB-MMC and hybrid MMC are similar, the SSTI state-space model of the hybrid MMC can be derived by directly replacing the modulation signals of the HB-MMC by Eq. (2). Thus, the single phase SSTI state-space model of the hybrid MMC under static ABC frame can be obtained as shown in Eq. (5), where $C_{arm} = C_{sub}/N_{sm}$. The state variables (v_p^{Σ}, v_n^{Σ}, i_{diff}) relate to the internal dynamics of the converter. The AC current and DC terminal voltage are

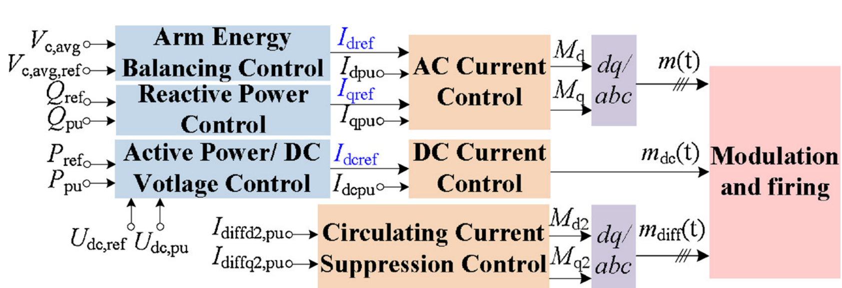

Fig. 2. Elementary control of a hybrid MMC.

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