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Zero-sequence voltage injection control scheme of modular multilevel converter supplying passive networks under unbalanced load conditions

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ABSTRACT

Modular multilevel converters have a promising application in passive network supply, such as offshore platforms and remote loads. In these applications, load imbalance is inevitable and the established unbalanced control strategies for active network applications, which are mainly based on negative-sequence voltage canceling, are no longer feasible. Novel control strategy for unbalanced load conditions is required to perform under the constraint of constant line-to-line voltages and uncontrollable load currents. And the major control object is to eliminate both the overcurrent and the thermal overload problems of arm currents due to the load imbalance. The former may cause the converter to switch offline, while the latter may exceed the I^2t capability of power semiconductors. This paper proposes a control strategy to balance the arm currents. On the basis of the equivalent relationship of dc-link active power and ac-link average active power, the dc component of the arm current is determined by the ac-link average active power in the corresponding phase. By adding a common zero-sequence voltage to the reference voltages, the average active power in each converter phase can then be regulated, and the arm current can be controlled. By balancing the peak value of the arm currents, the safe operation area of the converter can be increased under unbalanced operation conditions. Simulation results and experimental results verify the validity of the control scheme.

1. Introduction

Modular multilevel converters (MMCs) are enabling topology for high-voltage dc transmission (HVDC) systems because of their modular design, low switching frequency, high efficiency, and excellent output waveforms [1,2]. Major attention has been drawn to the application of MMC in ac grid interconnection and renewable energy integration, where MMC is interacted with active ac networks. However, the supplying passive networks are also typical scenario in cases such as power transmission to isolated or remote load centers, and offshore oil or gas platforms, where the receiving network lacks of local generation [3,4]. Compared to local generation supply, HVDC transmission can minimize emission of green house gases and reduce supply costs [5]. And for offshore platforms far from shore, HVDC transmission is the only feasible solution due to the ac cable charging current issues [4–6]. Especially, with the development of offshore platforms and future multi-terminal HVDC grid, supplying passive networks will become an emerging and promising application trend for MMC based HVDC systems [5,7]. The Troll A project and the Valhall project bringing power to offshore platforms with HVDC commissioned in 2005 and 2011, respectively [8,9]. Two additional HVDC links to the Troll A platform will be constructed by ABB in 2015 [9].

Unlike interconnecting active networks, MMC acts as a constant-frequency, constant-amplitude and balanced voltage source for load in passive networks, and operates in ac voltage and frequency control (VF control) mode [10]. The ac currents are thus determined by load. In passive networks, load imbalance is usually inevitable, even during normal operation when there is no fault. Some unbalanced control methods for the active network applications have been reported. A dynamic model for the MMC has been developed in negative and positive synchronous reference frames [1,11]. Then negative-sequence currents can be eliminated by canceling the negative-sequence grid voltage. The zero-sequence current can be controlled by using a PI feed-back controller with a zero-sequence grid-voltage feed-forward compensator [12]. An approach to suppress ac-link active power ripples and dc-link power ripples was proposed in [13] by controlling

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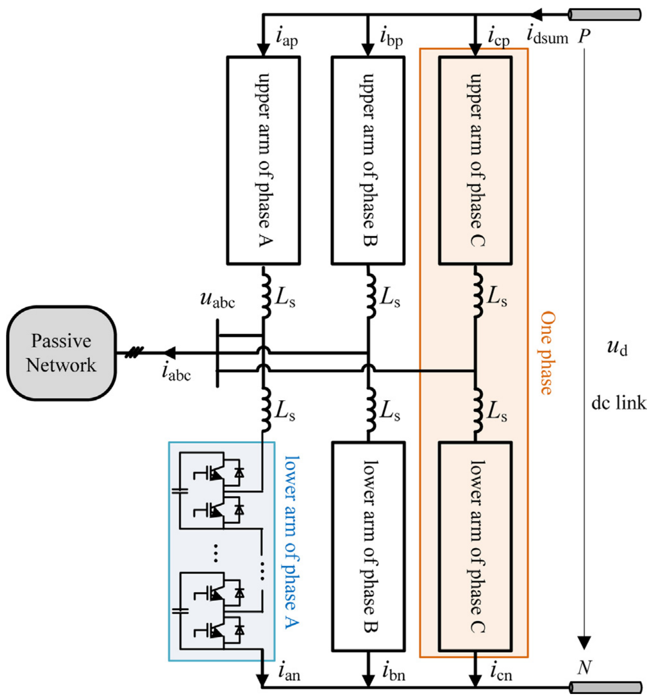

Fig. 1. Circuit diagram of MMC supplying passive networks.

the second harmonic circulating current. The above-mentioned approaches can improve the performance of MMC for the active network applications. However, they may be unfeasible for the MMC in applications supplying passive networks. This is because the unbalance control should be implemented under the constraint of uncontrollable ac current and constant line-to-line ac voltage. This is the major difference of unbalanced control for MMC between active and passive network applications.

During unbalanced load conditions, both overcurrent and thermal overload may arise on six arm currents and result in poor converter capacity utilization. To demonstrate these phenomena, an unbalanced load condition is chosen with unbalanced degrees $I_{2m}/I_{1m} = 10\%$, $\varphi_{i2} - \varphi_{i1} = 210^\circ$. I_{1m} (I_{2m}) and φ_{i1} (φ_{i2}) represent the amplitude and the phase of the positive- (negative-) sequence component of the load current, respectively. The configuration of MMC is shown in Fig. 1. The waveforms of the load currents and three upper-arm currents are shown in Fig. 2. The three lower-arm currents are similar to those of the upper-arm currents, with 180° lagging, and are thus not shown here. During unbalanced operation, load current of some phase may have larger amplitude over others, for instance the phase-c current in Fig. 2(a). Correspondingly, arm current of the same phase also has larger amplitude, as shown in Fig. 2(b) that the phase-c arm current has the largest peak value (red dot). It indicates that some arm current may exceed the overcurrent protection threshold, thereby tripping the MMC, even though those of other arms are lower than the threshold. Meanwhile, the phase-c arm current also has the largest root mean square (RMS) value (red shaded area), as shown in Fig. 2(b). It indicates that some arm current has to withstand more severe thermal stress. If the thermal stress of any arm exceeds the I^2t capability of power semiconductors, overload protection is triggered, even though the loads of other arms are lower than the rated capacity. That is, the safe operation area of MMC under unbalanced operation is smaller than the rated capacity of MMC. To fully utilize converter capacity, an unbalanced control strategy should be included in the controller to balance the working conditions of the six arms and to eliminate both the overcurrent and overload problems caused by unbalanced operations.

One approach to avoid the overcurrent and overload problems is to control the double-frequency circulating currents. It can be implemented by injecting double-frequency voltages [14] or various harmonic voltages [15]. Under unbalanced conditions, the positive-sequence and zero-sequence double-frequency circulating currents may arise, which can also be controlled by injected corresponding harmonic voltages [16–18]. Although the double-frequency circulating currents can affect the arm currents, it may also have significant impacts on many other aspects, such as the capacitor voltage ripples and power losses of the whole converter [15]. There is possibility that it may lead to some unwanted problems such as the rising of capacitor voltage ripples and the increase of the total power losses, which is not conductive to the converter operation. Therefore, determining the appropriate reference of the double-frequency circulating current is complicated and requires comprehensive consideration.

Another approach is to control the dc circulating current, instead of the double-frequency component, since the relationship between the dc circulating current and the peak of the arm current is much more clear and concise. In addition, the dc circulating current has slight impacts on the capacitor voltage ripples and power losses. From the power point of view, to balance the working conditions of six arms is to balance the average active power of three phases, since the ac-link average active power in each converter phase is a reflection of the arm currents in MMC. Furthermore, from the current point of view, to regulate the average active power among phases is to regulate the dc component of the arm currents. This is because the dc component of the arm current is proportional to the average active power transmitted by the corresponding phase, considering that the dc-link voltage is usually stable. Although the output line-to-line voltages are constrained, the average active power transmitted by each phase can be controlled by changing the line-to-neutral voltages [19]. That is, this approach can be implemented by adding a common zero-sequence voltage to the reference voltages.

This paper proposes a control scheme for an MMC-based HVDC system supplying passive networks under unbalanced load conditions. By introducing a zero-sequence voltage injection method, the balanced control for the arm currents can be achieved under constant output line-to-line voltages and uncontrollable load currents. The overcurrent and overload problems of the arm current caused by unbalanced load can be eliminated, resulting in the incensement of the safe operation area of MMC under unbalanced load conditions. The rest of this paper is organized as follows. Section 2 presents the principle on how unbalanced load currents affect arm currents, or the reason of the overcurrent and overload problems of arm currents. In Section 3, a control scheme based on zero-sequence voltage injection is proposed. The calculation approach of the injected zero-sequence voltage and the control block diagram are given. To validate the proposed scheme, simulation results based on PSCAD/EMTDC and experimental results based on a laboratory prototype are shown in Sections 4 and 5, respectively. The impacts of the proposed control strategy on the arm currents and modulation are also analyzed. Finally, conclusions are given in Section 6.

2. Impact of load current on arm currents

Unbalanced load currents affect both the ac and dc components of the MMC arm currents and may cause overcurrent and overload problems. The effect of the load currents on the ac component of arm current is obvious because the ac component is equivalent to half the load current. The load current indirectly affects the dc component of arm current through the power interaction between the ac link and the dc link.