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Comparison of bipolar sub-modules for the alternate arm converter

Harith R. Wickramasinghe [a,*], Georgios Konstantinou [a], Josep Pou [b]

[a] Room 325, Bldg H6, Tyree Energy Technologies Building (TETB), University of New South Wales, Sydney, NSW 2052, Australia
[b] Nanyang Technological University, Singapore

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ABSTRACT

The alternate arm converter (AAC) is an emerging dc-fault tolerant multilevel converter topology aimed at high-power and HVDC applications. This paper addresses the suitability of modular multilevel converter (MMC) submodules (SMs) for the AAC. Bipolar SMs are applicable for AACs depending on the complexity, controllability, device count, and operating losses. However, only the full-bridge SM (FB-SM) and the cross-connected SM (CC-SM) are fully controllable and functional in AACs. Based on the loss analysis of FB-SM- and CC-SM-based AAC with different device configurations, it is shown that: (i) complex SM structures do not benefit the operation of AAC, and (ii) the FB-SM provides the most functional advantages in an AAC.

1. Introduction

Research on dc-fault tolerant multilevel converters has gained noticeable attention over recent years [1–3], and the alternate arm converter (AAC) [4], a hybrid topology of the two-level converter and the modular multilevel converter (MMC) is such an emerging multilevel converter topology. Since its introduction [5], the modular multilevel converter (MMC) has become the state-of-the-art in high-voltage direct current (HVDC) systems and medium voltage applications [6]. Apart from the inherited features of multilevel voltage source converters (VSCs), additional features of the MMC and its hybrid topologies in high-power applications include: (i) modularity, (ii) scalability, (iii) ability to handle wide power and voltage ratings, (iv) relative simplicity of submodule (SM) capacitor voltage balancing, and (v) redundant configuration [7]. Owing to the large number of voltage levels, MMCs provide near sinusoidal output voltages and currents with low harmonic distortion.

The MMC topology shown in Fig. 1(a) consists of N series connected SMs per arm, and two inductors (L) connecting the two arms to form one phase-leg. SM capacitor voltage balancing, circulating current control, and arm energy balancing are the key control requirements of MMCs. A variety of modulation methods [2,8,9] can be applied to MMC-based topologies, and the staircase modulation techniques are the most efficient over the alternatives as the number of voltage levels increases [10]. Different strategies can also be applied for SM capacitor voltage balancing [11,12] where the most commonly used is based on a 'sort and select' algorithm. Two major circulating current control techniques based on stationary reference frame with proportional-resonant (PR) controllers [13,14], and double-frequency rotating reference frame with decoupled current control [15] are applicable to MMCs.

MMC SMs can be divided in two categories based on the capability to generate negative voltage levels in the output. Unipolar SMs generate only positive voltage levels, and bipolar SMs generate both positive and negative voltage levels [16]. One of the major drawbacks of MMCs based on unipolar SMs [17] is the lack of dc-fault handling capability. The use of bipolar SMs in MMCs offers voltage blocking capability during dc-faults. A variety of SM configurations [16,17] are available for MMCs which can offer additional functionalities and dc-fault tolerant capability at the cost of increased semiconductor device count and higher losses.

The AAC [4], shown in Fig. 1(b), consists of bipolar and fully controllable SMs which provide the blocking voltage during dc-faults [18] and has been introduced in order to address the dc-fault handling issues of the MMC. The structure of the AAC maintains traits of the MMC structure with the addition of director switches (DSs) in the upper and lower arms as shown in Fig. 1(b). Owing to the use of bipolar SMs, the AAC can generate peak ac voltages above the dc-link voltage up to a maximum ac peak voltage of $4/\pi$ times the dc-link voltage, (as it will be demonstrated in Section 2). This is called "sweet-spot" [4] operation, and is defined as the operating point where the net energy exchange within the arms is equal to zero. Non-sweet-spot operation leads to non-zero net energy

* Corresponding author.
E-mail address: harith@student.unsw.edu.au (H.R. Wickramasinghe).

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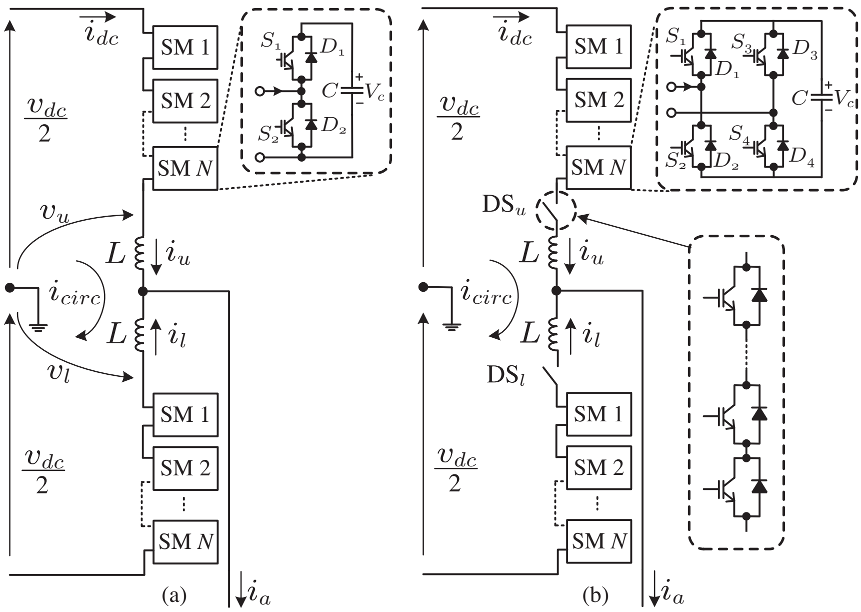

Fig. 1. MMC and AAC circuit configurations: (a) MMC phase-leg and (b) AAC phase-leg.

exchange within the AAC arms, causing deviations in the steady-state SM capacitor voltages.

The arm energy regulation and the upper/lower arm energy balancing can be achieved using overlap period based methods [19,20] or current injection methods [21,22]. Arm energy balancing of the AAC at non-sweet-spot operation is challenging due to the alternate operation of the DSs. The arms of an AAC phase-leg alternatively conduct the total phase current during each half of the voltage cycle. Hence, the energy has to be exchanged between the two arms by overlapping the operation of two DSs [19] or by injecting a zero-sequence current. Zero-sequence voltage injection can also be utilized to change the span of overlap period and ac voltage push-up period [21]. Additionally, use of an star-connected transformer at the ac-side of the AAC with a neutral connection to the dc-side allows the zero-sequence current to transfer energy between AAC arms and the dc-side [22]. The non-zero net energy exchange at non-sweet-spot operation and the zero-current switching of the director switches should also be considered in AAC SM capacitor sizing [23] and arm inductor sizing [24].

The similar structural characteristics between MMCs and AACs in terms of the topology and SM capacitor voltage sorting and balancing [18,12], make it feasible to apply MMC SMs to the AAC depending on their: (i) suitability, (ii) full controllability, (iii) complexity, (iv) ease of capacitor voltage balancing, and (v) component count [16,17]. Although there are several bipolar SM configurations in addition to the FB-SM, only the cross-connected SM (CC-SM) is suitable for the AAC, as it offers the fully controllable bipolar operation with full voltage blocking capability [16].

Existing literature evaluates the fitness of different SM configurations for MMCs, based on the circuit complexity, capacitor voltage balancing capability, and SM losses [16,17,25]. A CC-SM-based generalized SM structure is proposed for AACs in [26] using nonidentical switching devices, and the device count is reduced compared to the FB-SM-based AAC. Although the CC-SM with nonidentical switching devices reduces the device count, it becomes less modular in device-level, which adds to the overall complexity. Moreover, CC-SMs with different switching device configurations leads to significant differences in AAC losses. Although bipolar SMs are proposed as applicable to AACs, the suitability of those SMs for the AAC is yet to be investigated subject to complexity, voltage balancing, and operating losses. The aim of this paper is to provide a comparison and loss analysis of bipolar SMs for the AAC, investigating the relative merits of complex bipolar SM structures for AACs.

The paper is organized in the following manner. Section 2 provides an overview of the basic operating principles of the AAC, and a description of applicable SMs is presented in Section 3. Simulation results of FB-SM- and CC-SM-based AACs are demonstrated in Section 4. Section 5 offers an evaluation of the losses in CC-SM and FB-SM-based AACs, demonstrating impact of identical and nonidentical switching devices on the losses of CC-SMs. Section 6 summarizes the conclusions of the work.

2. AAC operating principles

2.1. Structure

The single-phase AAC topology is shown in Fig. 1(b). Each phase-leg of the AAC consists of two arms with N series-connected SMs, one inductor (L), and a director switch (DS) per arm. A single dc-source is utilized on the dc-side of the three-phase AAC topology. The SM, which is the basic building block of the AAC, is based on bipolar configurations [16,17].

The AAC topology has a similar structure to the MMC as shown in Fig. 1 with the exception of the DSs (DS_u and DS_l). The DSs operate alternatively during the positive and negative half-cycles of the reference waveform (v_{am}) of the output voltage:

$$v_{am} = m_a \cos(\omega t), \tag{1}$$

respectively. The duty-ratios of the upper and lower arms (d_u and d_l) are then defined as:

$$d_u = 1 - v_{am}, \tag{2}$$

$$d_l = 1 + v_{am}, \tag{3}$$

where the duty-ratios are limited to $|d_{u,l}| \le 1$, and define the number of SMs (n_u and n_l) of the arm to be inserted. When the AAC operates above the dc-link voltage ($m_a > 1$), the duty-ratios become negative for a small period. The negative sign of the duty ratios represents the insertion of SMs in the opposite direction.