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Controlled transition bridge converter: Operating principle, control and application in HVDC transmission systems

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ABSTRACT

This paper employs an amplitude modulation with sinusoidal plus third harmonic injection instead of trapezoidal modulation to operate a controlled transition bridge (CTB) converter as ac/dc and dc/ac converter terminals. With such an operation, the CTB converter may require small ac filters; thus attractive for high-voltage direct current (HVDC) transmission systems. To facilitate ac voltage control over a wide range and black-start capability, the injected 3rd harmonic allows the cell capacitor voltages of the CTB converter to be regulated independent of the modulation index and power factor. The insertion of 3rd harmonic into modulating signals achieves two objectives: extends the regions around voltage zeros so that the total voltage unbalanced can be distributed between the cell capacitors, thereby exploiting the bipolar capability of the full-bridge cells in each limb; and to ensure that each limb can be clamped to the positive and negative dc rails every half fundamental period independent of the modulation index to allow recharge of the cell capacitors from the active dc link. The suitability of the CTB converter for HVDC type applications is demonstrated using a two-terminal HVDC link that employs a 21-cell CTB converter, considering normal operation and ac faults.

1. Introduction

Multilevel converters have found many applications at generation, distribution and transmission systems. This increasing trend started with the introduction of half and full bridge modular multilevel converters (HB-MMC and FB-MMC), which are well suited for high-voltage high-power applications [1–5]. Afterward, several multilevel converters were developed to overcome some of the main weaknesses of the MMCs such as: large footprint due to excessive use of cell capacitors, complex power circuit with many possibilities for malfunctions and high conversion losses should dc fault reverse blocking functionality is required [2,6–17]. Among reverse blocking converters, mixed cell modular multilevel converter (MC-MMC) retains the elegancy and modularity of the FB-MMC and offers relatively low semiconductor losses, without the drawbacks of the hybrid converters such as an alternative arm converter (AAC) and the hybrid cascaded two-level converters presented in Refs. [4,18–25]. The majority of the MMC type converters proposed, such as those employing flying capacitor cells, three-level cells and five-level cells do not offer new features beyond those offered by the HB-MMC and MC-MMC [7,26]. Therefore, these converters are less likely to be adopted in practical systems due to increased topology and control complexity. However, hybrid multilevel converters such as AAC and controlled transition bridge converter (CTB) have advantages over the FB-MMC and MC-MMC such as small footprint, competitive level of semiconductor loss, and high power density [20,27]. However, their large input dc link capacitors for characteristic harmonic filtering is a major drawback that may hamper their applications in HVDC transmission systems; particularly, in multi-terminal HVDC networks. Amongst the non-reverse dc fault blocking converters (with the exception of the conventional two-level converter), the CTB converter combines the lowest semiconductor loss and smallest footprint, which are attractive in applications with confined space requirements such as offshore wind farms and oil platforms. Ref. [28] presented an alternative version of the CTB converter, in which the split dc link capacitors of the CTB converter are replaced by two blocks of full-bridge chain-links aim to achieve the following objectives:

a) Avoids the increase of dc fault level during dc short circuit fault; as blocking of these additional chain links will be sufficient to stop discharge of the full-bridge cell capacitors to the dc fault.
b) The capacitance of the actively controlled cell capacitors could be increased in order to act as proper buffer between converter ac and

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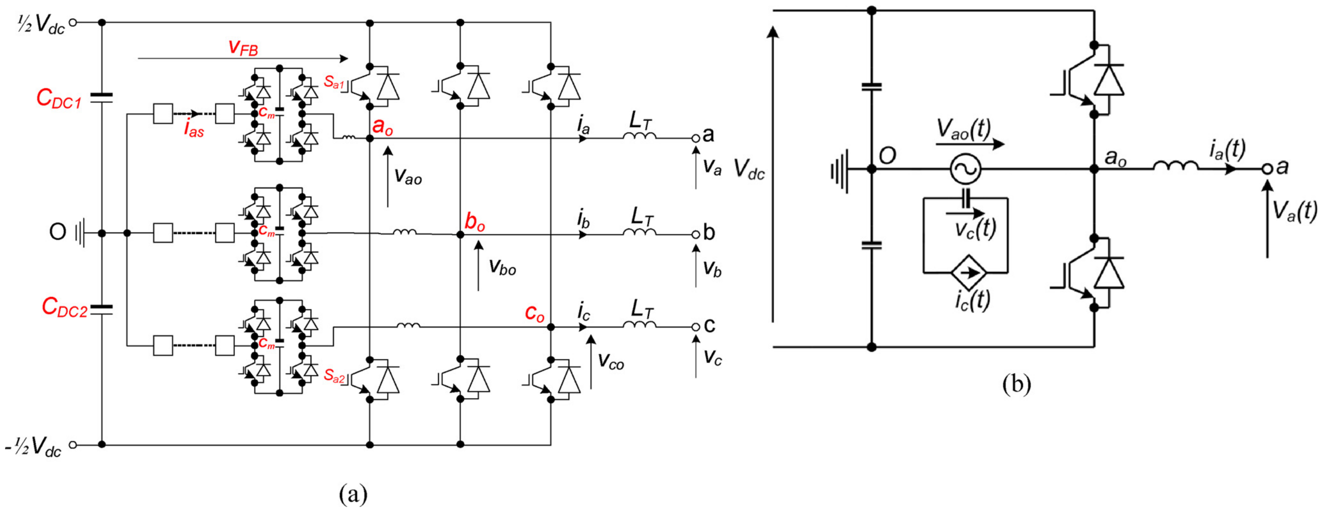

Fig. 1. (a) Three-phase controlled transition bridge multilevel converter, and (b) per phase simplified model of the controlled transition bridge multilevel converter.

dc side to ensure harmonic free continuous dc link current, without the adverse effect stated in (a). Thus, opening the way for the CTB converter to be applied to multi-terminal HVDC networks, instead of being limited to point-to-point HVDC links.

Nevertheless, the use of fourth leg (two chain links connected across the dc link) in the alternative version of the CTB converter compromises the main attributes of the original version of the CTB converter such as reduced footprint and losses.

The authors in Ref. [29] presented a full-bridge version of the CTB converter, where the full-bridge chain link of each phase must be rated for the full dc link voltage instead of half as in original version of the CTB converter. Also, the use of common dc inductor per three-phase in the dc link necessitates incorporation of an active device to circulate the stored energy in the dc link inductor in a zero voltage when the conduction path between converter and dc side is interrupted. This makes the full-bridge CTB converter less attractive in HVDC applications.

Ref. [30] proposed a thyristor based CTB converter for ultra-high-voltage direct current (UHVDC) transmission systems, where the full-bridge chain links are exploited to enable forced commutation of the thyristors in the principle conduction path to further reduce semiconductor losses of the CTB converter to the level comparable to that of the conventional line commutated converter (LCC). Despite the switching limitations of thyristors employed in the main power stage, the CTB converter proposed in Ref. [30] is able to control active and reactive powers independently, and operate with zero dc power, while exchanging leading or lagging reactive power as any other voltage source converter. But it requires a number of large ac tuned filters to be able to achieve the desired voltage quality for grid operation.

Refs. [31,32] presented a hybrid converter that uses three limbs of cascaded half-bridge cells, which are connected across the positive and negative dc rail, and with each limb of cascaded half-bridge cells belongs to one phase-leg. Each limb of cascaded half-bridge cells is being exploited to generate a rectified dc voltage at the dc input of the high-voltage full-bridge converter of each phase-leg, which is responsible for synthesis of ac voltage to be imposed on the isolation transformer at the converter output. The cascaded half-bridge cells of each limb must be rated to block the maximum dc voltage equal to half of the dc link voltage, and composite (series connected) switching devices of each high-voltage full-bridge cell of each phase leg must be rated to block the maximum dc voltage of one limb (half of the dc link voltage), and switch at fundamental frequency and turn on and off zero voltage switching (ZVS). Given that the number half-bridge cells per phase in the hybrid converter in Refs. [31,32] is equal to one-quarter of that of the MMC and no concentrated dc link capacitors, its space requirement is expected to be lower than that of the MMC and CTB of similar rating. However, lack of modulation index control (inability to vary ac voltage) of the hybrid converter in Refs. [31,32] represents a major concern from the system prospective; particularly, inability to perform black-start and provision of reactive power during operation in ac grid. The above concerns have been addressed in the improved version of the above hybrid converter, which is refer to as series bridge converter (SBC) proposed in Ref. [33]. But the SBC has higher semiconductor losses and space requirement (footprint) compared to original version in Refs. [31,32], but its footprint is expected to remain lower than that of the MMC, assuming the number of cell capacitors is a good indicator for converter volume.

This paper describes multilevel operation of a CTB converter and its modulation and control strategies that can facilitate operation independent of modulation index and power factor to be suitable for flexible ac transmission system (FACTS) devices and HVDC transmission system applications. Open simulation waveforms show that 51-cells CTB converter can operate successfully with low and high modulation indices and power factors, with its cell capacitor voltages are tightly regulated. Furthermore, its suitability for FACTS devices and HVDC applications is assessed using a point-to-point VSC-HVDC link that employs 21-cell CTB converters, considering normal operation and ac network faults. The main conclusions drawn from this study, including key findings and observations are presented.

The rest of this paper is organized as follows: Section 2 discusses the basic operating principle of the CTB converter and its modulation and capacitor voltage balancing methods, and sizing of the cell capacitance. Also, it presents open loop simulations to support the theoretical discussions presented earlier. The test systems which will be used to assess the suitability of the CTB converter for dc transmission system and its control associated systems are described in Section 3. Section 4 provides comprehensive assessment of the CTB converter when applied to HVDC transmission systems, considering normal operation and ac fault. Section 5 compares the CTB converter to the half-bridge MMC considering a number of aspects, including semiconductor losses. The main conclusions of this paper are summarized in Section 6.

2. Controlled transition bridge (CTB) multilevel converter

2.1. Basic operating principles

Fig. 1(a) shows the three-phase CTB converter proposed in Ref. [27]. Its circuit structure is similar to that of the T-type inverter discussed in, except that the series connected switches of the T-inverter between each output pole (a_o, b_o and c_o) and the neutral-point (O) are