Electric Power Systems Research 143 (2017) 544–553

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A novel MMC control scheme to increase the DC voltage in HVDC transmission systems

Rui Li[a,*], John E. Fletcher[b]

[a] Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK
[b] School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, Australia

ARTICLE INFO

Article history:
Received 7 April 2016
Received in revised form 14 October 2016
Accepted 5 November 2016
Available online 11 November 2016

Keywords:
DC transmission loss
HVDC transmission
Modular multilevel converter (MMC)
Sinusoidal modulation
Third harmonic injection

ABSTRACT

This research investigates third harmonic injection applied to a modular multilevel converter (MMC) to generate a higher DC voltage. This is achieved using a proposed novel control scheme that activates existing submodules (SMs) in the converter arms. The technique is fundamentally different to, and does the reverse of, the well-known third harmonic injection techniques utilized to increase the AC output voltage in three-phase converter systems for a given DC link voltage. In the proposed scheme, the number of inserted SMs in each converter leg is greater than the number of SMs per arm, whence the MMC can operate with a higher DC link voltage while the SM number per arm and their capacitor voltages remain unchanged. This lowers the DC current and the DC transmission loss is significantly reduced by 22%. Station conduction losses with the operational scheme are lowered by 2.4%. The semiconductor current stresses are also lowered due to the reduced DC component of arm currents. Additionally, the phase energy variation is reduced by 18%, which benefits circulating current control. The operating principles are presented in detail and mathematical models for conduction losses, energy variation, and circulating voltage are derived. Simulation of a point-to-point HVDC system demonstrates the effectiveness of the proposed MMC operational scheme.

1. Introduction

Modular multilevel converter (MMC) deployment is increasing in HVDC application, due to its advantages over thyristor based line commutated converters (LCCs) and two-level voltage source converters (VSCs). MMC technology is more likely to be used to transmit renewable energy with large scale power capacity. A three-phase transformer is used on the MMC AC-side for converter isolation and to suit the required AC and DC voltages. Thus sinusoidal modulation can generate the required voltage and control the MMC. Additionally, it has good harmonic characteristics and can be simply implemented in digital controllers. As a result, sinusoidal modulation is widely used in the control of MMCs [1–5].

Selective harmonic elimination (SHE) modulation is used to control the MMC in [6,7] to eliminate low order harmonics and reduce switching losses. Trapezoidal modulation has been proposed for the solid-state DC transformer and in the hybrid cascaded MMC [8,9] respectively, to reduce switching losses and effectively utilize the DC voltage to produce an output AC voltage with higher fundamental amplitude. However, this is achieved at the expense of higher capital cost and a larger footprint.

By adding zero-sequence components into the reference voltage, discontinuous modulation is achieved which increases the modulation gain and reduces switching losses [10,11]. However, additional submodules (SMs) are required in each arm to avoid over-modulation and reduce SM capacitor voltage ripple. In Ref. [12], a second harmonic is injected into the arm current to optimize the current distribution among the SMs and reduce the SM capacitor voltage ripple, but at the expense of higher semiconductor current stresses.

Third harmonic injection is another attractive approach for MMC control, as it improves the DC voltage utilization ratio. In Ref. [13], the MMC was first proposed for high voltage application and triplen harmonics, mainly third harmonic, were injected to effectively utilize the DC voltage. The advantage of third harmonic injection over sinusoidal modulation is discussed in Ref. [14] and the system performance under a DC fault is improved. However, the influence of the third harmonic during normal operation is not considered.

MMC dynamics under both balanced and unbalanced grid conditions with third harmonic injection are evaluated in Ref. [15]. However, the influence of the third harmonic on losses and SM

* Corresponding author.
E-mail address: rui.li@strath.ac.uk (R. Li).

http://dx.doi.org/10.1016/j.epsr.2016.11.004
0378-7796/

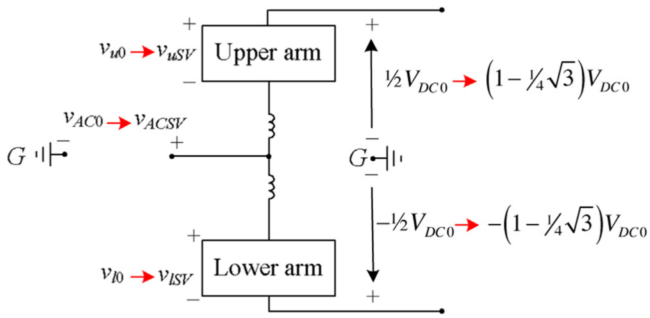

Fig. 1. The MMC circuit for one phase, where the voltage measurements of the sinusoidal modulation and the proposed control are illustrated before and after the arrows respectively.

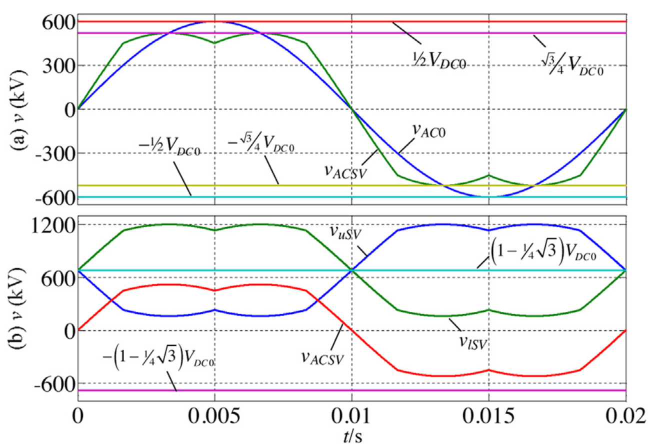

Fig. 2. Reference voltages to generate the fundamental voltage amplitude $\frac{1}{2}V_{DC0}$: (a) comparison between sinusoidal modulation and third harmonic injection, where V_{DC0} = 1200 kV, and (b) proposed higher DC voltage operation, where $V_{DCSV} = \left(2 - \frac{1}{2}\sqrt{3}\right) V_{DC0} = 1361$ kV.

capacitance is not considered. Modified space vector (SV) nearest level modulation (NLM) is discussed in Ref. [16] to increase the DC voltage utilization ratio thus reduce the DC voltage. However, the reduced DC voltage means a higher DC current in order to transfer rated power, resulting in higher power transmission losses.

Although third harmonic injection is extensively used in MMC control, its use in increasing the DC voltage has not been fully explored in the MMC [13–16]. By injecting the third harmonic, the DC voltage utilization ratio is increased from ½ to $\frac{1}{\sqrt{3}}$ [10,17]. The MMC circuit for one phase is shown in Fig. 1, where the voltage measurements of the sinusoidal modulation and the proposed control are illustrated before and after the arrows respectively. Compared with sinusoidal modulation, the maximum output voltage peak with reference to the mid-point of the DC link is reduced from $\frac{1}{2}V_{DC0}$ to $\frac{1}{4}\sqrt{3}V_{DC0}$ as demonstrated in Figs. 2(a) and 3(b), while the amplitude of the output fundamental voltage remains $\frac{1}{2}V_{DC0}$, where V_{DC0} is the DC voltage. For simplicity, it is assumed that $\frac{1}{2}\sqrt{3}N$ is an integer, where N is the SM number per arm. Only $\frac{1}{2}\sqrt{3}N$ of the SMs are utilized when third harmonic injection is used rather than sinusoidal modulation. In real application, the potentially used SM number is *ceil* $\left(\frac{1}{2}\sqrt{3}N\right)$, which is close to $\frac{1}{2}\sqrt{3}N$ given that HVDC systems typically use hundreds of SMs per arm. To utilize the remaining 13.4% SMs, a novel control scheme for MMCs is proposed that results in a higher DC voltage. This principle reduces the DC current, yielding lower overall system losses.

This study focuses on the novel higher DC voltage operation of MMC incorporating third harmonic injection, in a HVDC system. The paper is organized as follows. In Section 2, the principles to operate a MMC with higher DC voltage are discussed along with resultant SM capacitance requirements, power losses, and circulating voltage. In Section 3, the control strategy is presented. System performance using the proposed MMC operational mode is assessed in Section 4, by considering a point-to-point HVDC link. Section 5 draws the conclusions.

2. Higher DC voltage operation

An MMC conventionally operates with the requirement that the number of inserted/bypassed SMs in each converter leg equals the SM number per arm N [13,18]. In this section, a novel MMC control scheme is proposed, where the inserted SM number per leg is greater than N. The technique, whilst achieving a higher DC voltage hence reduced DC current and associated losses, also has a significant positive impact on other performances of the station.

2.1. Operating principle

Conventionally, third harmonic injection is used to extend the linear operating range of an MMC when compared with sinusoidal modulation. With AC-side voltage and DC voltage remaining unchanged, the MMC can effectively utilize the DC voltage and generate relatively higher AC line voltage under abnormal conditions, e.g. system-level events causing raised AC voltage or reduced DC voltage, etc., benefitting from the higher DC voltage utilization ratio provided by third harmonic injection [14–16]. Conventionally, in each arm, the number of inserted SMs equals the number of bypassed SMs:

$$\begin{cases} N_{Iu0} + N_{Il0} = N \\ N_{Bu0} + N_{Bl0} = N \end{cases} \tag{1}$$

where N_{Iu0} and N_{Il0} are the numbers of inserted SMs in the upper and lower arms respectively; N_{Bu0} and N_{Bl0} are the numbers of bypassed SMs in the upper and lower arms respectively, under conventional control.

As shown in Fig. 3(b), only $\frac{\sqrt{3}}{2}N$ SMs are utilized per arm in conventional third harmonic injection. If the other redundant $\left(1 - \frac{\sqrt{3}}{2}\right) N$ SMs were removed from the MMC, it would increase the SM capacitor voltages and result in high voltage stresses on semiconductors and SM capacitors. Alternatively, with the SM capacitor voltages unchanged, the $\left(1 - \frac{\sqrt{3}}{2}\right) N$ redundant SMs can be used to support a higher DC voltage, Fig. 3(c). This forms the basis of the proposed novel control scheme. With this novel higher DC voltage operation, MMC operation does not comply with the requirement that the inserted SM number per leg equals the SM number per arm N, as depicted by Eq. (1). Now, in each converter leg, the inserted SMs are always more than the bypassed SMs to support the higher DC voltage while the SM capacitor voltages remain unchanged:

$$\begin{cases} N_{IuSV} + N_{IlSV} = \left(2 - \dfrac{1}{2}\sqrt{3}\right) N > N \\ N_{BuSV} + N_{BlSV} = \dfrac{1}{2}\sqrt{3}N < N \end{cases} \tag{2}$$

where N_{IuSV} and N_{IlSV} are the numbers of inserted SMs in the upper and lower arms respectively and N_{BuSV} and N_{BlSV} are the numbers of bypassed SMs in the upper and lower arms respectively, in the proposed scheme.