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A Modified Phase-Shifted Pulse Width Modulation to Extend Linear Operation of Hybrid Modular Multi-level Converter

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Abstract- *Recently, hybrid modular multi-level converters, which are configured as full and half bridge sub-modules, are developed and utilized in wide area of applications. Compared to its non-hybrid counterpart, these converters have several advantages such as the ability to nullify the DC side fault current and controlling AC side reactive power during the faults. This paper proposes a modified phase shifted PWM method (PS-PWM) which uses a combination of an improved PS-PWM with cancelled mismatch pulses and a third harmonic injection method. The proposed method not only reduces output voltage harmonic content and uneven loss distribution between sub-modules but also extends the linear operating range of the inverter, which improves the DC bus utilization. The mathematical analysis is derived for the proposed method and in order to study the efficiency of the system using proposed method, the loss calculation has been done and compared with traditional PS-PWM method. Simulation results in Matlab/Simulink show the suitable performance of the presented scheme.*

Keyword: DC bus utilization, Hybrid-MMC, Over modulation, Phase-shifted PWM, Third harmonic injection.

1. INTRODUCTION

After invention of the modular multi-level converter (MMC) by Marquardt [1,2], it has been developed continuously and subjected to extensive researches. The main reason of this attention is its attractive properties such as (i) modularity and scalability to meet any voltage requirements, (ii) high efficiency which is of significant importance for high power applications, (iii) superior harmonic performance and (iv) reduced filter size specially in high voltage applications where a large number of identical sub-modules (SMs) with low voltage ratings are stacked up [3]. It also has low values of dv/dt and di/dt which are the result of staircase structure of output voltage/current [4]. These properties make MMC a suitable choice for wide range of applications like high voltage direct current (HVDC) transmission systems[3,5], flexible alternating current transmission system (FACTS) controllers [7-8], unified power flow controllers [9], integration of renewable energy sources to electrical grid [10-11] and medium voltage drives [12]. However its main application is in HVDC transmission systems [13].

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It is well known that the DC side short circuit fault is considered as a serious problem for MMC based HVDC's reliable application, particularly in the situations of overhead transmission line [14].

MMCs which use half bridge converters as sub-modules, are unable to block DC side short circuit currents. So in order to protect the converter in the case of this fault, a circuit breaker should operate which results in outage of the whole system [15]. This can be avoided by using Full Bridge Sub-Modules (FBSMs) instead of half bridge ones. This construction allows voltage source converter system based on MMC to quickly respond to DC side faults. However this practice increases the initial investment cost as well as system running cost [16]. This is because the current has to flow through two power devices in each FBSMs instead of one power device in Half Bridge Sub-Modules (HBSM) [17], so the conduction loss increases significantly. As a result with a tradeoff consideration of cost, efficiency and IGBT series operation problems, hybrid MMC consisting of HBSMs and FBSMs is a promising solution[14]. In addition to DC side short circuit current blocking capability, this construction can also supply the AC side during the fault. This means hybrid MMC can ride through DC side short circuit fault [18].

Pulse width modulation (PWM) scheme is one of the most interesting research areas about MMC. The high number of switches in an MMC compared to a 2-level VSC, leads to a higher number of possible modulation schemes and more complicated modulation techniques [19]. Many PWM schemes have been proposed for the MMC. Space Vector Modulation is one the methods that was successfully applied to multilevel converters and also proposed for MMCs. But as the number of sub-modules and voltage levels increase, required calculation for this method become complicated and use of high performance powerful processors will be unavoidable. The nearest level modulation (NLM) is especially suitable for the applications with a large number of SMs [20]. In NLM, a round function is applied to find the required output voltage level, which introduces the round errors. To compensate the round errors, NLM is extended by introducing one SM working in the PWM mode [21]. The well-known carrier modulation schemes which are simple and easy to implement in the digital control platforms can also be used [22]. These schemes are categorized into level-shifted PWM and phase-shifted PWM. The main drawback of the level-shifted modulation is the uneven loss distribution among the SMs [23], which is not desirable for the MMC. However it has been reported that the output voltage harmonic profile of the level-shifted PWM is better than that of the phase-shifted one[24], but it should be noted these differences in the high-frequency harmonic contents are very small [23]. So phase-shifted PWM is chosen in this paper. This method doesn't need complicated calculation and heavy computational burden like SVM and also round errors which exist in NLM are not present in this method. As a result, among different modulation techniques for MMCs, phase-shifted carrier PWM(PS-PWM) is a superior method because of its special features such as even distribution of stress and power among SMs, high switching frequency and low total harmonic distortion (THD) of output voltage [25]. However, application of this technique for MMC with HBSMs and FBSMs will result in some mismatch pulses in the output voltage. Also the loss distribution will not be even among SMs. The reason of these phenomena is that the effective switching frequency and switch count of FBSMs is twice the HBSMs [18]. In order to solve these problems, the carrier frequency of FBSMs is proposed to be chosen half of the carrier frequency of HBSMs in [18]. Although the mentioned improved PS-PWM method causes the mismatch pulses of output voltage to disappear and causes even loss distribution between SMs, but the studied hybrid MMC in [18] has limited linear operating region and also its DC bus is not fully utilized.

In this paper a modified phase shifted pulse width modulation scheme based on combination of improved PS-PWM and third harmonic injection is introduced.

Third harmonic injection extends the linear operating range of the converter and also increases DC bus utilization which is of great importance in the case of decreasing DC side voltage in HVDC transmission system, integration of off-shore wind farms to the grid and medium power motor drives. Also in order to control capacitor voltages of the hybrid MMC, a simple and effective voltage control method is used which helps the control system not to be complex.

The rest of this paper is organized as follows. Section (2) describes the topology and operating principle of the hybrid MMC. Proposed modulation method and its mathematical basics are explained in section (3). Simulation results are given in section (4). Section (5) presents a study about the losses and efficiency of the system for the traditional and proposed modulation methods. Finally, section (6) concludes the paper.

2. TOPOLOGY AND OPERATING PRINCIPLE

One leg of the hybrid MMC is shown in Fig. 1. It consists of upper and lower arms which are connected to the midpoint of the leg through buffer inductors. Each arm is constructed by cascade connection of full bridge and half bridge sub-modules. It should be noted that in the hybrid MMC, HBSMs are bypassed during the fault and converter operates like full bridge based MMC [26]. As a result to have DC side short circuit fault ride through capability the number of FBSMs should be greater than or equal to the number of HBSMs [18]. Every sub-module in this converter uses capacitor instead of voltage source that is used in cascaded half bridge converter.

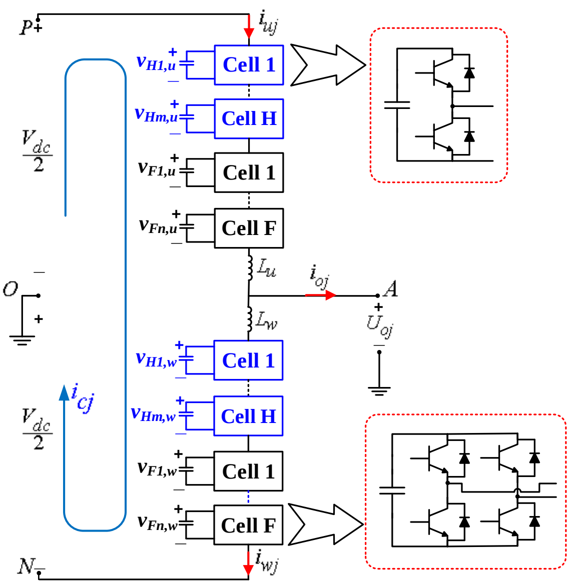


Fig 1. One leg structure of Hybrid-MMC

As a result adjusting capacitor voltages at the correct value is important to get good shaped waveforms of arm voltages. For each arm of converter we have

$$r_u i_{uj} + L_u \frac{di_{uj}}{dt} = \frac{V_{dc}}{2} - U_{uj} - U_{oj} \tag{1}$$

$$r_w i_{wj} + L_w \frac{di_{wj}}{dt} = \frac{V_{dc}}{2} - U_{wj} + U_{oj} \tag{2}$$

Where r_u and r_w are the resistance of upper and lower arms to model ohmic losses, L_w and L_u are the buffer inductors of arms,and U_{uj} is the DC input voltage, V_{dc} jth phase are the voltages of upper and lower arm of U_{wj} and U_{oj} is the output phase voltage.

It should be noted that some researchers prefer to use coupled inductors instead of separate ones but it's just matter of compactness and generally makes no difference. From the above equations output phase voltage can be calculated as

$$U_{oj} = \frac{1}{2}\left(U_{wj} - U_{uj}\right) \tag{3}$$

Each arm current in this converter consists of two parts: one is half of the load current and the other is circulating current [27]. Thus

$$i_{uj} = i_{cj} + \frac{1}{2} i_{oj} \tag{4}$$

$$i_{wj} = i_{cj} - \frac{1}{2} i_{oj} \tag{5}$$

In these equations, i_{wj} and i_{uj} are the upper and lower arm currents of jth phase leg, i_{cj} is the circulating current and i_{oj} is the output phase current. Circulating current as its name shows circulates throughout the converter leg and does not contribute to load current. This current is typically used to balance and stabilize the internal MMC dynamics [27]. But most of the times because it increases current stress and power losses, leads to oversized ratio values and higher cooling requirements [12], buffer inductors are used to limit it. These inductors also suppress high frequency components in the arm current [3]. The existence of circulating current has two reasons. First one is the HBSMs that can only generate two voltage levels and the second one is unbalanced capacitor voltages of sub-modules. This current can be calculated as mean value of the arm currents.

3. MODULATION METHOD

One of the most attractive and widely used modulation schemes for MMCs is PS-PWM. This method offers special features like even power distribution between sub-modules that eases the voltage balancing of sub-module capacitors. However if this method is applied to the hybrid MMC, two problems will arise. The first one is appearance of some mismatch pulses in output voltage waveform and the second problem is uneven loss distribution between sub-modules. To solve these problems it was proposed to choose carrier frequency of FBSMs to be half of the carrier frequency of HBSMs [18]. Although this method can solve the aforementioned problems, it results in a limited linear operating range and also the DC bus is not fully utilized.

To overcome these problems a novel PS-PWM scheme is proposed in this paper. For modulation of the converter with this method a reference waveform for HBSMs and two reference waveforms for FBSMs of upper arm are needed. These references are given by Eq. (6) for HBSMs and Eqs. (7) and (8) for FBSMs.

$$\begin{aligned} u_{ref-uj}(i) = \frac{V_{dc}}{2N}\Big(1 + M\cos\left(\omega_o t + \varphi_j + \pi\right) \\ - M/6 \cos\left(3\omega_o t + \pi\right)\Big) + \Delta u_{h-uj}(i) \end{aligned} \tag{6}$$

$$\begin{aligned} u_{ref\_uj\_left}(i) = \frac{3V_{dc}}{4N} + \frac{V_{dc}}{4N}\Big(M\cos\left(\omega_o t + \varphi_j + \pi\right) \\ - M/6 \cos\left(3\omega_o t + \pi\right)\Big) + \Delta u_{f-uj}(i) \end{aligned} \tag{7}$$

$$\begin{aligned} u_{ref\_uj\_right}(i) = \frac{V_{dc}}{4N} + \frac{V_{dc}}{4N}\Big(M\cos\left(\omega_o t + \varphi_j\right) \\ - M/6 \cos\left(3\omega_o t\right)\Big) - \Delta u_{f-uj}(i) \end{aligned} \tag{8}$$

Where N is the total number of SMs in one arm, M is the modulation index, ω_o is the output voltage frequency andis the phase shift angle. The amplitude of the φ_j third harmonic component in these equations is chosen to be 1/6 of fundamental component to extend linear range by 15 percent. However this can be 1/4 of the fundamental component which gives a little better THD but the linear operating range extension will be only 12 percent [28]. For the lower arm SMs the same references with π radian displacement is used.

In these equations the last term is an adjustment whose magnitude depends on the SMs capacitor voltages and is used to balance them. With method used here to control capacitors' voltage, which is called individual balancing control, this term is indicated in Eq. (9).

$$\Delta u_{ij}(i) = \begin{cases} k_p\left(u_c - u_{c\_uj}\right) + k_i \int \left(u_c - u_{c\_uj}(i)\right)dt & i_{uj} > 0 \\ -k_p\left(u_c - u_{c\_uj}\right) - k_i \int \left(u_c - u_{c\_uj}(i)\right)dt & i_{uj} < 0 \end{cases} \tag{9}$$

Although (9) is written for upper arm, it is also true for lower arm with its corresponding quantities replaced. Fig.2 shows block diagram of the capacitors' voltage control. In this figure $v^*_{c,i}$ and $v_{c,i}$ are reference and actual values of any capacitor voltage of any sub-module, i.e. FBSMs or HBSMs of upper or lower arm.

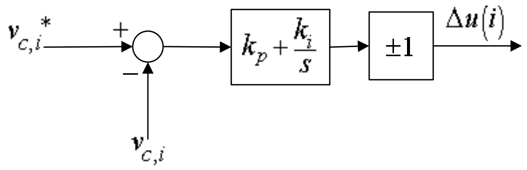


Fig 2. Block diagram of the capacitors' voltage control method

To modulate mentioned reference waveforms a carrier is used for each SM. The phase shifts between these carriers determine harmonic characteristics of output voltage [25]. So the phase shift between carriers of the same kind of SMs of one arm e.g. HBSMs of upper arm should be incrementally to achieve best harmonic cancellation [29]. Care should be taken that the angles we use here are with respect to carrier frequency of HBSMs. The other phase shift in this method is the phase shift between sub-modules of upper and lower arms i.e. between HBSMs of upper and lower arm and also between FBSMs of upper and lower arm. By adjusting these phase shifts we will have two important mode of harmonic cancellation which are output voltage harmonics cancellation (OVHC) and circulating current harmonics cancellation (CCHC).

Based on the analysis that has been conducted in [18] to get into the first mode the phase shift between carriers of upper and lower arms should be

$$\theta = \begin{cases} 0 & N \text{ is odd} \\ \dfrac{\pi}{N} & N \text{ is even} \end{cases} \tag{10}$$

And for second mode

$$\theta = \begin{cases} \dfrac{\pi}{N} & N \text{ is odd} \\ 0 & N \text{ is even} \end{cases} \tag{11}$$

It is worth noticing that at a first glance circulating current harmonics cancellation doesn't seem so important. But when considering current stress and losses caused by these current harmonics and also have in mind that output voltage itself has good quality this mode becomes important. Modulation waveforms are shown in Fig. 3.

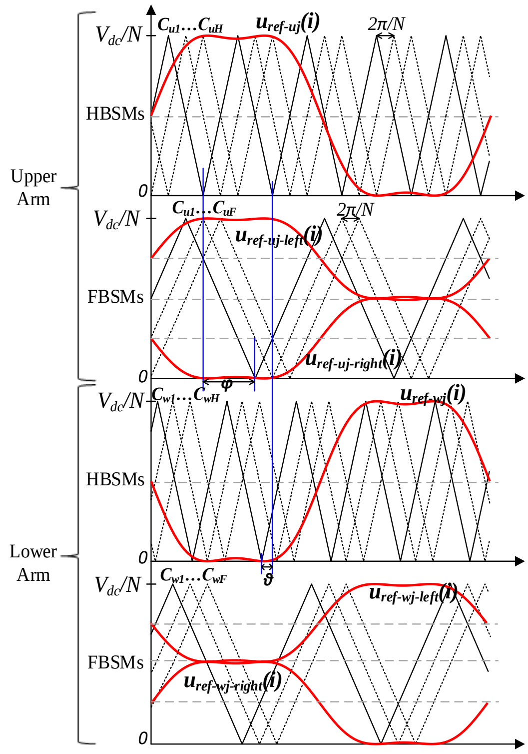


Fig 3. Modulation waveforms

4. SIMULATION RESULTS

In this section, the whole system using the mentioned method of [18] and the proposed method of this paper is simulated in MATLAB/Simulink environment. These simulations help us to analyze characteristics and effectiveness of the proposed method. Parameters of simulation are given in Table 1. It is worth noticing the capacitors of sub-modules are selected based on Eq. (12) [30].

$$c_{\min} = \frac{2S}{3\varepsilon \bar{u}_c^{\,2} kN\omega}\left(1-\left(\frac{k\cos\varphi}{2}\right)^2\right)^{\frac{3}{2}} \tag{12}$$

Whereis ε is the apparent power of converter, S the percent of capacitor voltage ripple, $\bar{u}_c$ is the average voltage of capacitor, k is the normalized output voltage peak ($k = 2\hat{v}_o/v_{dc}$ and v_{dc} is dc side voltage), N is the number of sub-modules in each arm, ω is output frequency in rad/sec and φ is load displacement angle. Due to this formula by considering 1.5 MW as apparent power, 5 percent for capacitor voltage ripple and a power factor of about 0.75 for load, the capacitors are chosen as is written in Table 1. It should be said that capacitor voltage ripple also depends on other factors like controllers and this formula assumed an ideal condition for the other factors.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Number of SMs in each arm	6	Load inductance	57 mH
Number of FBSMs in each arm (n)	3	DC bus voltage	9 kV
Number of HBSMs in each arm (m)	3	SM capacitor voltage	1.5 kV
SM capacitance	6.9 mF	Carrier frequency of FBSMs	225 Hz
Buffer inductor	1 mH	Carrier frequency of HBSMs	450 Hz
Load resistance	20.25 Ω	Output frequency	50

Another point to notice is that the mentioned equation for calculating capacitance of sub-modules was introduced for MMC with half bridge sub-modules, but as we expect modularity and even distribution of energy among sub-modules, it can also be used for the hybrid-MMC.

4.1. Traditional method

In this part the mentioned method of [18] is applied to hybrid MMC. This method due to phase shift that was described in previous section has two parts.

4.1.1. Output Voltage Harmonic Cancelation (OVHC):

A big portion of output voltage harmonics are cancelled in this mode. Fig. 4 shows output line voltage and its harmonic spectra. As can be seen THD of output voltage is so low that leads to reduced size of output filter. Circulating current and its harmonic spectra are also shown in Fig. 5.

4.1.2. Circulating Current Harmonics Cancellation(CCHC):

Output voltage and its harmonic components are shown in Fig. 6. It can be deduced that output voltage magnitude is not so different with previous mode but its THD is doubled. Circulating current waveform and its harmonic content which are given by Fig. 7 show the THD of circulating is reduced to less than half of the first mode. This reduces harmonic losses.

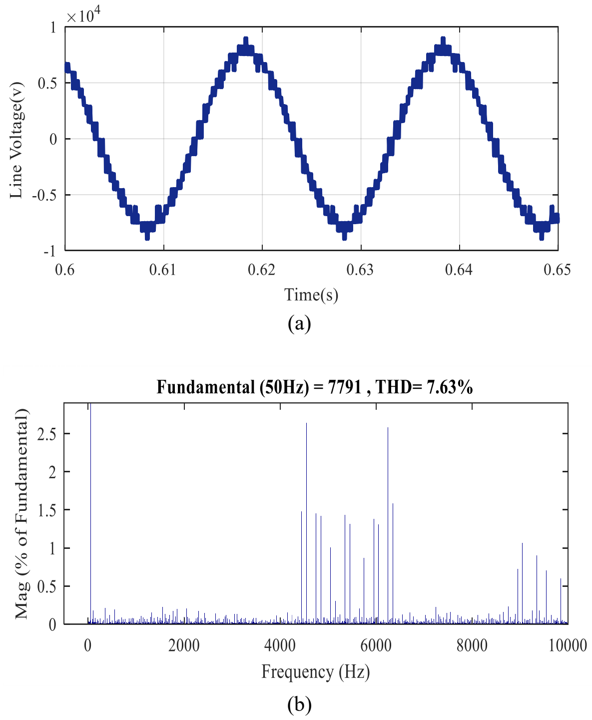


Fig 4. Output voltage in OVHC mode of the traditional method: a) waveform b) harmonic spectra

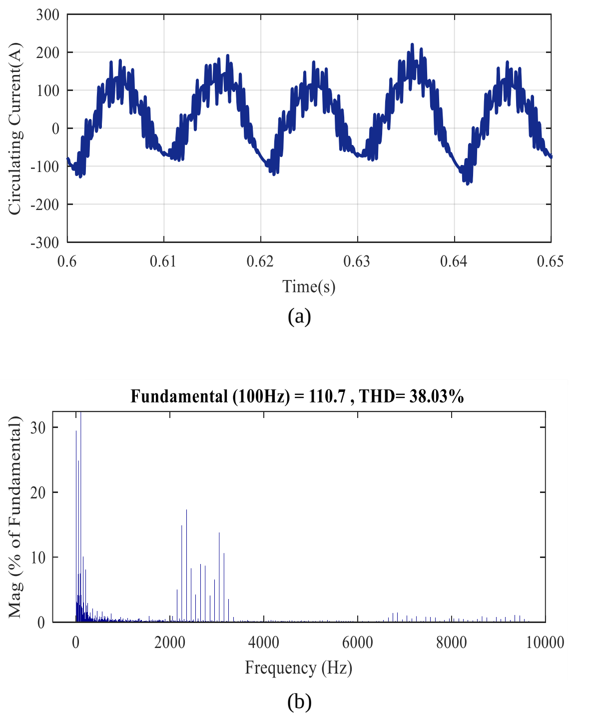
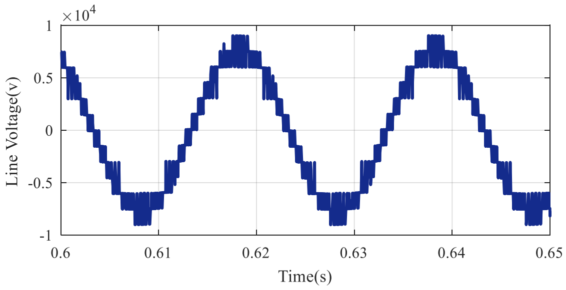
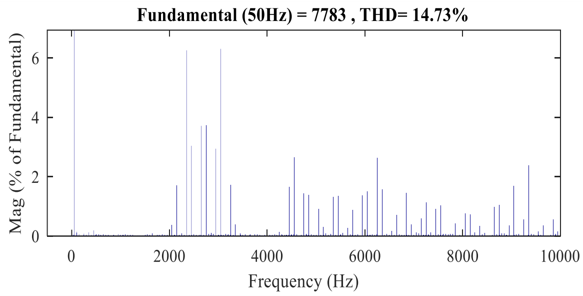


Fig 5. Circulating current in OVHC mode of the traditional method: a) waveform b) harmonic spectra

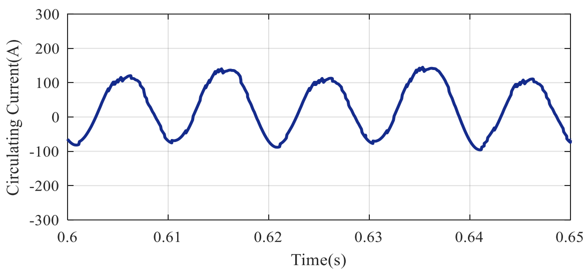


(a)

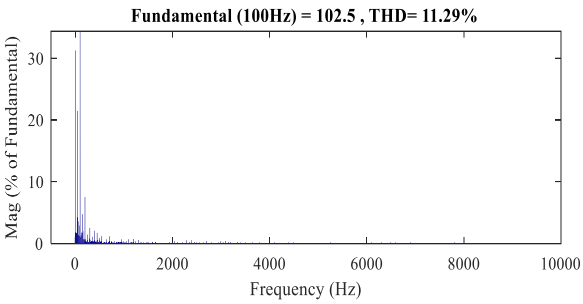


(b)

Fig 6. Output voltage in CCHC mode of the traditional method: a) waveform b) harmonic spectra



(a)



(b)

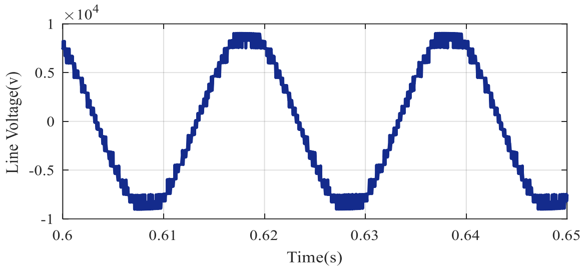
Fig 7. Circulating current in CCHC mode of the traditional method: a) waveform b) harmonic spectra

4.2. Proposed method

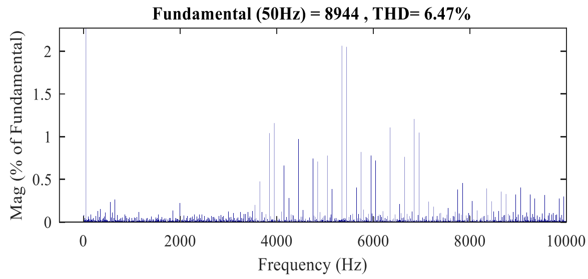
In this part the modulation method that was described in section (2) is applied to the converter. This method like traditional one has two modes. In each mode all important quantities of converter are shown.

4.2.1. Output Voltage Harmonics Cancellation (OVHC):

As can be seen from Fig. 8 output voltage magnitude is increased by 15 precent with respect to traditional method and it has also very low THD. Circulaing current and its harmonic content are shown in Fig. 9. In this mode the circulating current experiences an increase in its magnitude and its THD is decreased. Capacitor voltages of SMs are shown to be well balanced with the control method that has been used here. Upper and lower arm currents are shown in Fig. 11. Also as can be seen in Fig. 12 the load current is nearly sinusoidal.

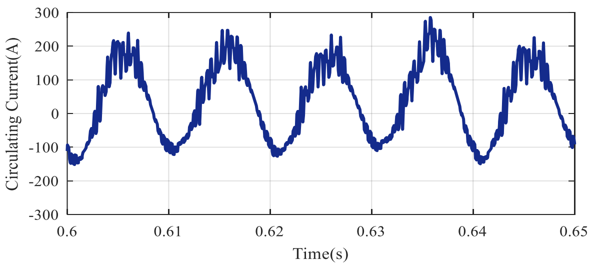


(a)



(b)

Fig. 8. Output voltage in OVHC mode of the proposed method: a) waveform b) harmonic spectra



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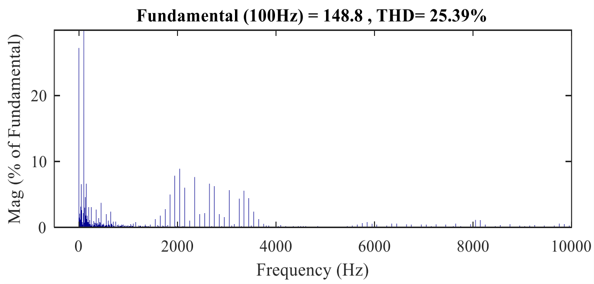

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Fig. 9. Circulating current in OVHC mode of the proposed method: a) waveform b) harmonic spectra

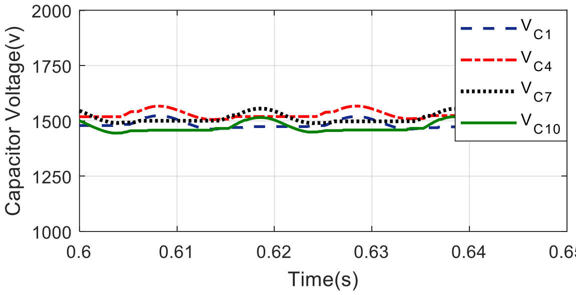


Fig. 10. Capacitor voltages of SMs in OVHC mode of the proposed method

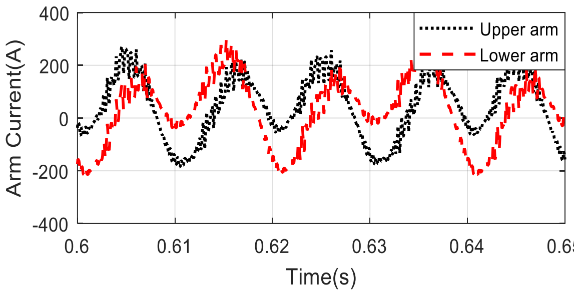


Fig. 11. Arm currents in OVHC mode of the proposed method

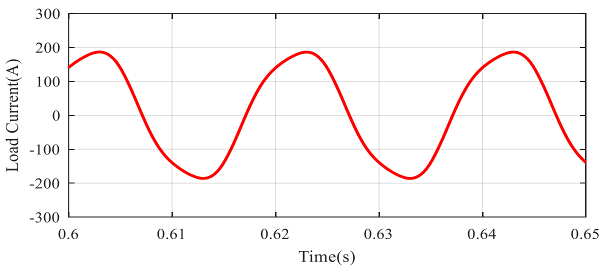
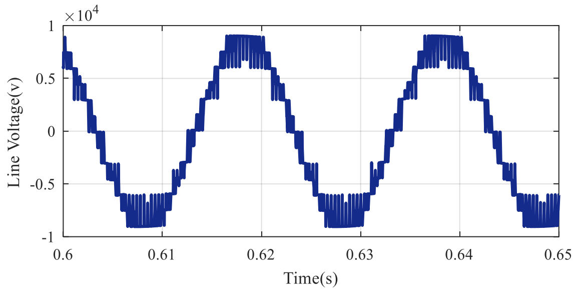


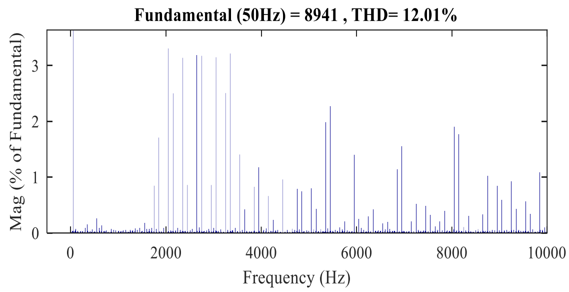
Fig. 12. Load current in OVHC mode of the proposed method

4.2.2. Circulating Current Harmonics Cancellation (CCHC):

In this mode dominant harmonics of circulating current are cancelled. As a result, size of arm inductors, which high frequency components of arm currents filtering and equivalently circulating current is one of their duties, can be reduced. Like previous mode output voltage magnitude is increased 15 percent and its THD as shown in Fig. 13(b) is decreased. Circulating current magnitude is increased with respect to traditional method. Its harmonic content is also increased by about 3 percent. Capacitor voltages are well balanced and their ripple is within acceptable range as shown by Fig. 15. Arm current and load current waveforms are given in Fig. 16 and Fig. 17.It is interesting that by simulating the system with different amounts of loads, we can see arm currents and thus circulating current waveforms strongly depend on capacitor voltage ripple which in part depends on output power.

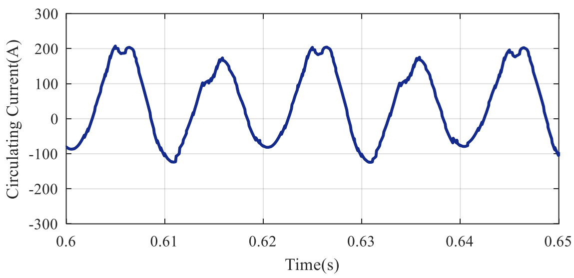


(a)

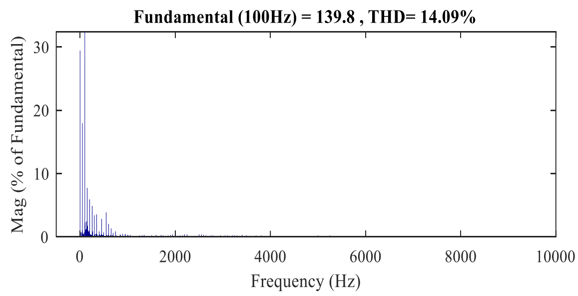


(b)

Fig. 13. Output voltage in CCHC mode of the proposed method: a) waveform b) harmonic spectra



(a)



(b)

Fig. 14. Circulating current in CCHC mode of the proposed method: a) waveform b) harmonic spectra

5. LOSS AND EFFICIENCY EVALUATION

This section introduces loss and efficiency calculation for two different operating modes of the traditional and proposed modulation methods. There are four different types of loss for any kind of power electronics device which are: 1) Conduction losses, 2) Switching losses, 3) Off-state losses and 4) Gate losses

[31]. The Off-state and Gate losses are very small and normally neglected. Hence, in this paper, only conduction and switching losses have been considered for the analysis. To calculate these losses a thermal model of IGBT module for Infineon FF450R33TE3 is used. This Model includes thermal model of IGBT and diode, heat sink and the interface between them. Important characteristics of these parts like thermal capacitance and resistance are used in the modelling based on datasheet values. Thanks to this model, junction temperature of IGBTs and diodes can be calculated, and because switching and conduction losses are temperature dependent, they can be calculated using datasheet values and interpolation.

It should be noted that in this model a heat sink with natural convection is chosen for each IGBT module(which includes two IGBTs and diodes) in such a way that the case temperature of them are held at reasonable value. Also for interface between heat sink and module surface it is assumed that a suitable thermal paste with good coverage and mounting torque of heat sink is used.

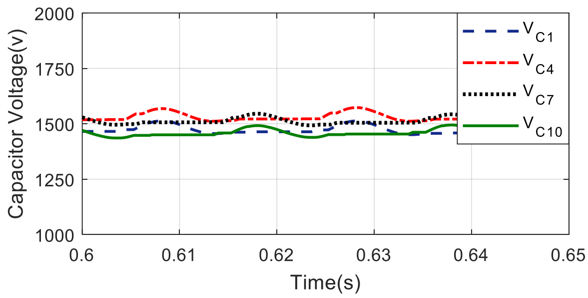


Fig. 15. Capacitor voltages of SMs in CCHC mode of the proposed method

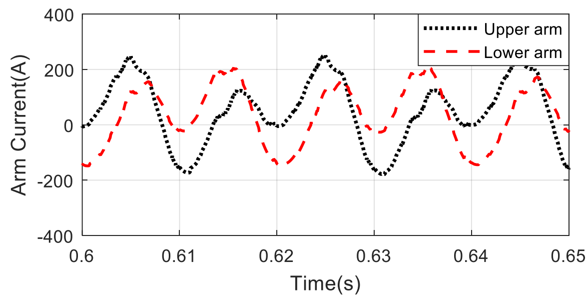


Fig. 16. Arm currents in CCHC mode of the proposed method

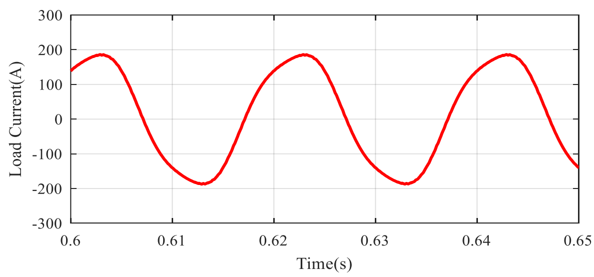


Fig. 17. Load current in CCHC mode of the proposed method

It is worth noticing there are some other ways for calculating losses which are not computationally efficient or accurate enough, but the model used here gives good accuracy with reasonable computational burden and time. Fig. 18 and Table 2 show the calculated losses and efficiency of the system for two different modulation methods with output voltage harmonics cancellation.

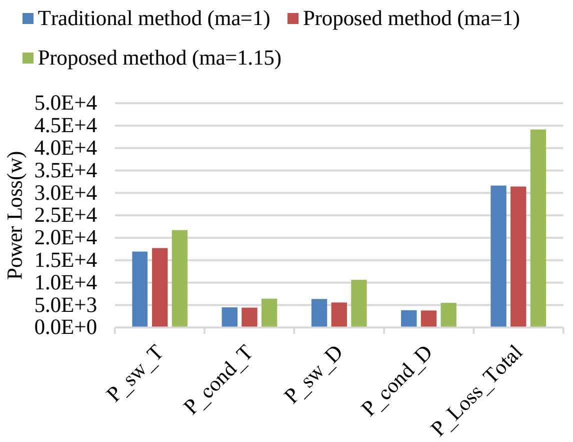


Fig. 18. Hybrid-MMC losses in OVHC mode

Table 2. Power and efficiency calculations for OVHC mode

		Output Power (kw)	Total loss (kw)	Efficiency
Traditional method	ma=1	841.10	32.25	96.30%
Proposed method	ma=1	846	31.42	96.41%
	ma=1.15	1110	44.13	96.17%

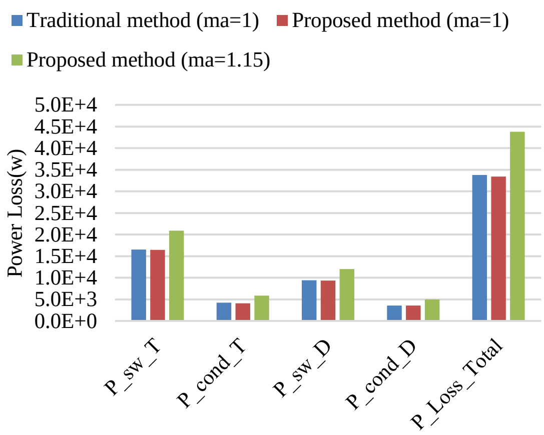


Fig. 19. Hybrid-MMC losses in CCHC mode

Table 3. Power and efficiency calculations for CCHC mode

		Output Power (kw)	Total loss (kw)	Efficiency
Traditional method	ma=1	841.10	32.25	96.30%
Proposed method	ma=1	846	31.42	96.41%
	ma=1.15	1110	44.13	96.17%

It is obvious that the proposed method increases the amount of circulating current. However, neither modulation index of 1 nor 1.15 has significant impact on efficiency. The slight change for efficiency in over modulation region is acceptable in the case of DC voltage drop where the system works with the proposed method. So with the cost of more losses, this method can compensate the DC voltage drop.

Figure 19 and Table 3 show the calculated losses and efficiency of the system for circulating current harmonics cancellation. From Table 3, it can be seen that efficiency doesn't have big change in circulating current harmonics cancellation mode with the proposed method.

6. CONCLUSIONS

This paper proposes a modulation method to extend linear operating range of the Hybrid MMC and increases its DC bus utilization. This method is also able to eliminate mismatch pulses which will appear in the output voltage of Hybrid-MMC by using the conventional phase shifted carrier pulse width modulation. Operating principles of the proposed method were explained and simulations for both output voltage harmonics cancellation and circulating current harmonics cancellation modes carried out in order to depict characteristics and effectiveness of the proposed method. Simulation results depict increasing 15 percent in DC bus utilization by using the proposed method. Finally the loss and efficiency calculations for two different operation modes of the traditional and proposed modulation methods show that efficiency of the system doesn't change significantly using the proposed method. So it can be acceptable choice where the DC voltage drop can be compensated by the proposed method.

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