# Application of Improved Phase-Shifted Pulse Width Modulation with Third Harmonic Injection to Hybrid Modular Multi-level Converter

Mohammad Mohsen Rahimian
*University of Mohaghegh Ardabili, Ardabil, Iran*

Majid Hosseinpour
*University of Mohaghegh Ardabili, Ardabil, Iran*

Malabika Basu
*Technological University Dublin*, mbasu@tudublin.ie

*See next page for additional authors*

# Application of Improved Phase-Shifted Pulse Width Modulation with Third harmonic injection to Hybrid Modular Multi-level Converter

Mohammad Mohsen Rahimian[1], Majid Hosseinpour[1], Malabika Basu[2], Michael Farrell[2], Shahab Sajedi[2]
[1]Department of Electrical Engineering, Faculty of Engineering, University of Mohaghegh Ardabili, Ardabil, Iran
[2]Dublin Institute of Technology, Dublin, Ireland

***Abstract*— Hybrid modular multi-level converters (Hybrid-MMCs) which are modular multi-level converters including full and half bridge sub-modules, are recently used in high-voltage direct current (HVDC) transmission systems. 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 novel 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 depict the suitable performance of the presented scheme.**

***Index Terms*—DC bus utilization, Hybrid-MMC, Over modulation, Phase-shifted PWM, Third harmonic injection**

## I. INTRODUCTION

The modular multi-level converter (MMC) since its invention by Marquardt [1] always has been under extensive research and development. 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, and (iii) superior harmonic performance specially in high voltage applications where a large number of identical sub-modules (SMs) with low voltage ratings are stacked up thereby the size of passive filters can be reduced [2]. These properties make MMC a suitable choice for wide range of applications like high voltage direct current (HVDC) transmission systems [2], flexible alternating current transmission system (FACTS) controllers, unified power flow controllers, integration of renewable energy sources to electrical grid and medium voltage drives. However its main application is in HVDC transmission systems.

It is well known that the DC short circuit fault is considered as a serious problem for MMC based HVDC's reliable application, particularly in the situations of overhead transmission line [3].

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 [4]. This can be avoided by using full bridge sub-modules (FBSMs) instead of half bridge ones. This construction allows voltage source converter HVDC 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 [5]. 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) [6], so the conduction loss significantly increases. 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 [3]. 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 has DC side short circuit fault ride through capability [7].

Among different modulation techniques for MMCs, phase shifted carrier pulse width modulation(PS-PWM) is a superior method because of its special features including even distribution of stress and power between SMs, high switching frequency and low total harmonic distortion (THD) of output voltage [8]. However, application of this technique for MMC with HBSMs and FBSMs will result in some mismatch pulses in the output voltage and also the loss distribution will not be even between SMs anymore. The reason of these phenomena is that the effective switching frequency and switch count of FBSMs is twice the HBSMs [7]. In order to solve these problems, the carrier frequency of FBSMs is proposed to be chosen half of the carrier frequency of HBSMs in [7]. Although the mentioned improved PS-PWM method, as its authors called it, causes the mismatch pulses of output voltage to disappear and causes even loss distribution between SMs, but the studied hybrid MMC in [7] has limited linear operating region and also its DC bus is not fully utilized.

In this paper a novel 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 so complex.

The rest of this paper is organized as follows. Section II describes the topology and operating principle of the hybrid MMC. Proposed modulation method and its mathematical basics are explained in section III. Simulation results are given in section IV. Section V presents a study about the losses and efficiency of the system for the traditional and proposed modulation methods. Finally, section VI concludes the paper.

## II. Topology and Operating Principle

Fig. 1 shows one leg of the hybrid MMC. 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 [9]. So 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 [7]. Every sub-module in this converter uses capacitor instead of voltage source that is used in cascaded half bridge converter. 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, $L_u$ and $L_w$ are the buffer inductors of arms, $V_{dc}$ is the DC input voltage, $U_{uj}$ and $U_{wj}$ are the voltages of upper and lower arm of j$^{th}$ phase 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

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

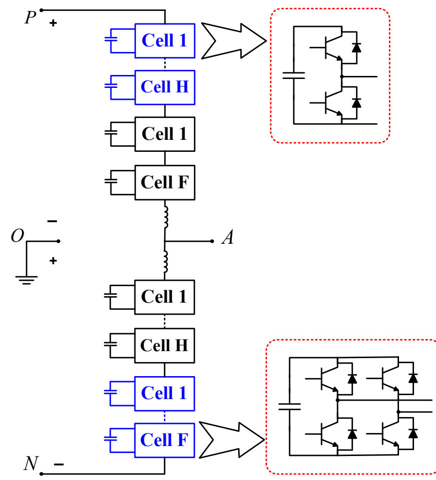



Figure 1. One leg structure of hybrid MMC

Each arm current in this converter consists of two parts: one is half of the load current and the other is circulating current [10]. 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, $i_{uj}$ and $i_{wj}$ are the upper and lower arm currents of j$^{th}$ 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 [10] and most of the times because it increases current stress and power losses leads to oversized ratio values and higher cooling requirements, buffer inductors are used to limit it and also suppress high frequency components in the arm current [2].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.

## III. 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 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 [7] proposed to choose carrier frequency of FBSMs to be half of the carrier frequency of HBSMs. 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 (6) for HBSMs and (7) and (8) for FBSMs.

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

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

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

where N is the total number of SMs in one arm, M is the modulation index, $\omega_o$ is the output voltage frequency and $\varphi_j$ is the phase shift angle. The amplitude of the 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 [11]. For the lower arm SMs the same references with $\pi$ rad 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 voltages this term is

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

Although (9) is written for upper arm, it is also true for lower arm with its corresponding quantities replaced. To modulate these reference waveforms a carrier is used for each SM. The phase shifts between these carriers determine harmonic characteristics of output voltage [8]. So the phase shift between carriers of the same kind of SMs of one arm e.g. HBSMs of upper arm should be $2\pi/N$ rad incrementally to achieve best harmonic cancellation [12]. 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 modes of harmonic cancellation which are output voltage harmonics cancellation and circulating current harmonics cancellation. Based on the analysis that was done in [7] to get into the first mode the phase shift between carriers of upper and lower arms should be

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

And for second mode

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

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.

## IV. Simulation Results

In this section the whole system using method of [7] 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 I.

TABLE I. Simulation parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Number of SMs in each arm | 6 | Load inductance | 57 mH |
| Number of FBSMs in each arm | 3 | DC bus voltage | 9 kV |
| Number of HBSMs in each arm | 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 Hz |

### A. Traditional Method

In this part the method of [7] is applied to hybrid MMC. This method due to phase shift that was described in previous section has two parts.

*1) Output Voltage Harmonics Cancellation(OVHC):* A big portion of output voltage harmonics are cancelled in this mode. Fig. 2 and Fig. 3 show 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. 4(a) and Fig. 4(b).

*2) Circulating Current Harmonics Cancellation(CCHC):* Fig. 5 and Fig. 6 show output voltage and its harmonic components. 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(a) and Fig. 7(b) show the THD of circulating is reduced to less than half of the first mode. This reduces harmonic losses.

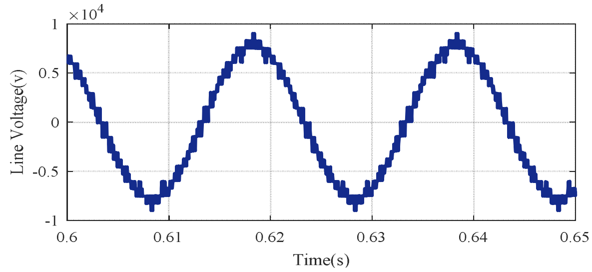


Figure 2. Output Voltage in first mode of traditional method

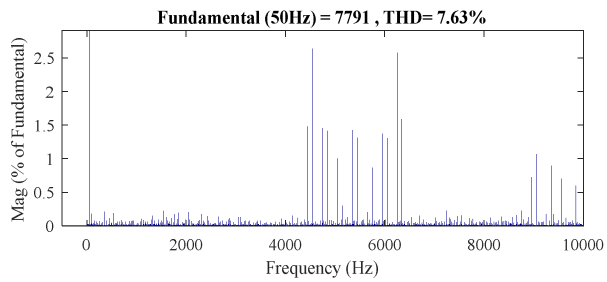
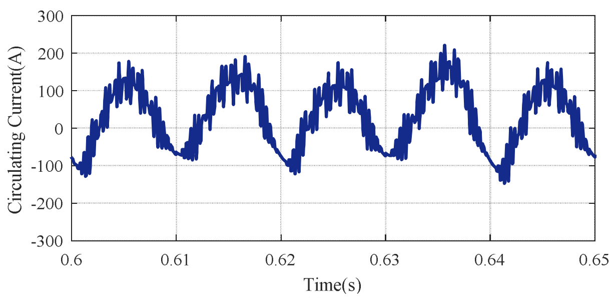
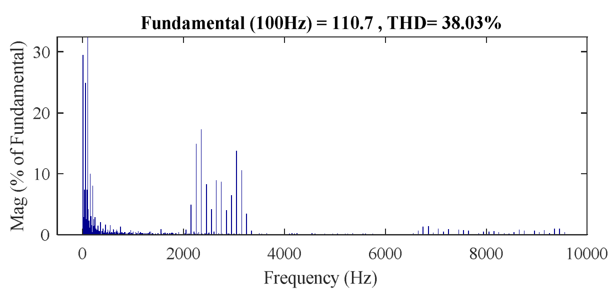


Figure 3.Output Voltage harmonic spectra in first mode of traditional method



(a)



(b)

Figure 4. Circulating current in first mode of traditional method: a) Waveform b) Harmonic spectra

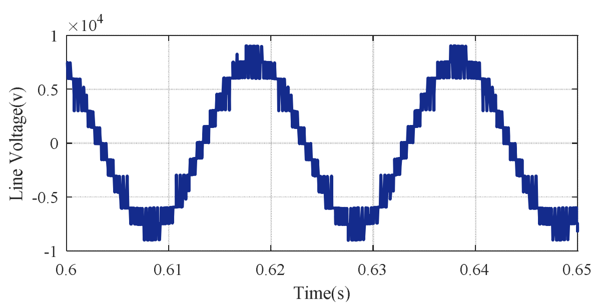


Figure 5. Output voltage in second mode of traditional method

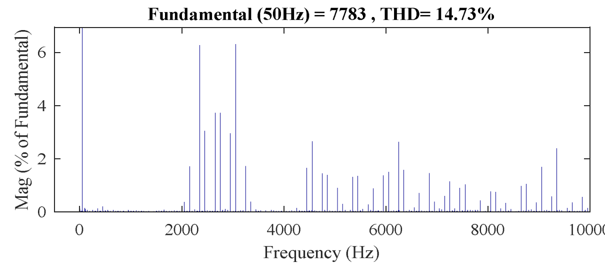
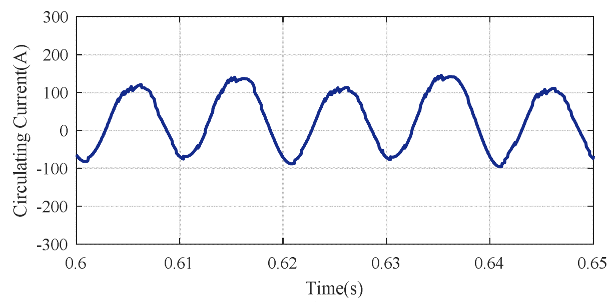
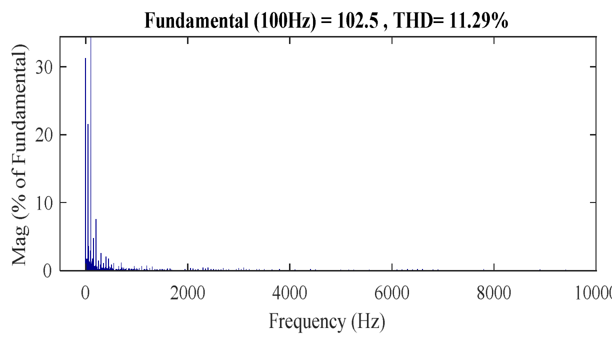


Figure 6. Output voltage harmonic spectra in second mode of traditional method



(a)



(b)

Figure 7. Circulating current in second mode of traditional method: a) Waveform b) Harmonic spectra

## B. *Proposed Method*

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

*1) Output Voltage Harmonics Cancellation(OVHC):* As can be seen from Fig. 8 and Fig. 9 output voltage magnitude is increased by 15 precent with respect to traditional method and it has also very low THD. Fig. 10 shows circulaing current and its harmonic content. In this mode the circulating current experiences an increase in its magnitude but its harmonics are decreased. Capacitor voltages of SMs are shown to be well balanced with the control method that was used here.

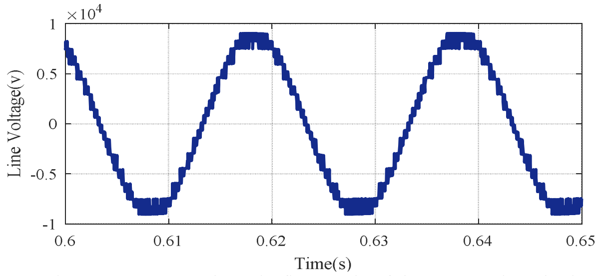



Figure 8. Output voltage in first mode of the proposed method

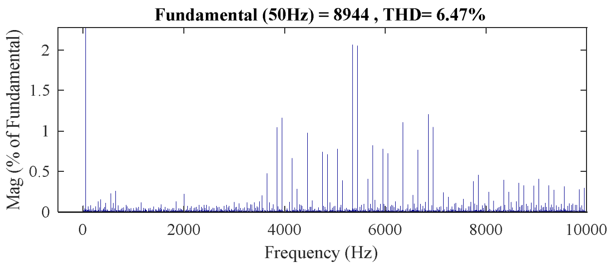
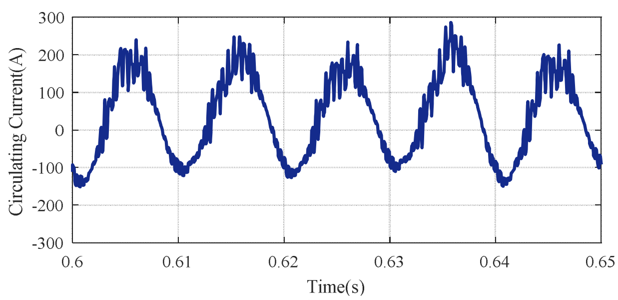
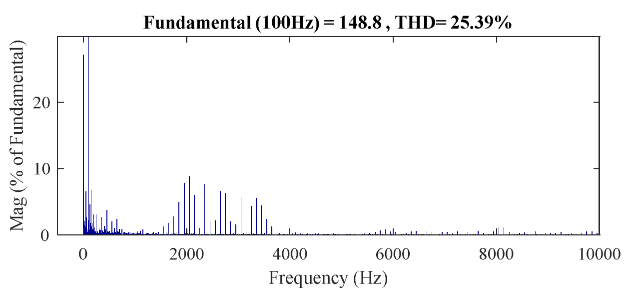



Figure 9. Output voltage harmonic spectra in first mode of the proposed method




(a)




(b)

Figure 10. Circulating current in first mode of the proposed method: a) Waveform b) Harmonic spectra

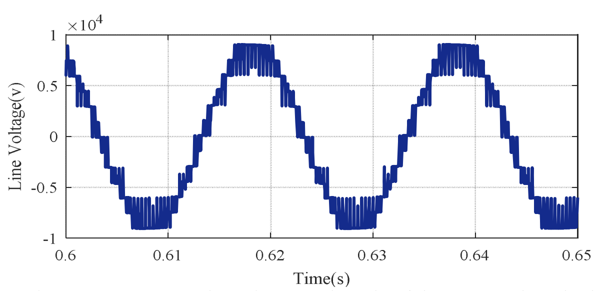



Figure 11. Output voltage in second mode of the proposed method Waveform

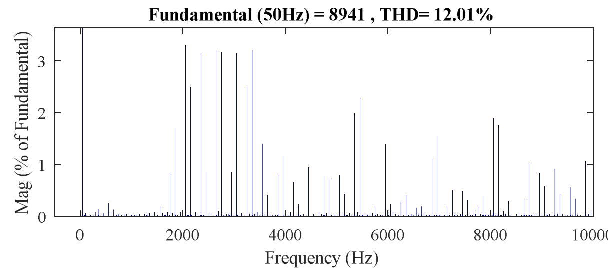



Figure 12. Output voltage harmonic spectra in second mode of the proposed method

2) *Circulating Current Harmonics Cancellation(CCHC):* In this mode dominant harmonics of circulating current are cancelled out. Like previous mode output voltage magnitude is increased 15 percent and its harmonics as shown in Fig. 12 are 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.

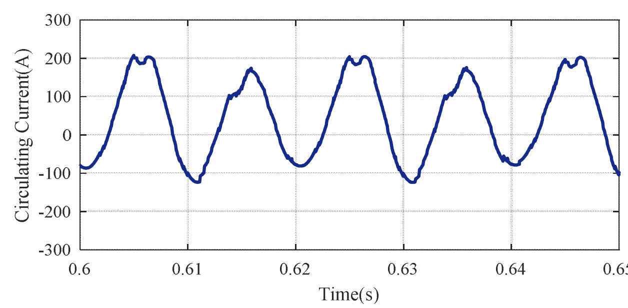



Figure 13. Circulating current in second mode of the proposed method

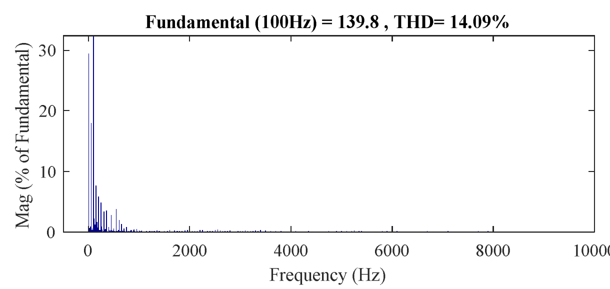



Figure 14. Circulating current harmonic spectra in second mode of the proposed method

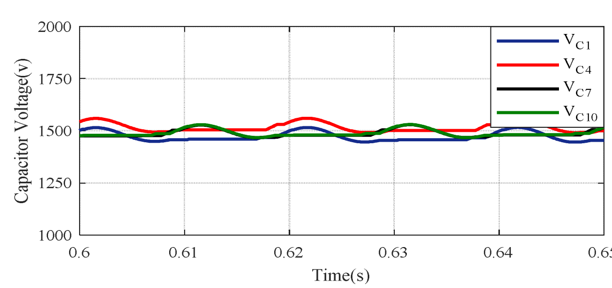



Figure 15. Capacitor voltages of SMs in second mode of the proposed method

## V. A STUDY ABOUT THE LOSSES AND EFFICIENCY OF THE SYSTEM

This section introduces loss and efficiency calculation for two different operation 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. 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 [14] 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.

Table II and Table III show the calculated losses and efficiency of the system for two modulation methods in OVHC and CCHC mode of operation. From these tables, it can be seen that efficiency doesn't have big change in two modes of the proposed method compared to traditional method. The slight change for efficiency 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.

TABLE II. Power and efficiency calculations for OVHC mode

| | | Output Power (kw) | Total loss (kw) | Efficiency |
|---|---|---|---|---|
| **Traditional method** | $m_a$=1 | 841.10 | 32.25 | 96.3% |
| **Proposed method** | $m_a$=1 | 846 | 31.42 | 96.41% |
| | $m_a$=1.15 | 1110 | 44.13 | 96.17% |

TABLE III. Power and efficiency calculations for CCHC mode

| | | Output Power (kw) | Total Loss (kw) | Efficiency |
|---|---|---|---|---|
| **Traditional method** | $m_a$=1 | 839 | 33.83 | 96.12% |
| **Proposed method** | $m_a$=1 | 843.70 | 33.44 | 96.18% |
| | $m_a$=1.15 | 1116 | 43.836 | 96.22% |

## VI. CONCLUSION

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 minimization and circulating current harmonics cancellation 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 proposed method. So it can be acceptable choice where the DC voltage drop can be compensated by the proposed method.

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