INVESTIGATION OF POWER LOSS AND TOTAL HARMONIC DISTORTION ON MODULAR MULTILEVEL CONVERTER UNDER DIFFERENT MODULATION TECHNIQUES

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Abstract: *In this paper, the power loss occurs in single phase nine level modular multilevel converter for different pulse width modulation (PWM) techniques is investigated. The comparative analysis is carried out under variable switching frequency. The PWM techniques include phase disposition PWM (PDPWM), phase opposition disposition PWM (PODPWM), alternate phase opposition disposition PWM (APODPWM), and phase shift PWM (PSPWM). The simulation is carried out using MatLab-Simulink and verified experimentally.*
Key words: *Modular multilevel converter, pulse width modulation, power loss, MatLab.*

1. Introduction

Modular multilevel converter (MMC) has become popular for medium and high power applications [1-2].Unlike other voltage source converter, MMC avoids the difficulty of connecting power semiconductors in series [3]. The voltage rating can be scaled to desire rating by adding the sub modules and has low switching loss compared to other multilevel topologies [4]. The voltage balancing of MMC can be achieved easily and also any number of levels can be examined without the addition of filtering component. MMC has different circuit configuration in which the cascaded H-bridge based circuit configuration is considered due to certain aspects such as scalable, modularized layout, reduced harmonic distortion, operated at low frequency and no extra clamping diodes which is easy to implement [5]. The number of levels at the output is determined by the sub modules present in each leg. Each leg comprises of two arm separated by an inductor at the end [6]. The number of level (NL) is determined as given NL = 2(NSM) +1, where NSM is the number of sub module in each arm.

Modulation is the process that used to switch the power electronic device from one state to other. For MMC, the purpose of the modulation techniques is to generate the multilevel output waveform [7]. Each modulation technique generates different switching pulses to achieve the desired output waveform. The modulation strategies are also responsible for maintaining the output voltage balanced. The need for the multilevel modulation techniques are high voltage quality, modular design, eliminating the simultaneous switching of multiple voltage levels, etc [8].

Among the modulation techniques sine PWM (SPWM) techniques are characterized by constant amplitude pulses with different duty cycle for each period. The width of these pulses are modulated to obtain desired output voltage and to reduce the harmonic content. Hence, SPWM is mostly used in the inverter application [9]. Bipolar switching scheme is considered in this research work because of its advantages over unipolar switching such as redundancy, elimination of harmonic content which results in lower THD [10].

In this paper, the different modulation techniques have been applied and power loss on each sub module switches is examined. Fig. 1 shows the block diagram of the system.

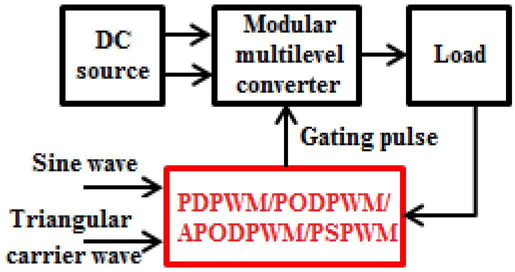

Fig.1. Block diagram of the system

The power loss is analyzed and compared at various switching frequencies. The simulation results carried out using MatLab-Simulink and validated experimentally.

2. Modulation techniques

The SPWM is classified into level shifted PWM and phase shifted PWM technique.

Level shifted carrier modulation technique for MMC requires N-1 carrier signals with same frequency and magnitude [11-12]. These carrier signals are vertically disposed with each other. The modulation index for level shifted PWM method is defined as the ratio of magnitude of reference sine wave to the magnitude of carrier wave.

$$m_a = \frac{2A_r}{(N-1)A_c} \qquad (1)$$

There are three types of level shifted PWM technique are discussed below

A. Phase disposition PWM

In this technique all the carriers are in phase to each other. The carrier and reference signals of PDPWM are shown in Fig. 2. It is most widely used technique since it results in lower harmonic distortion in output voltage and current of MMC. In the carrier based modulation technique at every instant of time the modulation signals are compared with the carrier and depending on which is greater, the switching pulses are generated. In the PWM scheme there are two triangles, the upper triangle ranges from 1 to 0 and the lower triangle ranges from 0 to –1. In the similar way for an N –level inverter, the (N-1) triangles are used.

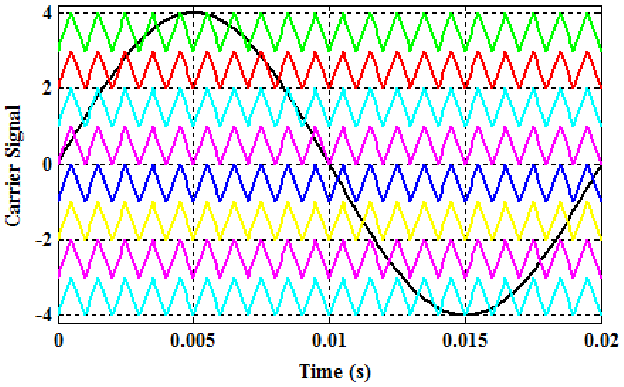

Fig. 2. Phase disposition PWM technique

B. Phase Opposition disposition PWM

In phase opposition disposition PWM technique all the carriers above the zero level are in-phase to each other and 180 degree out of phase with the carriers below the zero level is shown in Fig. 3.

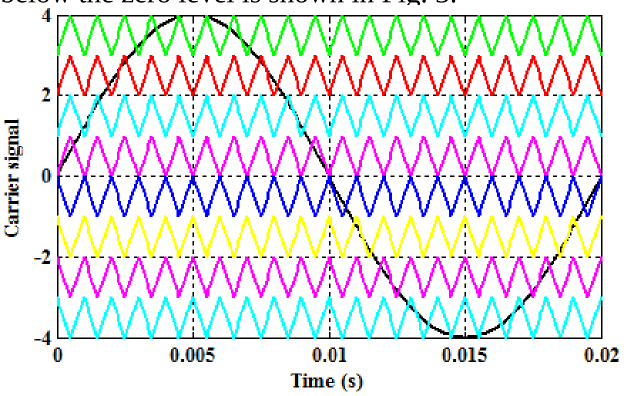

Fig. 3. Phase opposition disposition PWM technique

C. Alternate Phase Opposition disposition PWM

In alternate phase opposition disposition PWM technique all the carriers are 180 degree out of phase with each other is shown in Fig.4.

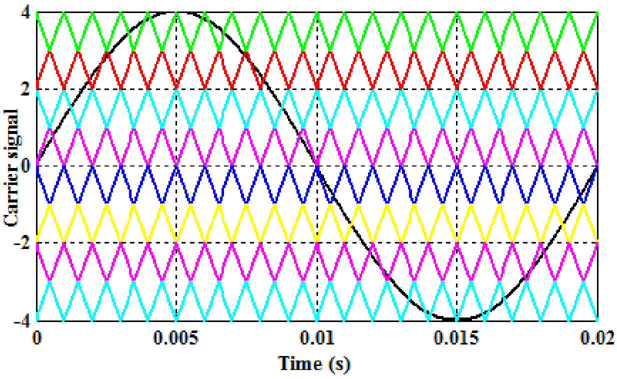

Fig. 4. Alternate phase opposition disposition PWM technique

D. Phase shifted PWM

In phase shifted modulation technique each carrier signal is phase with 360/(N-1) [13] is shown in Fig. 5. The modulation index for phase shifted modulation technique is given by

$$m_a = \frac{A_r}{\left(\frac{A_c}{2}\right)} \tag{2}$$

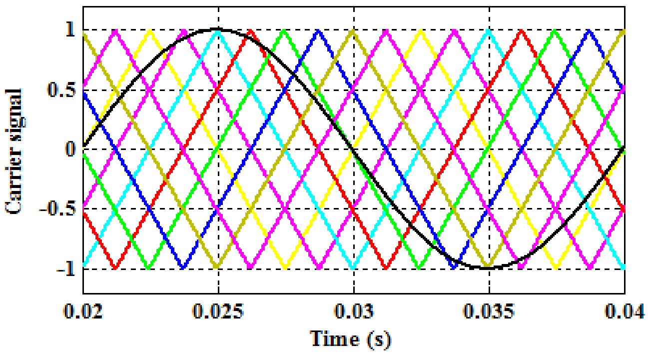

Fig. 5. Phase shift PWM technique

3. Analysis of power loss in MMC

The design, modeling and operating principle of Modular multilevel converter is based on the literature [1-4].The basic topology of MMC is shown in Fig. 6. The average sub module capacitor voltage is given as,

$$U_{sm} = \frac{U_{dc}}{n} \tag{1}$$

The reference voltage of single phase MMC is given by

$$U_{aref} = \frac{mU_{dc}}{2}\cos(\omega t) \tag{2}$$

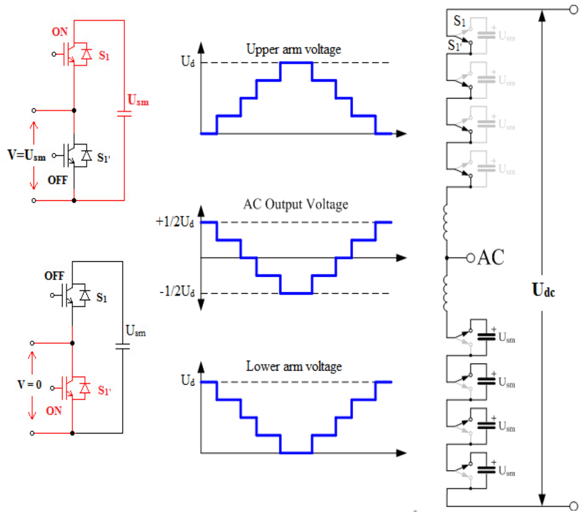

Fig.6. Topology of single phase MMC

4. Power loss analysis

A. Switching loss

Switching loss is the powers dissipated during the turn on and turn off switching transitions [14]. The equations governing the determination of switching loss for MOSFET (IRFP460) is given below

$$E_{on} = \int_0^{ton} P(t)dt \quad (3)$$

$$E_{off} = \int_0^{toff} P(t)dt \quad (4)$$

$$E_{sw} = E_{on} + E_{off} \quad (5)$$

$$E_{sw} = \frac{1}{2} V_{DS} I_D (t_{on} + t_{off}) \quad (6)$$

The switching loss of MOSFET is calculated as

$$P_{sw} = E_{sw} f_{sw} \quad (7)$$

$$P_{sw} = \frac{1}{2} V_{DS} I_D (t_{on} + t_{off}) f_{sw} \quad (9)$$

Where E_{on}- energy loss for on transient, E_{off}- energy loss for off transient, t_{on}-turn-on delay time, t_{off}- turn off delay time, f_{sw}- switching frequency

B. Conduction loss

Conduction losses are the losses that occur while the MOSFET is ON state and conducting current [15]. The conduction loss is determined by the following equation

$$P_{con} = I^2_{D(rms)} * R_{DS(ON)} \quad (10)$$

Where V_{DS} is the drain source voltage, I_D average drain current, $R_{DS(ON)}$ is drain-source on-state resistance.
Total power loss per MOSFET is

$$P_{total} = P_{sw} + P_{con} \quad (11)$$

5. Simulation results

The simulation is carried out using MatLab-Simulink. The results are presented under different modulation techniques at switching frequency of 5 kHz as shown in Fig. 7, Fig.8, Fig. 9 and Fig. 10.

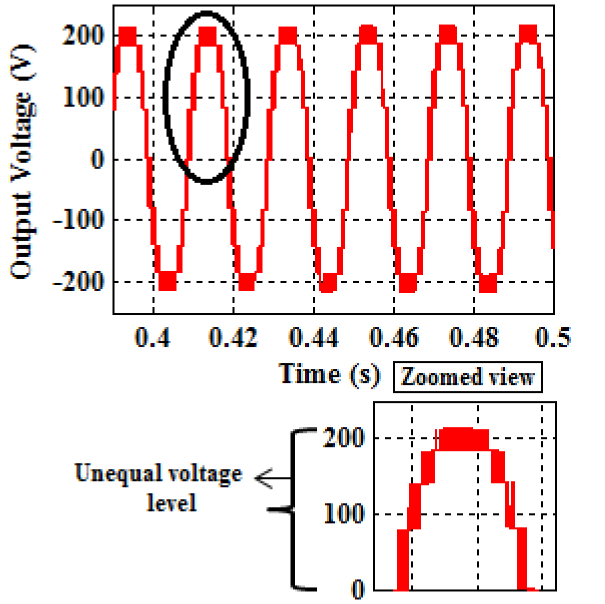

Fig.7. Output voltage using APODPWM

It is observed from Fig.7 that the voltage level is unequal and has harmonic content of about 18.86% by using MatLab FFT tool analysis. To reduce the harmonic content and have equal voltage level it is preferred to implement other PWM techniques.

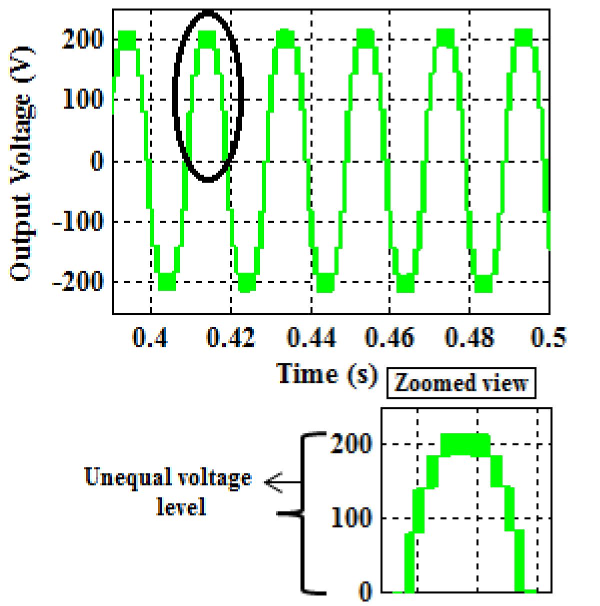

Fig.8. Output voltage using PODPWM

Fig.8 shows the output voltage of MMC using PODOWM technique. It is observed that the magnitude of voltage is not equal for each level and the harmonic content is about 18.36 %. Even though the harmonic content is reduced compared with APODPWM technique it does not have equal splitting voltage levels.

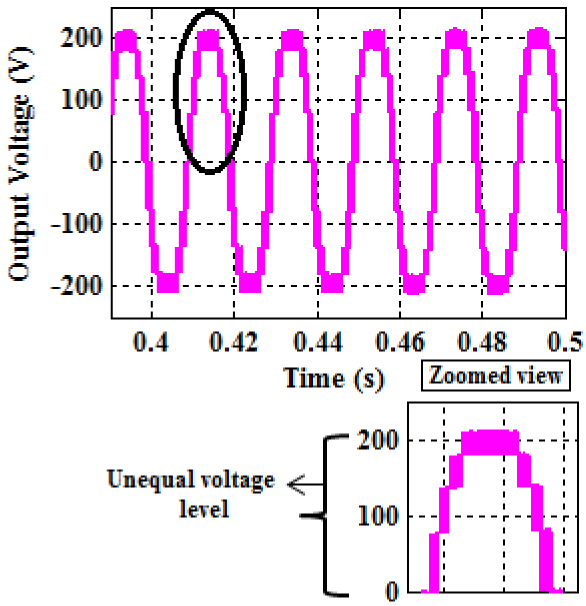

Fig.9. Output voltage using PDPWM

From Fig.9 is inferred that the voltage levels are still unequal but the harmonic content is reduced to 18.42% using FFT analysis in MatLab. To have a equal voltage levels the phase shift PWM technique is implemented.

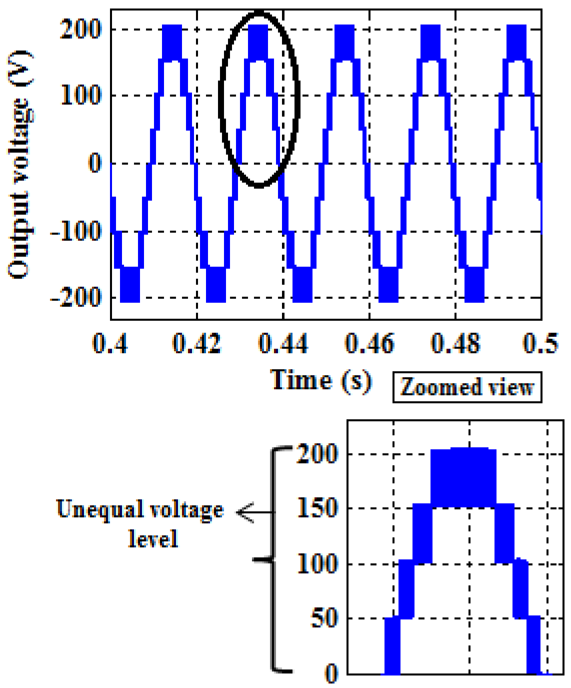

Fig.10. Output voltage using PSPWM

It is observed from the Fig. 10 that the output voltage has equal voltage levels and the harmonic content is also reduced to about 17.05% using PSPWM technique. Thus the PSPWM is preferred compared to other PWM techniques.

The loss analysis is carried out for different PWM technique under various switching frequencies. The losses have been calculated using equations (3)-(11).

Table 1 and Table 2 show the switching and conduction loss analysis for single switch in a sub module of MMC.

Table 1 Switching loss under different PWM techniques (for single switch)

Frequency (kHz)	PS (W)	APOD (W)	PD (W)	POD (W)
2.5	0.0222	0.0902	0.0990	0.0834
3.5	0.0230	0.0901	0.0883	0.0853
5	0.0232	0.0892	0.0878	0.0976

Table 2 Conduction loss under different PWM techniques (for single switch)

Frequency (kHz)	PS (W)	APOD (W)	PD (W)	POD (W)
2.5	0.0208	0.3435	0.4138	0.2937
3.5	0.0223	0.3429	0.3290	0.3073
5	0.0227	0.3356	0.3255	0.4018

It is inferred from the above analysis of Table 1 and 2, the switching and conduction loss is minimum in case of phase shift modulation technique compared with other PWM techniques under various switching frequencies.

Even though the power switches in each sub module conduct at different instants, the on/off time intervals are same for all the switches. Therefore the power loss in single switch is similar to all other switches in MMC and the calculations were extended for 18 switches present in single phase nine level MMC. The total power loss of MMC is shown in Fig.10 at different PWM techniques under vaious switching frequency.

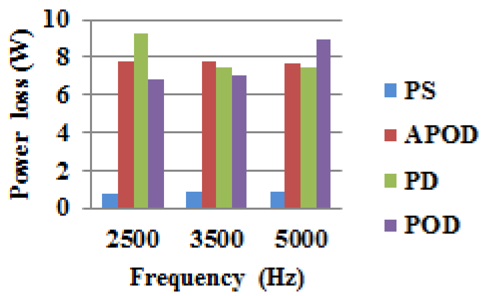

Fig.10. Graphical analysis of total power loss

From the obtained results it is observed that the power loss is minimum when the MMC is switched with phase shifted modulation technique.

The total harmonic distortion is evaluated under different switching frequency using phase shifted PWM technique. The graphical evaluation of THD at various switching frequencies is shown in Fig.11. From the obtained results it is concluded that the THD is reduced as the switching frequency is increased.

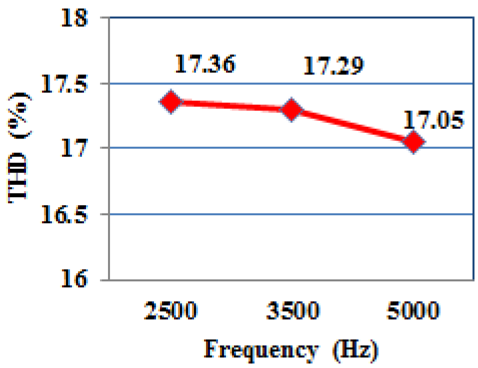

Fig.11. Graphical analysis of THD percentage under different switching frequency using PSPWM technique

6. Hardware Implementation

The hardware realization of single phase MMC is carried out and setup is shown in Fig.12. The supply voltage of 460 V is given to the MMC. To provide supply to both optocoupler and transistor power supply circuit is used which consists of step down transformer, bridge rectifier and regulator. The transformer steps down the ac supply voltage to 15V. The bridge rectifier converts 15V ac to dc and 1000µF capacitor is used as filter to remove the ripple. The regulator 7812 ensures 12V dc supply to both optocoupler and the transistor. The control pulses generated from the FPGA SPARTAN 6 processor are given to the optocoupler circuit MCT2E. Then the pulses from the optocoupler circuit are given to the MMC in which the stair case ac signal is obtained.

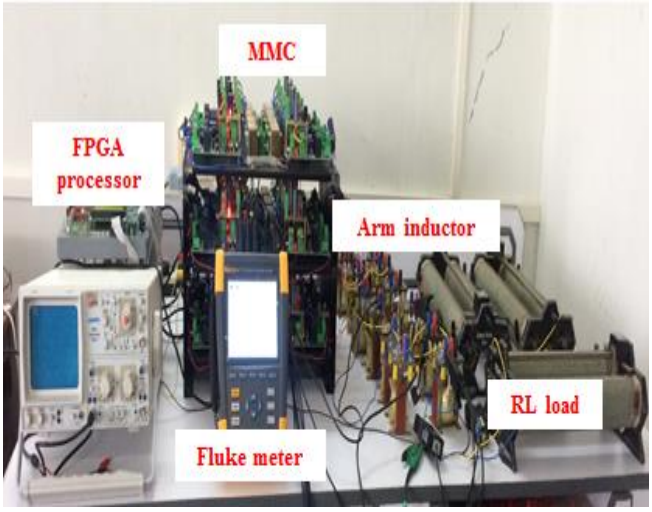

Fig. 12. Hardware setup of MMC

The output voltage and current of MMC using phase shifted modulation technique is shown in Fig. 13.

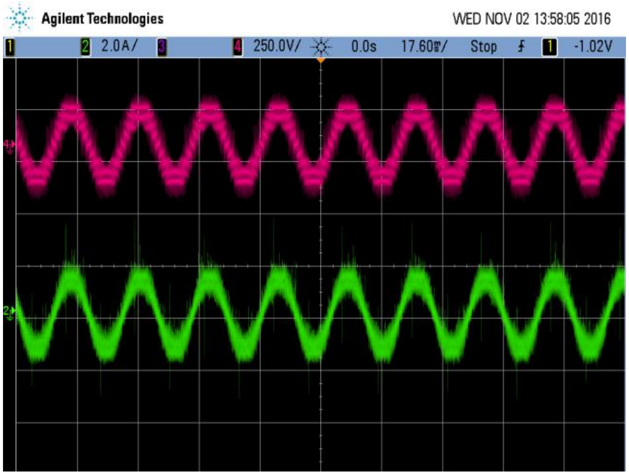

Fig. 13. Output voltage and current of MMC

The THD is analyzed using fluke meter for different switching frequency and shown in Fig. 14, Fig. 15 and Fig. 16.

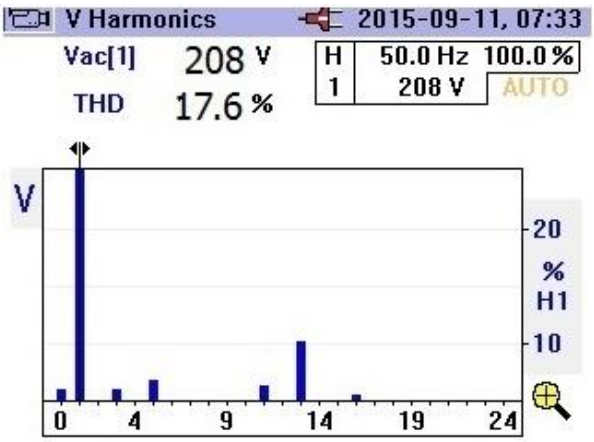

Fig. 14. THD at 2.5 kHz

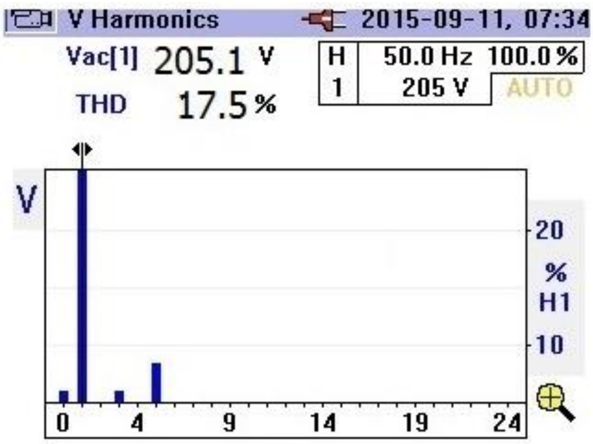

Fig.15. THD at 3.5 kHz

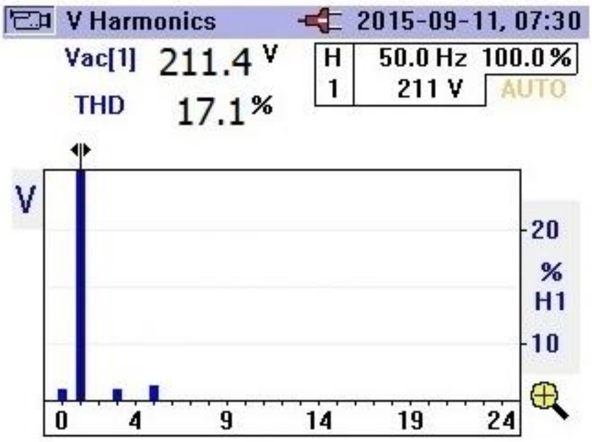

Fig. 16. THD at 5 kHz

From the above obtained hardware results the THD is reduced as increase in the switching frequency. Fig.17 shows the comparative graph of simulated and experimental results of the proposed system. It is observed that the experimental results obtained are similar to that of simulated results.

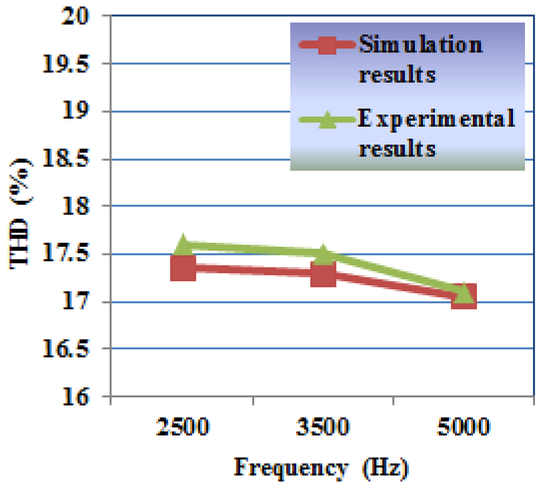

Fig. 17. Graphical analysis of simulation and experimental results

7. Conclusion

The design and implementation of MMC is carried out using MatLab-Simulink. Different modulation techniques are implemented and the results are compared under various frequencies. It is observed that the PSPWM technique has low THD and equal voltage levels compared with other level shifted PWM techniques. The power loss is also analyzed for different modulation techniques under various switching frequencies. It is concluded from the obtained results that the PSPWM has low power loss. Under various switching frequencies the THD is also reduced as the frequency is increased in case of PSPWM technique. The results are validated experimentally and the results are presented.

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