Proceedings of the 2019 5th International Conference on Advances in Electrical Engineering (ICAEE), 26-28 September, Dhaka, Bangladesh

Improvement in Performance of Asymmetric Multilevel Inverter Used for Grid Integrated Solar Photovoltaic Systems

Md. Tariqul Islam[1], Md. Rabiul Islam[2], Md. Sayead Bin Islam[1], Md. Shizer Rahman[1]

[1]Department of Electrical and Electronic Engineering, Pundra University of Science & Technology, Bogura, Bangladesh

[2]Faculty of Engineering and Information Sciences, University of Wollongong, New South Wales 2522, Australia
ashamim617@gmail.com; mrislam@uow.edu.au; sayead.bin.islam@gmail.com; rshizer@yahoo.com

Abstract— The multilevel inverter has gained significant attention for medium and high voltage applications. The neutral point-clamped, flying capacitor, and cascaded H-bridge (CHB) inverters are the bais topologies. It tends to be more gorgeous by increasing the number of levels in output waveform with lower rated voltage sources and power semiconductor devices. This significantly improves output power quality, e.g. lower total harmonic distortions (THDs). However, switching loss of the inverter is the critical issue as the inverter uses a large number of switches. This paper proposes different multicarrier switching techniques which are applied to a CHB inverter having two unequal dc supplies to generate seven level output voltage. These proposed topologies generate more output level than conventional topology which results in reduced total harmonic distortion. Additional vital feature of this proposed multicarrier switching topology is that fundamental rms output voltage increases which increases the output power level. These new proposed multicarrier switching topologies are compared with conventional techniques. This comparison is made in terms of THDs, fundamental output voltage and inverter loss. Finally, the efficacy of the proposed system has been validated through simulation analysis in the MATLAB/Simulink software environment.

***Keywords*— Multilevel inverter, total harmonic distortion, modified carrier, conventional carrier, modulation algorithm, inverter loss, level shifted topology, asymmetric multilevel inverter, MATLAB/Simulink.**

I. INTRODUCTION

At the present time, multilevel control transformation is especially appreciated as a result of its use for medium and high voltage power applications. It doesn't accomplish just high-power rating yet in addition approve the utilization of sustainable power sources. This multilevel power conversion is done by multilevel inverter and is typically outfitted with more imperative than two voltage levels. The multiple steps in the output voltage waveform enables to produce ac power with less harmonics, which increases system efficiency and decreases system size and cost. The stepped waveform is gotten by different voltage levels which are delivered by the correct association of load. This is accomplished by the best possible switching of the power semiconductors. In order to reduce the harmonic in the output voltage waveform, high switching frequency based different modulation techniques were used to drive single or three stage voltage inverters [1]-[3]. The high switching frequency increases the switching and conduction losses of the inverter. Moreover, the power semiconductor devices have limited range of switching frequencies.

Currently, the multi-carrier pulse width modulation technique is very much admired because of its usage for controlling switches of the modular multilevel inverter. This technique uses a sinusoidal signal, trapezoidal signal, Third-harmonic Injection signal etc. as a reference signal and a triangular wave is used as a carrier signal [4]. Depending on the arrangement of a carrier signal, multicarrier pulse width modulation technique is divided into several categories like Phase opposition disposition, Alternative phase opposition disposition, In-phase disposition [1]. Multi-carrier technique has been more popular because of its advantages like low total harmonic distortion, increased fundamental output voltage [5]. As total harmonic distortion (THD) has an adverse effect on equipment and conductor. Higher THD offers increased heating loss, arising false triggering, a reduced lifetime of devices. In addition, it also increases the cost and size of the filtering devices. Then again, inferior THD offers an advanced power factor, lesser pick current, and higher efficiency [6-7]. That is why it is very essential to diminish the THD of the multilevel inverter. The chief objective of this paper is to investigate the reduction of the THD of a modular multilevel inverter.

Different modified Multicarrier pulse width modulation (PWM) techniques have been presented in this paper and tried to find out the optimal condition for the reducing of THD result on the output waveform of the asymmetric multilevel inverter. Therefore, in order to diminish the THD result, one of the best solutions is to enclosure a filter circuit in the output of inverter but this arrangement is costly as well as makes the inverter bulky. For the reduction of THD, this paper proposes three modified carrier based multicarrier pulse width modulation technique. These proposed topologies generate more voltage level than traditional topology which results in diminished third harmonic distortion. An additional significant element of these proposed multicarrier switching topologies is that fundamental rms output voltage upsurges which enlarges the output power level. This new control scheme is applied to seven-level asymmetric multilevel inverter and compared with conventional carrier-based multicarrier PWM technique. The comparison is made in terms of THD, fundamental output voltage and inverter loss. In order to confirm quality performance, level shifted conventional carrier and modified carrier-based sine pulse width modulation (SPWM) topologies are used for the asymmetric seven-level inverter with a carrier frequency of 2 kHz and modulation index of 0.8–1.20.

978-1-7281-4934-9/19/$31.00 ©2019 IEEE

This paper has been sorted out as pursues: segment two arrangements with reduced switch multilevel inverter, segment three arrangements with multicarrier pulse width modulation technique, segment four arrangements with calculation of inverter loss, segment five arrangements with simulation results, segment six arrangements with selection topology, at long last, the article closes with conclusion and references.

II. Asymmetric Multilevel Inverter

The proposed single-phase asymmetric inverter is shown in Fig. 1. In the proposed system, solar photovoltaic array interconnects the medium voltage grid without using a step-up/isolation transformer. By increasing number of cascaded H-bridge modules, the output voltage level as well as quality can be improved [8]. A high-frequency magnetic link is used to generate two isolated and balanced dc supplies of the H-bridge inverters [9], [10]. The high frequency inverter after dc-dc converter excites the primary windings of the magnetic link. Equal voltages are induced in the secondary windings. Beside the number of cascaded modules, advanced modulation techniques may help to reduce the harmonics in the output voltage of the inverter. Different advanced modulation techniques are well investigated in this paper.

The mode of procedure is explained via the Fig. 2 from a to h. The switching sequence is tabulated in Table I.

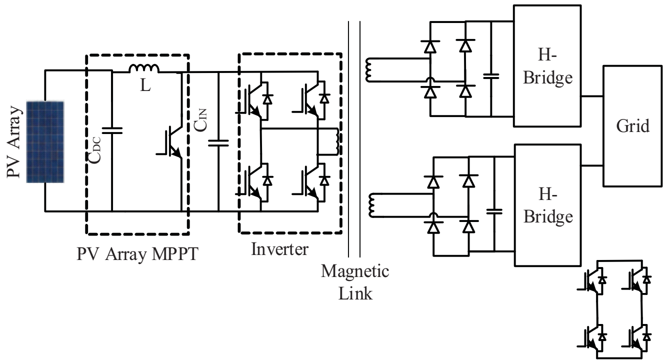

Fig. 1. Seven level single phase asymmetric photovoltaic (PV) inverter for direct medium voltage grid integration.

Mode 1: During mode-1, the progression of way begins from voltage source V1 and goes through the H-connect switches, for example, S1 and S4 and experiences S5 and S7 of the second H connect and finishes the way through and returns to V1 as appeared in Fig. 2(a). In this case, the output voltage is positive V1.

Mode 2: In mode-2, the progression of way begins from voltage source V2 and goes during that time H-bridge switches, for example, S5 and S8 and experiences S1 and S3 of the main H-bridge and finishes the way through and returns to V2 as appeared in Fig. 2(b). In this time, the output voltage is positive V2.

Mode 3: During mode-3, the progression of way begins from voltage source V1 and goes through the H-bridge switches, for example, S1 and S4 and experiences S5 and S8 of the second H bridge and finishes the way through and returns to V1 as appeared in Fig. 2(c). At this state, the output voltage is V1+ V2.

Mode 4: In mode-4, the zero level of output voltage can be achieved by turning on switches S2, S4, S5 and S7 as presented in Fig. 2(d).

Mode 5: In mode-5, the progression of way begins from voltage source V1 and goes through the H-bridge switches, for example, S2 and S3 and experiences S5 and S7 of the second H bridge and finishes the way through and returns to V1 as appeared in Fig. 2(e). At this situation, the output voltage is negative V1.

Mode 6: During mode-6, the progression of way begins from voltage source V2 and goes during that time H-bridge switches, for example, S6 and S7 and experiences S1 and S3 of the principal H-bridge and finishes the way through and returns to V2 as appeared in Fig. 2(f). In this time, the output voltage is negative V2.

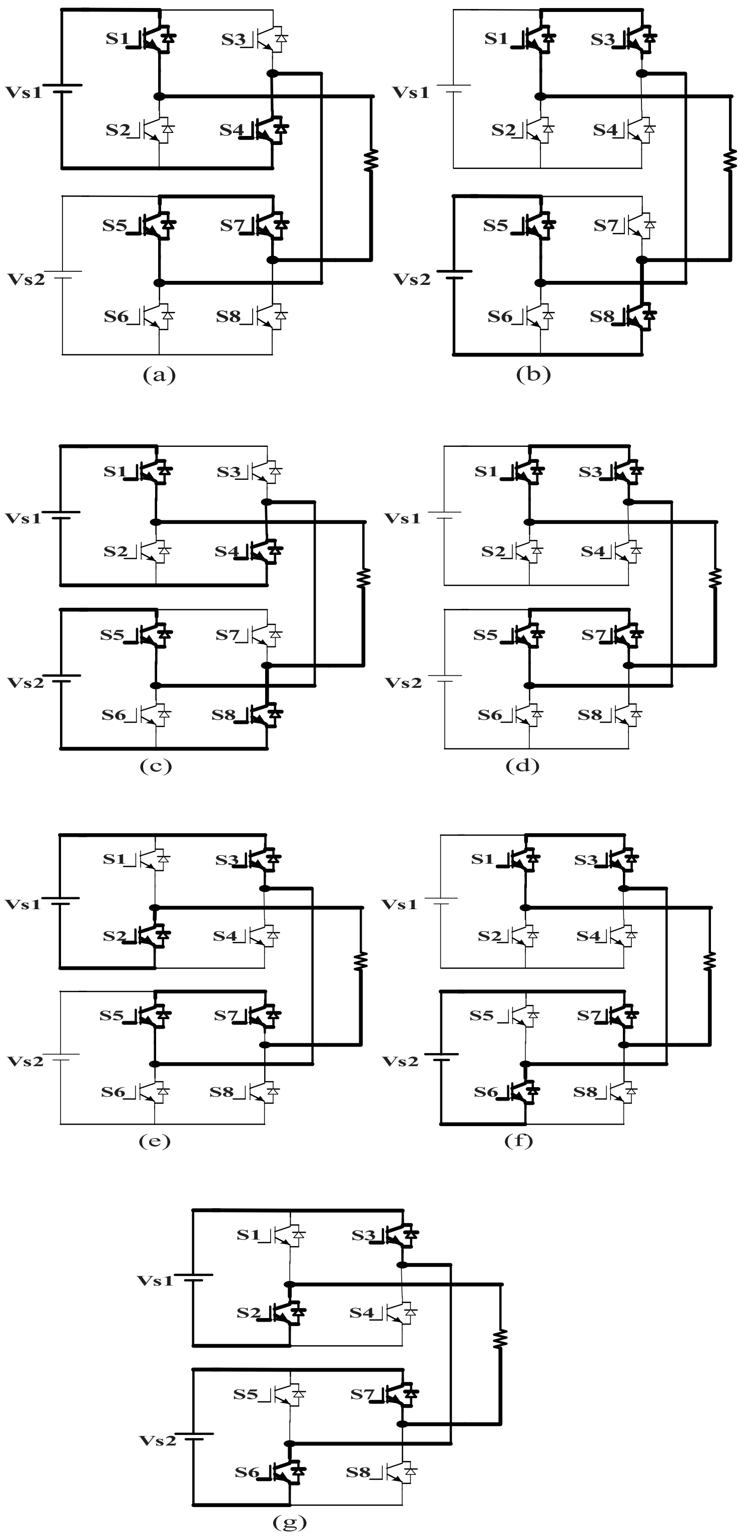

Fig. 2. Output voltage of the inverter (a) V1, (b) V2, (c) V1+V2, (d) 0, (e) –V1, (f) –V2, (g) –V1-V2.

Mode 7: During mode-7, the progression of way begins from voltage source V1 and goes through the H-bridge switches, for example, S2 and S3 and experiences S6 and S7 of the second H bridge and finishes the way through and returns to V1 as appeared in Fig. 2(g), In this case, the output voltage is negative (V1+ V2).

TABLE I
SWITCHING PATTERN FOR SINGLE PHASE SEVEN LEVEL REDUCED SWITCH MULTILEVEL INVERTER

Voltage levels	S1	S2	S3	S4	S5	S6	S7	S8
V1+V2	1	0	0	1	1	0	0	1
V2	1	0	1	0	1	0	0	1
V1	1	0	0	1	1	0	1	0
0	0	1	0	1	1	0	1	0
-V1	0	1	1	0	1	0	1	0
-V2	1	0	1	0	0	1	1	0
-V1-V2	0	1	1	0	0	1	1	0

III. MULTICARRIER PULSE WIDTH MODULATION TECHNIQUE

The named multicarrier means that this topology uses several carrier signals to generate the switching pulses for multilevel inverter. There are different types of multicarrier PWM technique like phase disposition (PD), phase opposition disposition (POD), alternative phase opposition disposition (APOD), variable frequency (VF), carrier overlapping (CO) [11]. For multicarrier PWM technique, the calculation of modulation index and frequency modulation ratio are given as [12].

Modulation index,

$$M_a = \frac{V_m}{(m-1)V_{cr}} \quad (1)$$

where V_{cr} is the peak value of each carrier wave, *m* is the number of levels and V_m is the peak value of modulating wave.

Frequency modulation index,

$$M_f = \frac{f_{cr}}{f_m} \quad (2)$$

where f_{cr} is the frequency of each carrier wave and f_m is the frequency of modulating wave.

Among these techniques, it is alternative phase opposition disposition pulse width modulation (APODPWM) technique which delivers an output with the smallest distortion [11]. For this reason, only APODPWM technique has been considered in this paper.

A. Conventional Triangular Carrier Signal

This triangular wave is periodic, linear and continuous function. This signal is generated in MATLAB using conventional block in MATLAB/Simulation. The mathematical equation for conventional carrier signal as a function of time is

$$y(t) = |A \sin^{-1}(\sin(2pift))| \quad (3)$$

where *A* is the amplitude of the signal and *f* is the carrier frequency.

B. Triangular M shaped Carrier Signal (TMC)

It is modified version of triangular signal. This modified triangular carrier signal is used as carrier signal for modular multilevel inverter. It has two parts. One is triangular signal generation part and another is modified part. The mathematical equation for Triangular M shaped Carrier Signal as a function of time is

$$y(t) = |A\{|\sin^{-1}(\sin(2pift))| + \tan^{-1}(\sin(2pift))\} - 0.4| \quad (4)$$

Fig. 3(c) shows a new carrier signal which is the modified version of triangular wave. It is also a periodic and continuous function of time. This modified triangular wave consists of a triangular wave along with a "M" shape wave. The proposed wave shape shows better performance than existing triangular wave.

C. Triangular Sinusoidal carrier Signal (TSC)

In this paper, a new carrier signal is offered for multicarrier pulse width modulation where sinusoidal wave is placed between two triangular waves. For this reason, this new carrier signal is known as triangular sinusoidal carrier. The mathematical equation for Triangular Sinusoidal Carrier Signal as a function of time is

$$y(t) = |A\{|\sin^{-1}(\sin(2pift))| + \tan^{-1}(\cos^{-1}((\sin(2pift)))\} - 0.4| \quad (5)$$

The carrier signal is presented in Fig. 3(d). It is also periodic and continuous function of time. This proposed wave shape shows better performance than existing triangular wave.

D. Trapezoidal triangular Carrier Signal

It is also modified version of carrier signal. It consists of two signals like trapezoidal signal and triangular signal as shown in Fig. 3(b). The mathematical equation for trapezoidal triangular carrier signal as a function of time is

$$y(t) = [A.\{((\cos^{-1}((\sin(2pift)) + \tan^{-1}(\sin(2pift))\} - 0.8] \quad (6)$$

E. Alternative Phase Opposition Disposition Pulse Width Modulation

In this Method, the carrier waves are out of phase with one another and the magnitude and frequency for every carrier are identical. APOD scheme for 7 level inverter is illustrated in Fig. 4.

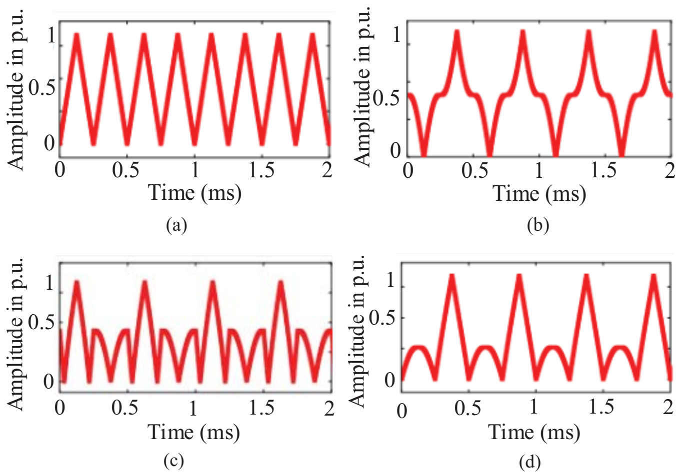

Fig. 3. Different types of carrier signal: (a) conventional carrier, (b) trapezoidal triangular carrier, (c) triangular M-shaped carrier, and (d) triangular sinusoidal carrier.

F. Pulse Generation Procedure

For generating gating pulse, these carrier waves are respectively compared with a modulating signal. If modulating sine wave is bigger than all the carrier waves, the converters give positive pulse and if modulating wave is bigger than inferior carrier but lower than a superior carrier, the converters give zero level and when modulating wave is less than all the carrier waves, converters give a negative pulse. In this way, we get multiple pulses for multilevel inverter.

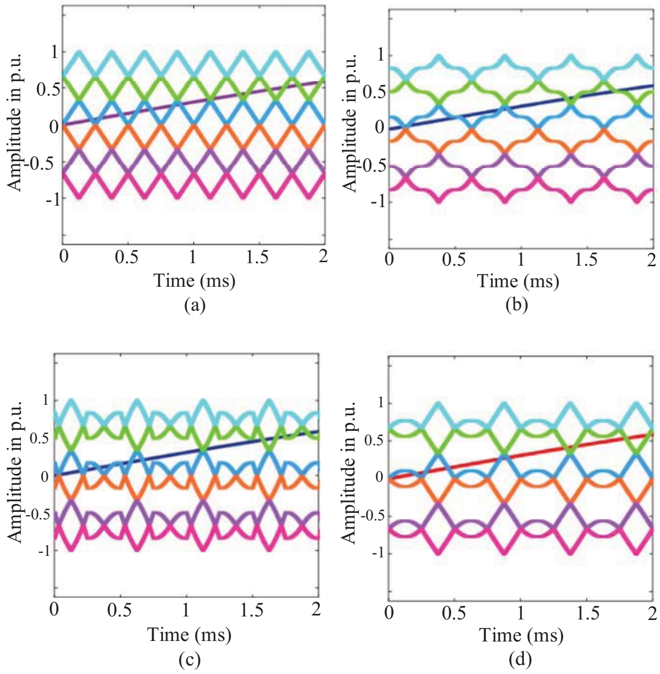

Fig. 4. APODPWM arrangement for: (a) conventional carrier, (b) trapezoidal triangular carrier, (c) triangular M-shaped carrier, and (d) triangular sinusoidal carrier.

IV. Calculation of Inverter Loss

Inverter loss includes two losses named as conduction loss and switching loss. For an IGBT module, it is switch conduction and anti-parallel diode conduction which assist conduction loss. The calculation of conduction power losses [13] can be given by

$$P_{cond\_IGBT} = \frac{1}{2\pi}\int_0^{2\pi} V_{ce}(\theta) \times I(\theta) \times V_{cmd}(\theta)\, d\theta \tag{7}$$

$$P_{cond\_D} = \frac{1}{2\pi}\int_0^{2\pi} V_F(\theta) \times I(\theta) \times V_{cmd}(\theta)\, d\theta \tag{8}$$

$$P_{cond} = P_{cond\_IGBT} + P_{cond\_D} \tag{9}$$

where $I(\theta)$ is the load current, $V_{cmd}(\theta)$ is the PWM signal of the IGBT, $V_{ce}(\theta)$ is the voltage across switch, and $V_F(\theta)$ is the voltage across diode.

Presently, novel high-power devices can switch quicker. Meanwhile switching losses have direct relation to the switching frequency, these losses are normally very high in PWM converter. The switching loss can be calculated as

$$P_{sw} = \frac{1}{T}\sum E_{on} + E_{off} + E_{rec} \tag{10}$$

where E_{on} is the turn on commutation, E_{off} is the turn off commutation, and E_{rec} is the diode reverse recovery process.

Here, IGBT module FF150R12KT3G is used for loss calculation. Mathematical models obtained for the IGBT module FF150R12KT3G [8] are given by

$$V_{ce} = 1.15e^{0.00226I(\theta)} - 0.6654e^{-0.044I(\theta)} \tag{11}$$

$$V_F = 1.2e^{0.002I(\theta)} - 0.72584e^{-0.0475I(\theta)} \tag{12}$$

$$E_{on} = 0.0051e^{0.0064I(\theta)} - 0.0037e^{-0.00811I(\theta)} \tag{13}$$

$$E_{off} = 0.0643e^{0.00121I(\theta)} - 0.0647e^{-0.00107I(\theta)} \tag{14}$$

$$E_{rec} = 0.01806e^{0.000412I(\theta)} - 0.0157e^{-0.06736I(\theta)} \tag{15}$$

$$I(\theta) = M{*}I_{max}Sin(\theta - \emptyset) \tag{16}$$

where M is the modulation index, $\emptyset$ is the phase shifted between voltage and current. In this paper, only switching loss has been considered.

V. Simulation Results

Both conventional and modified triangular based APODPWM techniques are analyzed for seven-level reduced switch multilevel inverter using MATLAB/Simulink software. The obtained result from MATLAB/Simulation will assist us to verify our proposed modified triangular based multicarrier SPWM techniques and also assists to prove that the proposed topologies are better than the conventional one.

Fig. 5 appearances the output voltage waveform of reduced switch 7-level inverter topology using modified and conventional triangular based APODPWM techniques. Here almost similar outputs of these topologies are observed. Distinct differences can be observed in harmonic spectrum of these output voltages presented in Fig. 6.

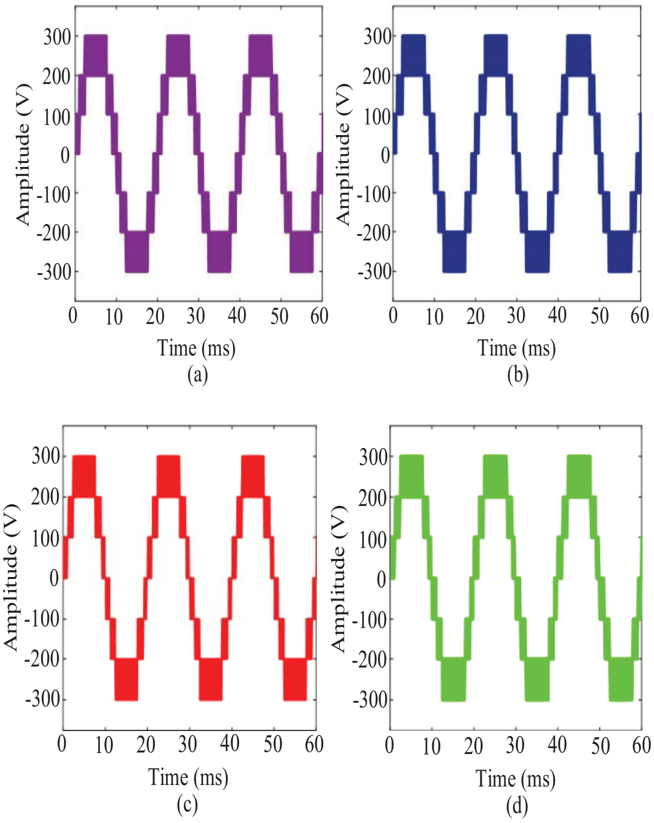

Fig. 5. Output response of asymmetric seven level inverter using: (a) conventional carrier APOD, (b) triangular M-shaped carrier APOD, (c) trapezoidal triangular carrier APOD, and (d) trapezoidal triangular carrier APOD.

VI. Topology Selection

In this section, the comparison between conventional carrier and modified carrier based APODPWM topology has been done with the help of simulation results. This comparison has carrier out based on THD, fundamental output voltage and inverter loss.

A. Total HarmonicDistortion (THD) Comparison

Total harmonic distortion has an adverse effect on equipment and conductor. Higher THD offers expanded warming misfortune, emerging false activating, diminished life time of gadgets. Notwithstanding, it additionally expands the expense and size of the sifting gadgets. So, it is fundamental to lessen the THD of inverter. The comparative result based on percentages of THD has been shown in Fig. 7. The accompanying figure will clear a route for better comprehension about the avocation of our proposed model.

From the Fig. 7, it is seen that the THD is lesser for modified carrier based APODPWM than conventional carrier based APODPWM technique. For fixed carrier frequency 2 kHz, the most reduced dimension of THD is watched for modified carrier based APODPWM at modulation index 1.15 for asymmetric seven level inverter.

For this modulation index, the THD of our proposed models is lesser than conventional carrier based APODPWM. In addition, Trapezoidal triangular Carrier based APODPWM offers less THD than other proposed topologies.

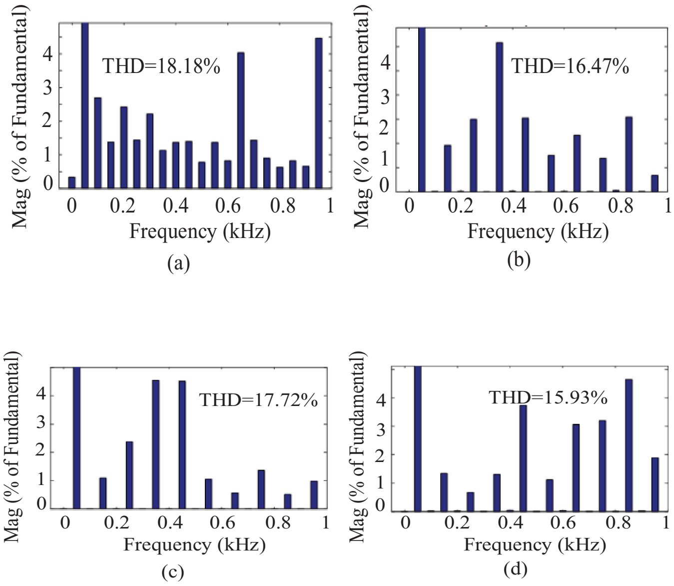

Fig. 6. THD spectrum of Output voltage of asymmetric seven level inverter using: (a) conventional carrier APOD, (b) triangular M-shaped carrier APOD, (c) trapezoidal triangular carrier APOD, and (d) trapezoidal triangular carrier APOD.

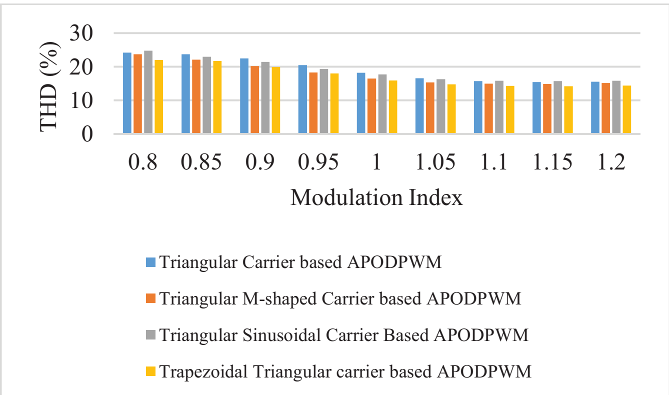

Fig. 7. THD comparison for proposed and existing topologies.

B. Fundamental Output Voltage Comparison

In this section, the comparison between conventional carrier and modified carrier-based level shifted PWM topologies has been done in terms of fundamental output voltages. The fundamental voltage comparison between two techniques has been publicized in Table II.

With the help of Table II, it is understood that fundamental output voltage increases with increasing of modulation index. For fixed carrier frequency 2 kHz, the highest level of the fundamental output voltage is obtained for our proposed topologies. Among our proposed topologies, triangular M shaped carrier based APODPWM topology is better than other proposed topologies in terms of fundamental output voltage.

TABLE II
FUNDAMENTAL OUTPUT VOLTAGE OF REDUCED SWITCH SEVEN LEVEL INVERTER USING CONVENTIONAL AND MODIFIED CARRIER BASED APODPWM

Modulation Index	**TCAPOD PWM**	**TMSCAPOD PWM**	**TSCAPOD PWM**	**TTCAPOD PWM**
	Volt. (RMS)	Volt. (RMS)	Volt. (RMS)	Volt. (RMS)
0.80	174.6	174.7	181.3	169.5
0.85	185.3	190.3	193.9	183.4
0.90	195.7	201.7	203.3	197.2
0.95	205.7	211.2	212.3	207.7
1.00	215.5	219.3	220.2	216.9
1.05	223	225.7	226.7	223.7
1.10	228.6	230.8	231.4	229.5
1.15	233.2	231.1	236.1	233.6
1.20	237.1	239.1	239.4	237.8

TABLE III
SWITCHING LOSS COMPARISON AMONG DIFFERENT TOPOLOGIES

Techniques	**Switching Loss (W)**
Triangular carrier based APODPWM	1.06
Triangular M shaped carrier based APODPWM	1.09
Triangular Sinusoidal carrier based APODPWM	1.7
Trapezoidal Triangular carrier based APODPWM	1.08

C. Switching Loss Comparison

After calculating the switching losses for conventional and modified carrier based APODPWM topologies, the simulation results are represented in Table III. With the help of this Table III, it is witnessed that, the switching loss of our proposed topologies is almost equal to conventional topology. But Triangular Sinusoidal carrier based APODPWM shows high switching loss than among proposed techniques.

VII. CONCLUSIONS

The proposed Triangular M shaped carrier based APODPWM, Triangular Sinusoidal carrier based APODPWM and trapezoidal triangular carrier based APODPWM provide the better spectra property in addition to almost equal switching loss compared with the conventional carrier based APODPWM. The proposed techniques can be used in single phase grid connected asymmetric inverters for cost effective PV systems. Among the proposed topologies, trapezoidal triangular carrier based APODPWM is the best for reducing THD but when considered on fundamental output voltage, triangular M shaped carrier based APODPWM is best among other topologies.

REFERENCES

[1] V. S. K. Devi and S. G. Srivani, "Modified phase shifted PWM for cascaded H bridge multilevel inverter," In: Proc. *2017 Third Int. Conf.*

Adv. Elec., Electron., Inf., Commu. Bio-Inf. (AEEICB), Chennai, 2017, pp. 89-94.

[2] G. Carrara, S. Gardella, M. Marchesoni, R. Salutari and G. Sciutto, "A new multilevel PWM method: a theoretical analysis," *IEEE Trans. Power Electron.*, vol. 7, no. 3, pp. 497-505, July 1992.

[3] M. R. Islam, A. M. Mahfuz-Ur-Rahman, K. M. Muttaqi, and D. Sutanto, "State of the art of the medium-voltage power converter technologies for grid integration of solar photovoltaic power plants," *IEEE Trans. Energy Conversion*, vol. 34, no. 1, pp. 372-384, Mar. 2019.

[4] M. R. Islam, Y. G. Guo, and J. G. Zhu, "H-bridge multilevel voltage source converter for direct grid connection of renewable energy systems," In: Proc. *IEEE Power & Energy Society Inn. Smart Grid Tech. Conf. (ISGT Asia)*, 13–16 Nov. 2011, Perth, Australia, pp. 1–7.

[5] P. Palanivel and S. S. Dash, "Multicarrier pulse width modulation methods based three phase cascaded multilevel inverter including over modulation and low modulation indices," In: Proc. *TENCON 2009 - 2009 IEEE Region 10 Conf.*, Singapore, 2009, pp. 1-6.

[6] A. Rahman, M. M. Rahman and M. R. Islam, "A study of THD minimization of three phase inverter using modified THPWM," In: Proc. *2017 3rd Int. Conf. Elec. Inf. Commu. Tech. (EICT)*, Khulna, 2017, pp. 1-4.

[7] N. Bhargava, S. Gupta, S. P. Phulambrikar "Analysis of asymmetrical cascaded 7 level and 9 level multilevel inverter design for asynchronous Motor," *Int. J. Eng. Res. & Tech.,* vol. 3, no. 8, august-2014.

[8] M. R. Islam, Y. G. Guo, J. G. Zhu, and D. Dorrell, "Design and comparison of 11 kV multilevel voltage source converters for local grid based renewable energy systems," In: Proc. *37th Annual Conf. IEEE Ind. Electron. Society (IECON 2011)*, 7–10 Nov. 2011, Melbourne, Australia, pp. 3596–3601.

[9] M. R. Islam, A. M. M. Rahman, M. M. Islam, Y. G. Guo, and J. G. Zhu, "A modular medium voltage grid connected converter with improved switching techniques for solar photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8887–8896, Nov. 2017.

[10] M. R. Islam, M. A. Rahman, K. M. Muttaqi, and D. Sutanto, "A new magnetic linked converter for grid integration of offshore wind turbines through MVDC transmission," *IEEE Trans. Appl. Superconduct.*, vol. 29, no.2, p. 5400905, Mar. 2019.

[11] T. Sengolrajan, B. Shanthi, S.P. Natarajan, "Comparative study of multicarrier PWM techniques for seven level cascaded Z-source inverter," *Int. J. Comp. Appli., Eng. Systems,* vol. 65, no. 6, pp. 45-53, 2010.

[12] S. Hr. Aghay Kaboli, J. Selvaraj, N.A. Rahim, "Performance evaluation of multicarrier PWM methods for solar cells powered multilevel inverters", In: Proc. *4th IET Clean Energy Tech. Conf. (CEAT 2016)*.

[13] C. Govindaraju, K. Baskaran, " Power loss minimizing control of cascaded multilevel inverter with efficient hybrid carrier based space vector modulation," *Int. J. Elec. Com. Eng. Systems,* vol. 1, no. 1, pp. 45-53, 2010.