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ASSESSMENT OF VARIOUS BIPOLAR VARIABLE AMPLITUDE SPWM STRATEGIES FOR A THREE PHASE TRINARY SOURCE NINE LEVEL INVERTER

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Abstract

This paper presents an inclusive analysis of various Bipolar Variable Amplitude Pulse Width Modulation (BVAPWM) techniques with Sinusoidal reference for three phase Trinary Source Nine level cascaded inverter. A new approach of nine levels is for medium voltage applications. The proposed topology adopts various new schemes such as constant switching frequency with variable amplitude triangular carrier control freedom degree combination concepts, which were developed and simulated for the chosen inverter using MATLAB-SIMULINK. The chosen asymmetrical inverter uses reduced number of switching devices, lower voltage stress of devices, lower electromagnetic interference, low level of high frequency noise, better RMS voltage, lower common-mode voltage and thus reducing losses and low THD in comparison with the literature of exploited conventional topologies existing so far. The configuration of the circuit is simple and easy to control. Performance factors such as %THD, V_{RMS} where measured and Distortion Factor (DF) of output voltage were calculated for different modulation indices and the results are compared. It is observed that BVAPODPWM technique provides minimum THD, BVAAPODPWM technique provides lower DF and BVACOPWM technique provides higher fundamental V_{RMS} output voltage.

Keywords: Asymmetrical inverter, Bipolar variable amplitude, Modulation, minimum switches, Multicarrier sinusoidal pulse width, Total harmonic distortion, Trinary source.

1. Introduction

The Cascaded multilevel inverter (CMLI) has many advantages over other multilevel inverters which is one of the attractive topologies in Asymmetrical multilevel inverters. However, current research studies only disclosed control of Single phase Trinary Source seven level inverter based Multi Carrier Pulse Width Modulation (MCPWM) techniques and there was no literature related to control of three phase Trinary Source Nine level inverter based MCPWM techniques.

To obtain a large number of output voltage levels with minimum devices, it presents a cascaded H-bridge multilevel inverter employing trinary DC sources. Benefiting from the trinary topology of the inverter, nine level can be synthesized with the fewest components. Particularly, a nine-level inverter is an optimization in the number of levels for a given number of power transistors in power converters. The main disadvantage of the conventional topology is the large number of power supplies and semiconductors required to obtain these multistep voltage waveforms. The proposed topology significantly reduces the number of IGBTs and their gate driver circuits as the number of output voltage level increases. The proposed inverter can synthesize high quality output voltage near to sinusoidal waves. The circuit configuration is simple and easy to control. In this paper, three phase Trinary Source nine level inverter based Bipolar Variable Amplitude SPWM techniques were presented, evaluated and analysed. The objective of this paper is to reduce the switching stress and to obtain the output voltage with multiple steps to achieve the lowest THD and improved fundamental V_{RMS}.

The main contribution of this paper is the proposal of new modulation schemes with Bipolar Variable Amplitude PWM (BVAPWM) techniques using Sinusoidal references with triangular carriers. The inverted Sine carrier for fundamental fortification in PWM inverters based FPGA is designed and developed by Jeevananthan et al. [1]. The performance evaluation of various unipolar SPWM techniques for trinary source MLI is focussed in [2]. Balamurugan et al presented a comparative study of COPWM techniques for three phase five level cascaded inverter and introduced a new Variable Amplitude carrier overlapping PWM (VACOPWM) techniques in [3, 4]. Najafi and Yatim [5] designed and implemented new MLI topologies. The power quality analysis for modular structured MLI with Bipolar Variable Amplitude MCPWM techniques (BVAMCPWM) were performed in [6]. Yousefpoor et al. [7] revealed about the THD minimization applied directly on the line to line voltage of MLI.

Kangarlu and Babaei [8] presented a generalized CMLI using series connection of submultilevel inverters. Symmetric and asymmetric new cascaded MLI were designed and implemented in [9]. Cascaded Multilevel Inverter with connection of Novel H-bridge basic units is carried out in [10]. A new modulation method for a 13-level asymmetric inverter toward minimum THD is presented in [11]. The THD and output voltage performance of CMLI using MCPWM techniques were analysed in [12]. Prabaharan et al. [13] presented the comparative analysis of various MCPWM methods for binary DC Source inverter. Various VAMCPWM strategies of MLI using dSPACE were simulated and implemented in [14]. Balamurugan et al. [15-17] discussed about advanced references and carriers based PWM in a symmetrical multilevel inverter, carried control techniques for various bipolar PWM strategies of three phase five level cascaded inverter and Z-Source fed H-type Diode clamped multilevel inverter in . Sengolrajan et al. [18, 19]

evaluated the simulation assessment of PWM strategies for three phase trinary source nine level inverter with rectified sine carriers and discussed about the prediction of trapezoidal variable amplitude PWM techniques for a three phase trinary source nine level inverter. Umamageswari et al. [20] introduced a novel technique for solar power generating system using multilevel inverter.

Comparing with the above recent paper, an inclusive analysis of current research studies only disclosed control of single-phase trinary source seven level inverter based MCPWM techniques and there was no literature related to control of three-phase trinary source nine level inverter based MCPWM techniques. In this paper, for the first time, three-phase trinary source nine level inverter based Bipolar Variable Amplitude SPWM techniques is presented, evaluated and analysed. The proposed system includes variable amplitude triangular carrier with sinusoidal reference based MCPWM techniques for three phase trinary source nine level inverters.

2. Three Phase Nine Level Trinary Source Cascaded Multilevel Inverter

The fundamental H-bridge cascaded topology increases the number of components required, which in turn makes the design complexity and increases the cost. It is also to be establishing that the maximum output voltage cannot go beyond the sum of voltage of individual sources, which becomes the most important setback of this topology. Because of the foresaid reason in an application, which requires high output voltage from low voltage level, it needs H-bridge module in addition or step-up transformers. To overcome that a new topology proposed is shown in Fig. 1 to reduce the component count.

Figure 1 shows the topology of the proposed three phase nine level cascaded Trinary source inverter. It views like a conventional cascaded H-bridge multilevel inverter apart from input DC sources. The topology comprises of floating input DC sources connected through power switches. The structure requires lesser active switches as compared with conventional cascaded H-bridge topology with much reduced switching losses. By using V_{DC} and $3V_{DC}$, it can synthesize nine output levels; $-4V_{DC}$, $-3\,V_{DC}$, $-2\,V_{DC}$, $-\,V_{DC}$, 0, V_{DC} , $2\,V_{DC}$, $3\,V_{DC}$ and $4\,V_{DC}$.

The lower inverter generates an elementary output voltage with three levels and then the upper inverter adds or subtracts one level from the fundamental wave to synthesize stepped waves. The lower bridge rating of the switches should be chosen 3 times greater than the upper bridge rating, then only the losses occurred will be equalised in the ratio 1:3. For the proposed circuit, an idea is given how the voltages have to be chosen for the upper limb as well as for the lower limb. The voltage level obtained from the two limbs can also be determined using the given equation. At this point, the final output voltage level becomes the sum of each terminal voltage of H-bridge [1] and it is given as

$$V_{out} = V_{HB1} + V_{HB2} \tag{1}$$

In the proposed circuit design, suppose the n number of H-bridge component has self-governing DC sources in sequence of the power of 3, a predictable output voltage level is given as

$$V_n = 3^n,\ n = 1, 2, 3, \ldots . \tag{2}$$

Where n is number of H bridges.

Waveforms of output voltage are denoted as (V_{out}), upper terminal voltage is (V_{HB1}) and the lower voltage is (V_{HB2}) inverter in sequence. Designing of switching strategy for obtaining nine levels is given below. It also gives the details how the output voltage levels is synthesized using these switch combinations. Table 1 shows the switch states and output voltage levels of trinary source nine level inverter.

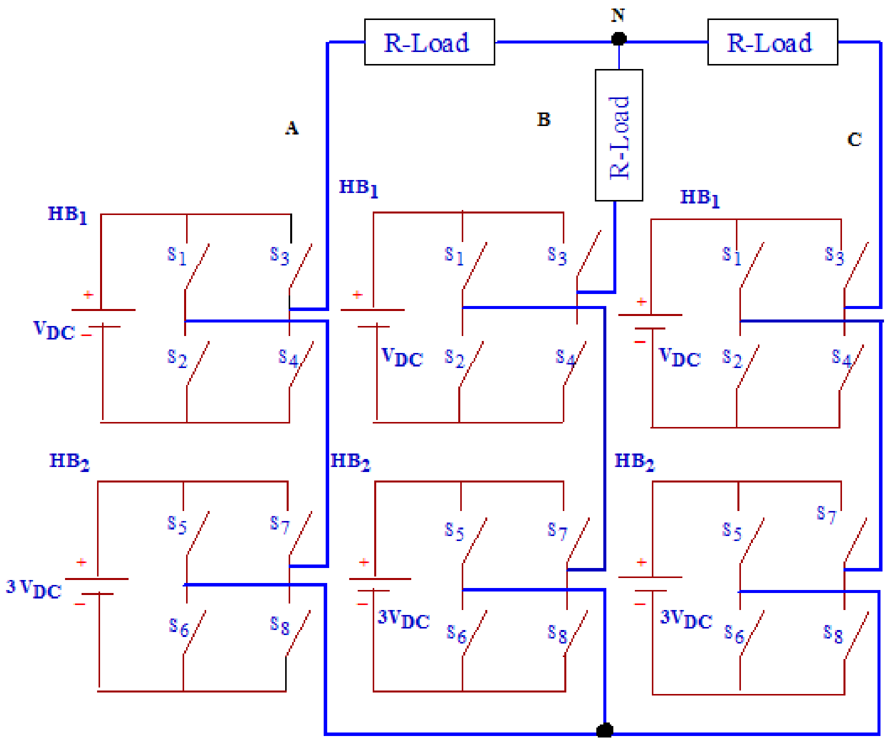

Fig. 1. Three phase nine level trinary source cascaded inverter.

Table 1. Switching states and output voltage levels of trinary source nine level inverter.

S_1	S_3	S_2	S_4	S_5	S_7	S_6	S_8	V_{out}
1	0	0	1	1	0	0	1	$-4V_{DC}$
1	1	0	0	1	0	0	1	$-3V_{DC}$
0	1	1	0	1	0	0	1	$-2V_{DC}$
1	0	0	1	1	1	0	0	$-V_{DC}$
1	1	0	0	1	1	0	0	0
0	1	1	0	1	1	0	0	$+V_{DC}$
1	0	0	1	0	1	1	0	$+2V_{DC}$
1	1	0	1	0	1	1	0	$+3V_{DC}$
0	1	1	0	0	1	1	0	$+4V_{DC}$

The output voltage has nine levels include zero level. Though it is close to a sinusoidal wave, it has lower order harmonics. Therefore, it needs more H-bridge modules or output filter to obtain high quality output voltages. Advantage of the proposed multilevel inverter scheme is the elimination of transformer in the main power stage. However, each cell of the proposed multilevel inverter requires its own isolated power supply. The provision of these isolated supplies is the main limitation in the power electronic circuit design. So, the proposed multilevel inverter is suitable for photovoltaic power generating systems equipped with distributed power sources.

3. Bipolar Variable Amplitude SPWM Strategies

The most popular method of controlling the output voltage is by incorporating PWM control within the inverters. In this paper, four different modulation strategies were tried in order to increase the output voltage and also to reduce the THD. It is generally recognized that, increasing the switching frequency of the PWM pattern results in reducing lower frequency harmonics. This paper includes reference waveform as sinusoidal and eight triangular carriers. To synthesize multilevel output AC voltage using different levels of DC inputs, semiconductor devices must be switched ON and OFF in such a way that desired fundamental is obtained with minimum harmonic distortion. There are different types of approaches for the selection of switching techniques for the Trinary source inverters.

Among all the PWM methods for Trinary source cascaded inverter, carrier based PWM methods and space vector methods are often used but when the number of output levels is more than five, the space vector method will be very complicated with the increase of switching states. So, the carrier based PWM strategy is preferred under this condition in Trinary source inverters. This paper focuses on carrier based PWM strategies, which have been extended for use in Trinary source inverter by using multiple carriers. Multicarrier based PWM strategies have more than one carrier that can be triangular waves or sawtooth waves and so on. The carrier waves can be either bipolar or unipolar. In this paper, a comprehensive analysis of the aforementioned topology is carried out using Bipolar Variable Amplitude PWM (BVAPWM) techniques. In this paper, various BVAPWM techniques like Bipolar Variable Amplitude Phase Disposition PWM (BVAPDPWM), Bipolar Variable Amplitude Phase Opposition Disposition PWM (BVAPODPWM), Bipolar Variable Amplitude Alternative Phase Opposition Disposition PWM (BVAAPOD) and Bipolar Variable Amplitude Carrier Overlapping PWM (BVACOPWM) were proposed for three phase nine level Trinary source cascaded inverter.

For an m-level inverter using BVAPWM technique, (*m*-1) carriers with same frequency f_c and variable peak-to-peak amplitude A_C are used. The reference waveform has amplitude A_m and frequency f_m are placed at zero reference for A-phase, -120degree reference for B-phase and +120 degree reference for C-phase. The reference wave is continuously compared with each of the carrier signals. If the reference wave is more than a carrier signal, then the active devices corresponding to that carrier are switched ON. Otherwise, the device will be switched OFF. In this paper, the frequency ratio m_f =40 and modulation index m_a is varied from 0.8 to 1.

$$m_f = f_c / f_m \tag{3}$$

$$m_a = 2A_m /(m-1)A_c \qquad \text{except for COPWM} \tag{4}$$

3.1. Bipolar variable amplitude PDPWM technique

The Principle of BVAPDPWM technique is to use the eight carriers with three modulating waveform. In BVAPDPWM, all the carriers are in phase and the carriers are disposed so that the bands they occupy are contiguous. The modulation wave is centered in the middle of the carrier set. Figure 2 shows the carrier arrangement for BVAPDPWM technique for m_a = 0.9 and m_f = 40.

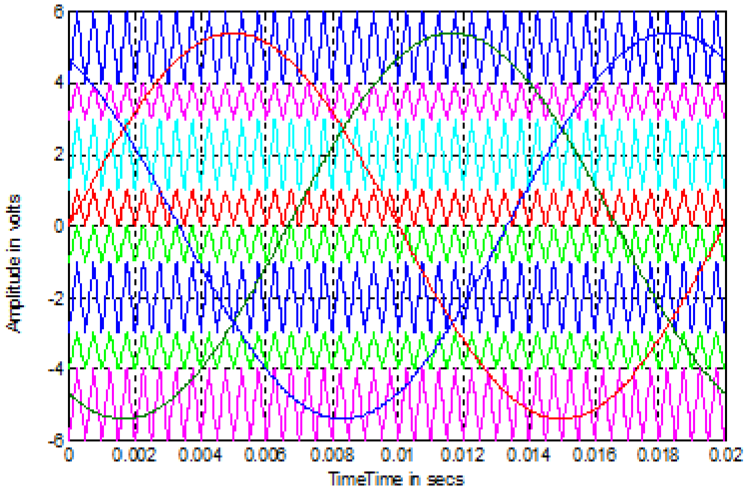

Fig. 2. Carrier arrangement for BVAPDPWM technique.

3.2. Bipolar variable amplitude PODPWM technique

With the BVAPODPWM method, the carrier waveforms above the zero reference value are in phase. The carrier waveforms below zero are also in phase but are 180° phase shifted from those above zero. Figure 3 shows the carrier arrangement for BVAPODPWM method for m_a = 0.9 and m_f = 40.

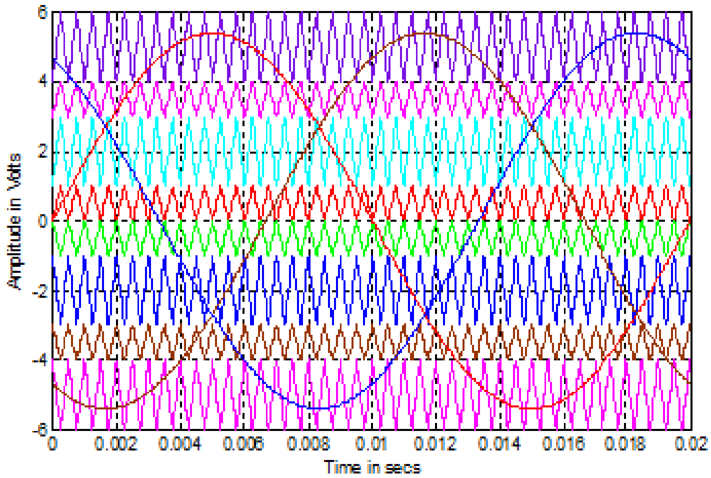

Fig. 3. Carrier arrangement for BVAPODPWM technique.

3.3. Bipolar variable amplitude APODPWM technique

This method requires each of the eight carrier waves for a nine level inverter to be phase displaced from each other by 180° alternately. Figure 4 shows the carrier arrangement for BVAAPODPWM method for m_a= 0.9 and m_f= 40.

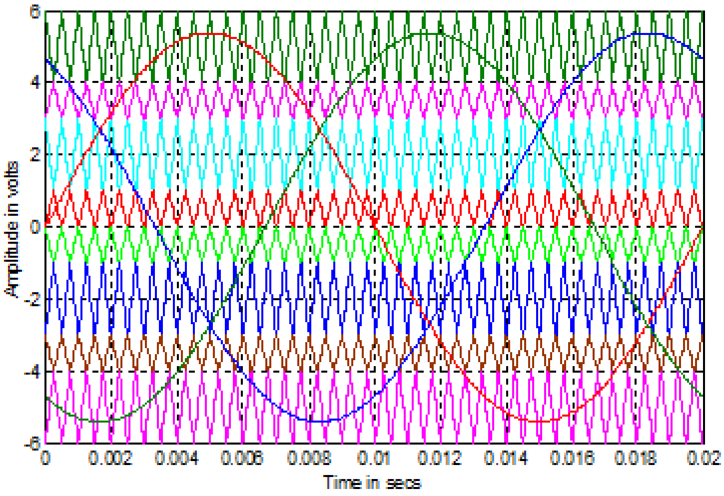

Fig. 4. Carrier arrangement for BVAAPODPWM technique.

3.4. Bipolar variable amplitude APODPWM technique

In the Carrier Overlapping technique, m-1 carriers are disposed such that the bands they occupy overlap each other, the overlapping vertical distance between each carrier is A_C /2 (A_C =1). The reference waveform is centred in the middle of the carrier signals. The amplitude modulation index m_a is defined as follows:

$$m_a = A_m /(2.5A_c) \tag{5}$$

The vertical offset of carriers for nine-level inverter with BVACOPWM technique is shown in Fig. 5.

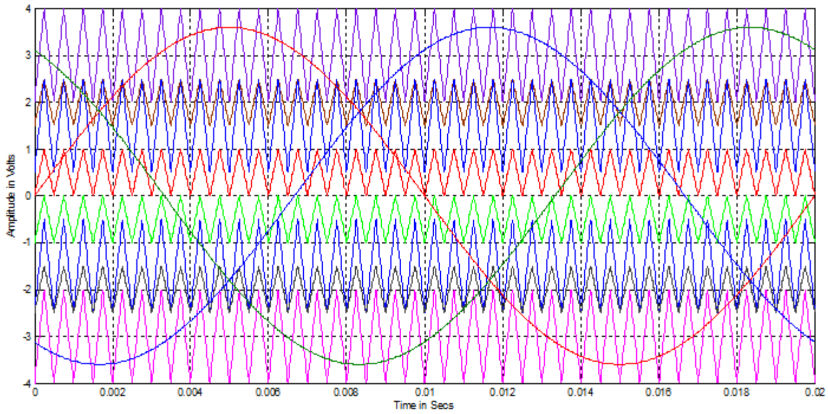

Fig. 5. Carrier arrangement for BVACOPWM technique.

4. Simulation Results and Discussion

The three phase Trinary source nine level cascaded inverter is modelled in SIMULINK using Power System block set. Switching signals for three phase Trinary source nine level cascaded inverter are developed using bipolar variable amplitude triangular carrier with sinusoidal PWM techniques. At present the performance measures of proposed inverter is tested with only linear load, to know the performance under static condition. The further investigations on the inverter may be with non-linear load and variable loads.

Simulations are performed for different values of ma ranging from 0.8 -1. Figs. 6-13 show the simulated output voltage of three phase Trinary source nine level cascaded inverter with their corresponding FFT plots shown for only one sample value of m_a= 0.9 for above said BVAPWM techniques. Figure 14 shows a graphical comparison of %THD of various techniques for different modulation indices.

The corresponding %THD (a measure of closeness in shape between a waveform and its fundamental component) is measured using the FFT block and their values are listed in Table 1. Table 2 shows the Distortion Factor of the output voltage of chosen CMLI. Table 3 displays the V_{RMS} of fundamental inverter output (a measure of DC bus utilization). The following parameter values are used for simulation: V_{DC}=100V, 3 V_{DC} =300V, f_m= 50 Hz, f_c=2000 Hz and load (R=100 Ω).

Table 2. Circuit parameters of components used for simulation.

Parameters	IGBT switch
R_{on} (Internal Resistance)	$1\times e^{-3}$ (ohms)
R_s (Snubber Resistance)	$1\times e^{5}$ (ohms)
C_s (Snubber Capacitance)	Inf (F)

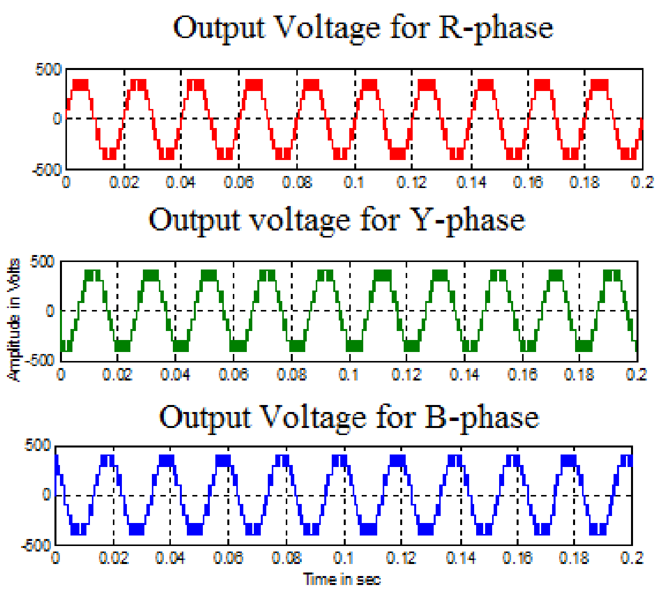

Fig. 6. Output voltage generated by BVAPDPWM technique.

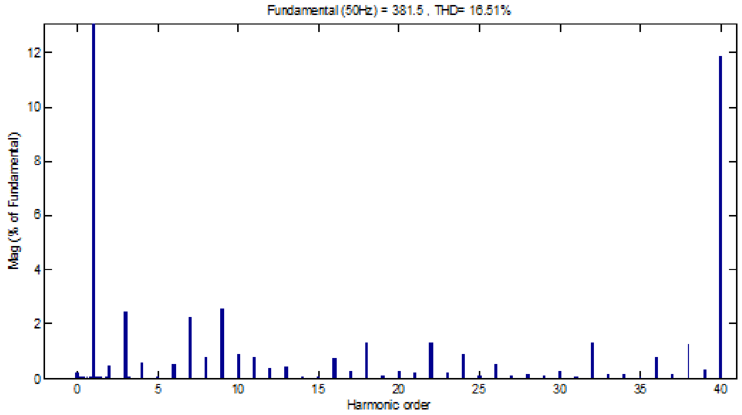

Fig. 7. FFT plot for output voltage of BVAPDPWM technique.

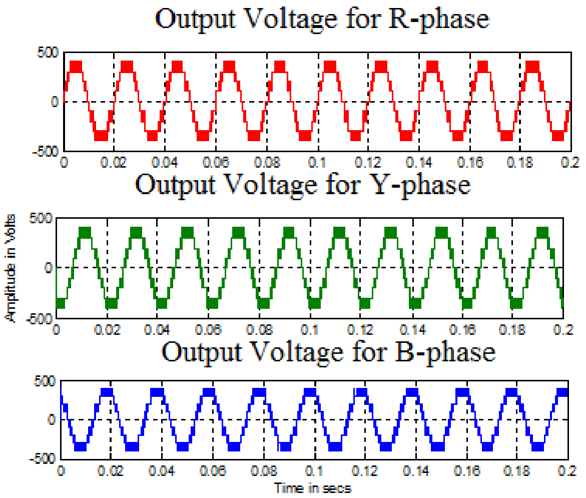

Fig. 8. Output voltage generated by BVAPODPWM technique.

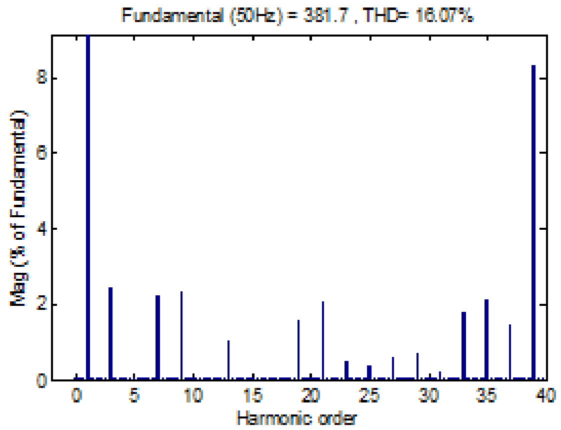

Fig. 9. FFT Plot for output voltage of BVAPODPWM technique.

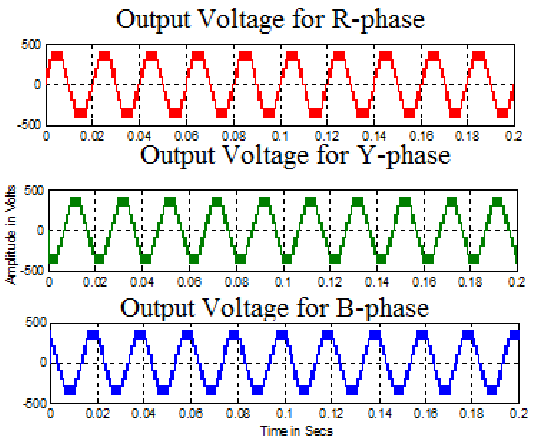

Fig. 10. Output voltage generated by BVAAPODPWM technique.

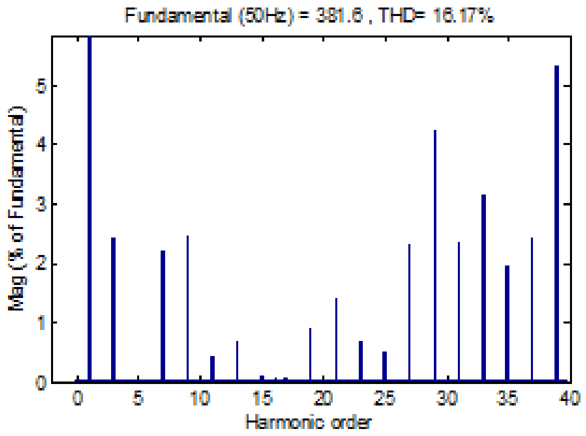

Fig. 11. FFT plot for output voltage of BVAAPODPWM technique.

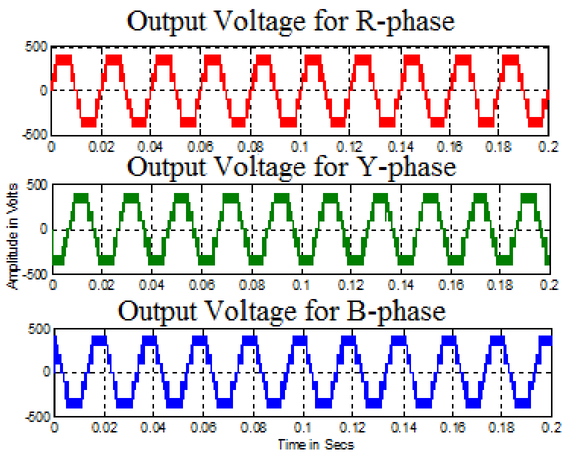

Fig. 12. Output voltage generated by BVACOPWM technique.

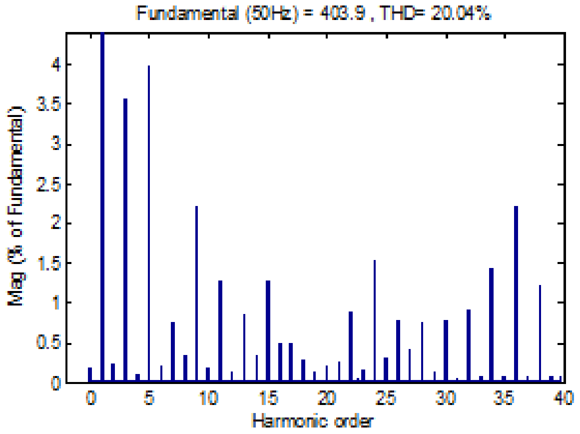

Fig. 13. FFT plot for output voltage of BVACOPWM technique.

Table 3. % THD for different modulation indices.

m_a	BVAPD	BVAPOD	BVAAPOD	BVACO
1	13.82	13.33	13.67	17.90
0.95	15.25	14.92	15.53	18.93
0.9	16.51	16.07	16.17	20.04
0.85	16.96	16.61	16.47	21.08
0.8	17.37	16.94	17.03	22.10

Table 4. % Distortion factor for different modulation indices.

m_a	BVAPD	BVAPOD	BVAAPOD	BVACO
1	0.4218	0.3957	0.3882	0.6689
0.95	0.3468	0.3417	0.3283	0.5586
0.9	0.3027	0.2767	0.2768	0.4316
0.85	0.2337	0.1851	0.2016	0.2983
0.8	0.1665	0.1710	0.1598	0.1981

Table 5. V_{rms} for different modulation indices.

m_a	BVAPD	BVAPOD	BVAAPOD	BVACO
1	293.4	293.8	293.5	304.2
0.95	281.7	281.6	281.7	295.1
0.9	269.7	269.9	269.8	285.6
0.85	257.5	257	257.3	275.4
0.8	244.9	245.2	245	264.7

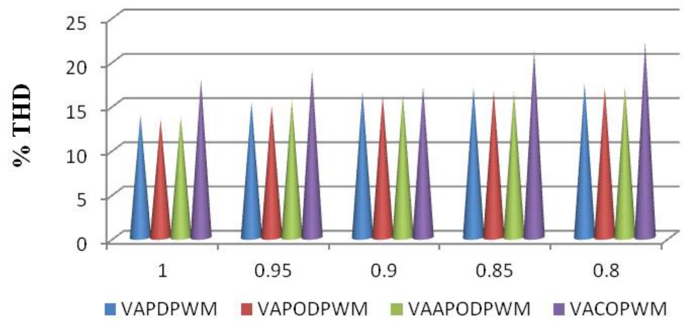

Fig. 14. %THD vs. m_a.

In this present work, a various parametric charts are used for the prediction of the performance characteristics (Figs. 15 and 16). These design charts are adapted from the Tables 5 and 6. The curves of those charts are interpolated using the above table values. These charts are used to investigate the performance parameters such as VRMS (Fundamental) and Harmonic spectra for proposed inverter. Figure 16 is drawn using the contents of Table 6, which contains the harmonic spectra of the output voltage for the proposed inverter for only one modulation index m_a = 0.9.

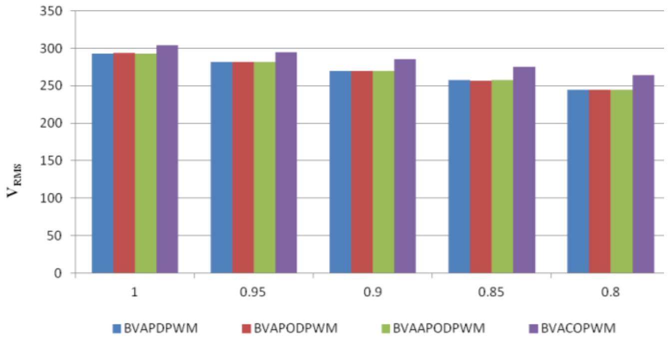

Fig. 15. V_{RMS} output voltage (fundamental) of three phase trinary source nine level cascaded inverter vs. m_a.

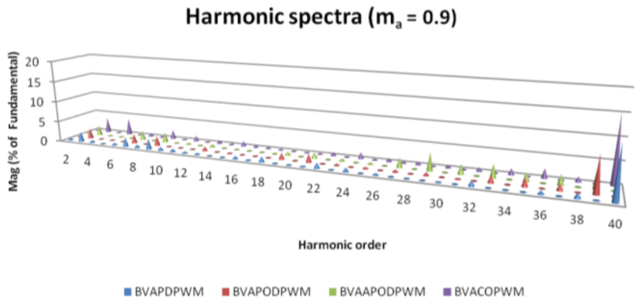

Fig. 16. Harmonic spectra of output voltage of three phase trinary source nine level cascaded inverter for different bipolar variable SPWM techniques (m_a=0.9).

It is observed from Table 3 that the harmonic content is found to be minimum in BVAPODPWM and maximum in BVACOPWM technique for chosen modulation indices. Table 4 shows that the variation in harmonic content of the output voltage after second order attenuation indicated by %DF is less in BVAAPODPWM and high in BVACOPWM technique. From Table 5, it is found that the BVACOPWM technique provide relatively higher DC bus utilization. Harmonic spectra indicating the purity of the output voltage. It is analysed from the above Table 6 and Fig. 16. The harmonic spectra drawn reveals that BVACOPWM technique provides higher harmonic order and BVAPODPWM technique provides less harmonic order. The applications of the presented topology are Variable Speed AC Motor drive, Uninterruptible power supply, Battery Vehicle drives and Induction heating. This paper focuses only on design and development of three phase trinary source nine level inverter with variable amplitude SPWM strategies. The performances of the above said inverter are not validated for particular application. In future, the presented inverter may be incorporated for particular application. Depending on the application, the relevant technique may be adopted.

Table 6. %Harmonic contents of output voltage with m_a=0.9 (Bipolar variable amplitude SPWM strategies).

m_a	BVAPD	BVAPOD	BVAAPOD	BVACO
2	0.47	0	0.01	0.22
3	2.43	2.44	2.44	3.56
4	0.57	0	0.01	0.09
5	0.03	0.07	0.03	3.99
6	0.49	0	0	0.21
7	2.25	2.23	2.23	0.75
8	0.74	0	0.01	0.33
9	2.58	2.36	2.45	2.19
10	0.85	0	0.01	0.19
11	0.75	0.05	0.43	1.26
12	0.37	0	0.01	0.1
13	0.41	0.99	0.68	0.84
14	0.04	0	0.01	0.32
15	0.01	0.06	0.12	1.27
16	0.7	0	0.02	0.5
17	0.28	0.05	0.07	0.47
18	1.32	0	0.01	0.27
19	0.08	1.55	0.92	0.11
20	0.24	0	0.01	0.19
21	0.2	2.06	1.42	0.26
22	1.3	0	0.01	0.87
23	0.19	0.48	0.69	0.15
24	0.89	0	0.01	1.53
25	0.09	0.39	0.49	0.3
26	0.49	0	0.01	0.78
27	0.09	0.58	2.31	0.41
28	0.16	0	0.01	0.76
29	0.08	0.72	4.23	0.12
30	0.24	0	0.01	0.77
31	0.07	0.21	2.33	0.04
32	1.31	0	0.01	0.91
33	0.13	1.76	3.15	0.06
34	0.16	0	0.01	1.44
35	0.06	2.07	1.96	0.05
36	0.74	0	0.02	2.21
37	0.14	1.49	2.42	0.08
38	1.24	0	0.01	1.21
39	0.28	8.33	5.31	0.07
40	11.89	0	0.01	15.14

5. Conclusions

In this paper, various bipolar variable amplitude PWM techniques for chosen three phase Trinary source nine level cascaded inverter have been developed and simulation results are presented for different modulation indices ranging from 0.8-1.

- Various performance factors like %THD, %DF and V_{RMS} of fundamental have been evaluated, presented and analysed.

- It is observed that BVAPODPWM technique provides lower THD. BVAAPODPWM technique provides lower DF. DF indicates the amount of harmonics that remains in the output voltage after it has been subjected to second order attenuation related to power quality issues have been evaluated, presented and analysed.
- The maximum DC bus utilization is achieved in BVACOPWM technique (Table 5).
- The result indicates that appropriate PWM techniques may be employed depending on the performance measure required in a particular application of three phase Trinary source inverter based on the criteria of output voltage quality (Peak value of the fundamental, THD and dominant harmonic components).
- The proposed topology provides with less THD and higher RMS voltage compared to conventional cascaded inverter that can be implemented in industrial applications such as AC Power conditioners, Static VAR Compensators, drive systems, etc., and in power generation industries.

Nomenclatures

$3\ V_{DC}$	DC Voltage source of lower inverter, V
A_c	Peak to peak amplitude of the carrier signal, V
A_m	Peak to peak amplitude of the modulating signal, V
f_c	Frequency of the carrier signal , Hz
f_m	Frequency of the Modulating signal, Hz
m	Number of levels at the output
m_a	Amplitude modulation index
m_f	Frequency ratio
n	Number of H-bridges
R	Resistive load, Ω
S_1-S_8	Switching devices of inverter
V_{DC}	DC Voltage source of upper inverter, V
V_{HB1}	H-bridge voltage of upper terminal inverter, V
V_{HB2}	H-bridge voltage of lower terminal inverter, V
V_{out}	Final output voltage, V
V_{RMS}	RMS output voltage, V

Abbreviations

AC	Alternating current
BVA	Bipolar Variable Amplitude
CFD	Control Freedom Degree
CMLI	Cascaded Multi Level Inverter
CSF	Constant Switching Frequency
DC	Direct Current
DF	Distortion Factor
EMI	Electro Magnetic Interference
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
MCPWM	Multicarrier Pulse Width Modulation
PWM	Pulse Width Modulation
RMS	Root Mean Square
SPWM	Sinusoidal Pulse Width Modulation

THD	Total Harmonic Distortion
VAAPOD	Variable Amplitude Alternative Phase Opposition Disposition
VACO	Variable Amplitude Carrier Overlapping
VAPD	Variable Amplitude Phase Disposition
VAPOD	Variable Amplitude Phase Opposition Disposition

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