



A GSA Based Generalised Formulation of SHE-PWM Problem of Multilevel Inverter for Both Equal and Unequal Source Voltages

Sayanti Ray¹, Pradip Kumar Saha², Goutam Kumar Panda³

P.G. Student [Power Electronics & Drives], Dept of EE, Jalpaiguri Govt. Engineering College, Jalpaiguri,
West Bengal, India¹

Professor, Dept. of EE , Jalpaiguri Govt. Engineering College, Jalpaiguri, West Bengal, India²

HOD, Dept. of EE , Jalpaiguri Govt. Engineering College, Jalpaiguri, West Bengal, India³

ABSTRACT: A generalised formulation of SHE-PWM technique applicable for high power voltage source cascaded multilevel inverter used in constant frequency utility applications has been discussed in this paper. The SHE-PWM scheme features a broad solution space. This paper aims at to eliminate low order dominant harmonics and at the same time maintaining fundamental also. Since SHE equations are non-linear transcendental in nature , to solve these equations a new artificial intelligence technique called Gravitational Search Algorithm has been implemented to find out switching angles with faster and guaranteed convergence. To illustrate the effectiveness of the proposed method, a 3-phase five level voltage source inverter has been considered with six no. of switching per quarter cycle. Since for a 3-phase balanced system all the triplen harmonics are absent in the line, thus in this case with six no of switching per quarter cycle, five dominant non-triplen harmonics (5th to 17th) was possible to eliminate using SHE-PWM technique for both equal and unequal source voltages for a wide range of modulation index and voltage ratio. Then the output voltage THD obtained using this approach is compared with another approach for minimum system voltage THD.

KEYWORDS: Gravitational Search Algorithm, five level Cascaded Multilevel Inverter, Selective Harmonic Elimination-Pulse Width Modulation, Harmonics

I.INTRODUCTION

Multilevel Inverters have drawn tremendous interest in recent years for high voltage and high power application. The term multilevel inverter starts with the introduction of three level inverter. To change a dc input voltage to a symmetric ac voltage of desired magnitude and frequency is the main function of inverter. To avoid the limitations of two level inverters as high switching losses and low efficiency, multilevel inverters are widely used for their better performance as lower common node voltage, lower dv/dt ratio, lower harmonics in output voltage/current and lower switching frequency with reduced switching loss. The unique structure of multilevel voltage source inverter allows them to attain high voltage with low harmonics .By increasing the no of level in a given topology, the output voltage waveform approaches close to the desired sinusoidal waveform with low harmonic distortion. To get improved quality output voltage from inverter, undesired harmonics is required to be eliminated. There are various methods to eliminate harmonics such as Sinusoidal Pulse Width Modulation, Space Vector Modulation, Selective Harmonic Elimination, Space Vector Pulse Width Modulation, Selective Harmonic Elimination-Pulse width Modulation. Among various techniques of harmonic elimination, SHE-PWM offers a better control over low-order harmonics and better dc source utilization. To obtain switching angles from those non-linear transcendental equations which have multiple set of solutions is the main challenge of these modulation techniques. Again to get optimal solution from non linear equations, there are various techniques with their individual advantages and disadvantages. Proposed GSA technique provides optimal solution with fast convergence.

There are different topologies of multilevel inverter with different modulation strategies and have been studied for several high voltage and high power applications [1]. Because of its modular nature among all the topologies, cascaded multilevel inverter is superior in high power applications [2]. SHE-PWM technique has been developed mainly for two level and three level converters [3]. SHE-PWM equations are non-linear in nature which contains trigonometric terms



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(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

that exhibit multiple set of solutions. The main challenge associated with SHE-PWM technique is to obtain optimal solution from those non linear transcendental equations. There are several algorithms to deal with the SHE-PWM problem which was either to rely on initial value for exact solution or to introduce transformation steps to ensure fast convergence and also to find out multiple set of solutions. There lots of efforts have been made to find out effective initial values to guarantee rapid convergence of Newton Raphson iterative method [4],[5],[12]. SHE-PWM technique is highly suitable for the control of single- phase and three-phase full-bridge three-level inverters for any switching angles[12]. The algorithms include introducing transformation steps to ensure convergence and to find out multiple set of solution through Homotopy based computation [6],use of Resultant theory [7],use of Walsh function[8],and optimisation technique such as genetic algorithm[9],through a colony of ants [10], and optimisation search[11].Resultant Theory converts the transcendental equations into polynomial equations and provides a complete solution [7].Instead of solving nonlinear transcendental equation, Walsh function solves linear equations which optimises the switching angles[8]. Genetic Algorithm has been used to find out the switching angles from nonlinear equation using. This solves the same problem with a simpler formulation and with any number of levels without extensive derivation of analytical expressions [9]. A new artificial intelligence technique is used through a colony of ants to solve non linear transcendental equation for better convergence [10]. There is a new technique has been introduced recently to eliminate higher order harmonic by simply generating the opposite of the harmonic to cancel them. But it has a disadvantage of using high switching frequency[13],[14].Optimal pulse-width modulation (OPWM) is often used in medium-/high-power inverters, to reduce the switching frequency. For two-level and multilevel inverters with unbalanced dc sources, equal area criteria-based four-equation method has been developed to realize OPWM [15]. A novel formulation of SHE PWM equation for multilevel inverter was proposed with quarter wave symmetry which was applicable to any level and any topology which increased the flexibility of the proposed model [16].A staircase modulation control has been implemented to achieve minimum output waveform distortion in single phase multilevel inverter when ratios between their dc sources are non-integer values with considering device voltage drops [17]. A generalised formulation is also developed for half wave symmetry selective harmonic elimination for voltage source inverter with illustrated basic concept of half wave symmetry, quarter wave symmetry and asymmetry wave forms. This method also gives the flexibility to deal with different phase shifting as phase shifting does not change the frequency spectrum of a waveform. The rule of equal area criteria and super position of CG of the PWM section with reference sine wave can also be adopted here [18]. A generalised formulation of SHE-PWM technique for multilevel inverter considering both equal and non equal DC source voltage has been formulated. Here the necessity of Hybrid Genetic Algorithm Implementation is also been mentioned distinctly [19]. Recently a new artificial intelligence technique named Gravitational Search Algorithm has been implemented to solve SHE-PWM problem with fast convergence to find out optimal solution [20].

In this dissertation, a generalized problem has been formulated considering variable DC voltages (for both equal and unequal source voltage) for 3 phase 5 level Cascaded Multilevel Inverter with quarter wave symmetry using SHE-PWM (Selective Harmonic Elimination-Pulse Width Modulation) technique to eliminate lower order dominant non triplen harmonics like fifth, seventh, eleventh, thirteenth and seventeenth with maintaining the desired fundamental component. The transcendental nonlinear SHE-PWM equations are solved using Gravitational Search Algorithm, a very recent artificial intelligence technique with fast convergence to find out the optimal solution. Further, to have better overall system THD, two methods has been employed here. Firstly, with calculated switching angles, THD upto 31st harmonics has been calculated. Secondly, considering upto 31st harmonics within the objective function, switching angles have been calculated and THD have been compared in between two methods. Finally the second method was found to be more efficient for overall system THD.

II.MULTILEVEL INVERTER AND ITS MODULATION TECHNIQUES

The term multilevel began with the three level converters. However, the elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. With the increase in number of voltage levels, harmonic contents of the output voltage waveform decreases significantly and output waveform becomes more smooth minimising harmonic distortion. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM).

Among three types of multilevel inverter, cascaded multilevel inverters are widely used because of following reasons--

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

1. With respect to diode clamped or flying capacitor types, cascaded multilevel inverter requires least number of components to reach the same number of level voltage.
2. There are no extra clamping diodes or voltage balancing capacitors.
3. Soft switching techniques can be used to reduce switching losses and dv/dt is decreased.
4. In case of any breakdown, each module can be replaced; this reduces the down time and increases the continuity of power supply.
5. With the increase in output levels, harmonic distortion is reduced.

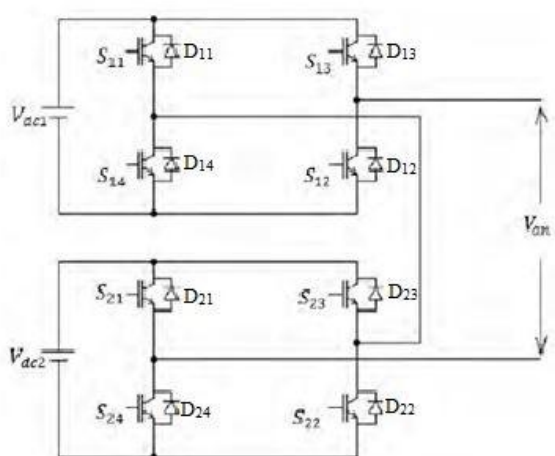


Fig 1. Topology for 5 level cascaded multilevel inverter

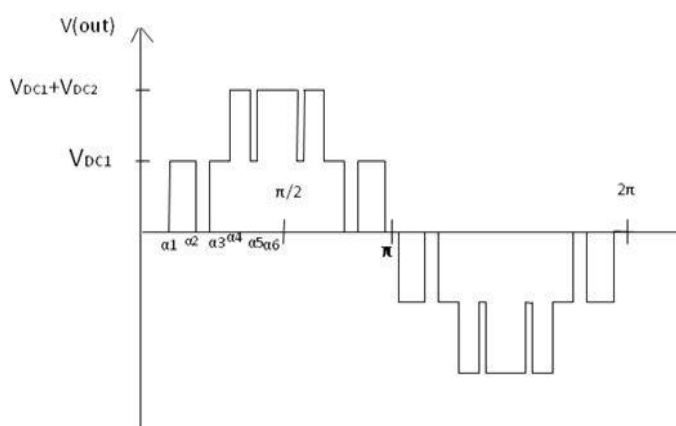


Fig2. 5 level phase output voltage

Each H-bridge shown in Fig. 1 could produce three different levels: $+V_{dc}$, 0 , $-V_{dc}$ by connecting the DC supply to AC output side by different combinations of the four switches S_{X1} , S_{X2} , S_{X3} , S_{X4} where X represents the H-bridge number. An n-level topology requires $2*(n-1)$ switches and $(n-1)/2$ isolated power supplies. The 5-level inverter shown above requires 8 switches and two DC sources per phase. The resulting output ac voltage swings from $-2V_{dc}$ to $+2V_{dc}$ with five-level i.e. $-V_{dc}$, $-2V_{dc}$, 0 , $+V_{dc}$, $+2V_{dc}$ are the possible voltage levels. To obtain $+V_{dc}$, S_{13} , S_{14} , S_{23} , D_{21} switches are turned on. The output voltage would be made zero while switching on either the switch pairs S_{X1} and S_{X3} or S_{X2} and S_{X4} where X represents the H-bridge number. To obtain $-V_{dc}$, S_{11} , S_{12} , S_{21} , D_{23} switches are turned on. Again to obtain $+2V_{dc}$, S_{13} , S_{14} , S_{23} , S_{24} switches are turned on and for $-2V_{dc}$, S_{11} , S_{12} , S_{21} , S_{22} switches are turned on. To obtain three phase connection, the outputs of three single phase inverters could be connected in star or delta shape. Fig 2 shows the per phase SHE-PWM output voltage wave form of a 5 level cascaded multilevel inverter with 6 switching angles considering quarter wave symmetry.

There are many popular methods used to reduce the harmonics in order to get effective results. The popular methods for high switching frequency are Sinusoidal PWM, Space Vector PWM and SHE-PWM. Selective harmonic eliminated PWM technique is such a method where the basic square-wave output is “chopped” a number of times, which are obtained by proper off-line calculations. In order to achieve a wide range of modulation indexes with minimized THD for the synthesized waveforms, a generalized selective harmonic modulation method was proposed, which is called virtual stage PWM. However, for the virtual stage PWM method, the number of switching angles is not equal to the number of dc voltages. With S no of switching, the number of harmonics that can be eliminated is limited $(S-1)$. In this paper, for 3 phase five-level cascaded multilevel inverter with 6 switching, there are five non triplen undesired low-order harmonics could be eliminated. In this case 5^{th} , 7^{th} , 11^{th} , 13^{th} and 17^{th} harmonic could be eliminated efficiently with maintaining fundamental. SHE-PWM offers several advantages over the other methods such as low switching frequency with a wider converter’s bandwidth, direct control over low-order harmonics and better dc source utilization. The main objective of the selective harmonic elimination is to eliminate or minimize the low-order harmonics or the harmonics close to the fundamental. The major difficulty for selective harmonic elimination methods is to solve the transcendental equations for switching angles.

III. A GENERALISED SHE-PWM PROBLEM FORMULATION

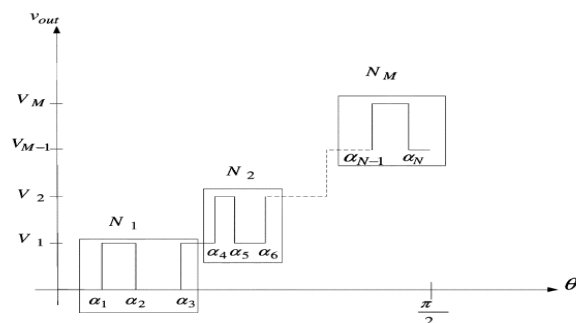


Fig3. Generalized multilevel PWM waveform

Fourier series expansion of the generalized multilevel PWM output waveform of the single-phase multilevel converter shown in Fig.3 can be expressed as follows

$$f(\alpha) = \sum_{n=1}^{\infty} (a_n \cos n\alpha + b_n \sin n\alpha) \quad (1)$$

Due to the PWM waveform characteristics of odd function symmetry and quarter-wave symmetry, the output voltage can be reduced to

$$f(\alpha) = \sum_{n=1}^{\infty} (b_n \sin n\alpha) \quad (2)$$

Where b_n is the Fourier coefficient.

A generalized expression of for any number of switching angles and any number of voltage levels and with equal and non equal dc source voltage is given by

$$b_n = \frac{4V_{dc}}{n\pi} \left[V_1 \sum_{i=1}^{P_1} (-1)^{i+1} \cos n\alpha_i \pm V_2 \sum_{i=P_1+1}^{P_2} (-1)^i \cos n\alpha_i \pm \dots \pm V_M \sum_{i=P_{M-1}+1}^{P_M} (-1)^i \cos n\alpha_i \right] \quad (3)$$

Where

V_1, V_2, \dots, V_M are several dc source voltages

$n=1, 3, 5, \dots, 2N-1$ for single phase system

$n=1, 5, 7, \dots, 3N-2$ for three phase system (N is odd)

$=1, 5, 7, \dots, 3N-1$ for three phase system (N is even)

M =No of dc source voltages

$V_M V_{dc}$ is the value of M^{th} dc source

$P_1=N_1$; $P_2=N_1+N_2$; $P_M= N_1+N_2+\dots+N_M$

N_1, N_2, \dots, N_M are the number of pulses per-quarter cycle at converters respectively

$N= N_1+N_2+\dots+N_M$ (total number of pulses per-quarter cycle)

α_i is the i^{th} switching angle

For a 3 phase cascaded multilevel inverter with 2 sources and 6 switching angles per quarter cycle, the above equation can be written as

$$\frac{4}{n\pi} [\rho(\cos n\alpha_1 - \cos n\alpha_2 + \cos n\alpha_3) + (\cos n\alpha_4 - \cos n\alpha_5 + \cos n\alpha_6)] = \frac{b_n}{E_2} = m_i \quad (4)$$

Where m_i is the Modulation Index

$$m_i = \frac{b_1}{E_2}$$

$$\rho = \frac{E_1}{E_2}$$



International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

b_1 is normalized fundamental component
M is the no of DC source
 V_{dc} is the input dc voltage source of each converter cell.
 ρ is the voltage ratio

Case I: EQUAL SOURCE VOLTAGES

First Approach: In this section, it is assumed that the levels of the dc sources of the cascaded converter cells are equal and constant, i.e. $V_1=V_2=..... V_M$, p.u., hence $\rho=1$.

Therefore, one can rewrite the above equation (4) as follows:

$$\frac{4}{n\pi} [(\cos n \alpha_1 - \cos n \alpha_2 + \cos n \alpha_3) + (\cos n \alpha_4 - \cos n \alpha_5 + \cos n \alpha_6)] = m_i \quad (5)$$

For $n=1,5,7 \dots 17$, equation (15) will be successively as follows:

$$\begin{aligned} \frac{4}{\pi} (\cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3 + \cos \alpha_4 - \cos \alpha_5 + \cos \alpha_6) &= b_1 = m_i \\ (\cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3 + \cos 5\alpha_4 - \cos 5\alpha_5 + \cos 5\alpha_6) &= b_5 = 0 \\ (\cos 7\alpha_1 - \cos 7\alpha_2 + \cos 7\alpha_3 + \cos 7\alpha_4 - \cos 7\alpha_5 + \cos 7\alpha_6) &= b_7 = 0 \\ \dots\dots\dots \\ (\cos 17\alpha_1 - \cos 17\alpha_2 + \cos 17\alpha_3 + \cos 17\alpha_4 - \cos 17\alpha_5 + \cos 17\alpha_6) &= b_{17} = 0 \end{aligned} \quad (6)$$

An objective function describing a measure of effectiveness of eliminating selected order of harmonics while controlling the fundamental must be solved to obtain the optimal switching angles and that is defined as

$$F(\alpha_1, \alpha_2, \dots, \alpha_6) = \{ w^*(b_1 - m_i)^2 + b_5^2 + b_7^2 + b_{11}^2 + b_{13}^2 + b_{17}^2 \} \quad (7)$$

$b_5, b_7, b_{11}, b_{13}, b_{17}$ are the 5th, 7th, 11th, 13th, 17th harmonics accordingly.

The optimal switching angles are obtained by minimizing above objective function when it is subjected to the below written constraint.

$$0 \leq \alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \dots \alpha_6 \leq \pi/2; \quad (8)$$

$V_{THD}(\%)$ has been calculated considering upto 17th harmonics and $V_{THD(31)}(\%)$ has been calculated considering upto 31st harmonics.

Second Approach: In this case, six switching angles have been calculated including 31st harmonics within the objective function. The objective function is given by

$$F(\alpha_1, \alpha_2, \dots, \alpha_6) = \{ w^*(b_1 - m_i)^2 + b_5^2 + b_7^2 + b_{11}^2 + b_{13}^2 + \dots + b_{31}^2 \} \quad (9)$$

With this obtained switching angles, $V_{THD(31)}(\%)$ has been calculated.

Case II: UN-EQUAL SOURCE VOLTAGES

First Approach: In this case we assume that the levels of the dc sources are non-equal ($V_1 \neq V_2 \neq \dots \neq V_M$). Voltage ratio ρ has been varied from 1.1 to 2. For $n=1,5,7 \dots 17$, equation (4) will be successively as follows:

$$\begin{aligned} \frac{4}{\pi} \{ \rho(\cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3) + (\cos \alpha_4 - \cos \alpha_5 + \cos \alpha_6) \} &= b_1 = m_i \\ \rho(\cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3) + (\cos 5\alpha_4 - \cos 5\alpha_5 + \cos 5\alpha_6) &= b_5 = 0 \\ \rho(\cos 7\alpha_1 - \cos 7\alpha_2 + \cos 7\alpha_3) + (\cos 7\alpha_4 - \cos 7\alpha_5 + \cos 7\alpha_6) &= b_7 = 0 \\ \dots\dots\dots \\ \rho(\cos 17\alpha_1 - \cos 17\alpha_2 + \cos 17\alpha_3) + (\cos 17\alpha_4 - \cos 17\alpha_5 + \cos 17\alpha_6) &= b_{17} = 0 \end{aligned} \quad (10)$$

Again using objective function as given by equation no (7) with the constraint as given by equation (8), switching angles are being calculated. Similarly $V_{THD}(\%)$ has been calculated considering upto 17th harmonics and $V_{THD(31)}(\%)$ has been calculated considering upto 31st harmonics.

Second Approach: In this case, six switching angles have been calculated including 31st harmonics within the objective function as given by equation (9). With this obtained switching angles, $V_{THD(31)}(\%)$ has been calculated again.

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

IV.GSA AND ITS IMPLEMENTATION IN PROPOSED PROBLEM

In solving optimization problems with a high-dimensional search space, the classical optimization algorithms do not provide a suitable solution because the search space increases exponentially with the problem size. Over the last decades, there has been a growing interest in algorithms inspired by the behaviours of natural phenomena

In this paper, a new optimization algorithm based on the law of gravity, namely Gravitational Search Algorithm (GSA) is proposed. This algorithm is based on the Newtonian gravity. The obtained results confirm the high performance of the proposed method in solving various nonlinear functions.

In this section, we introduce our optimization algorithm based on the law of gravity. In the proposed algorithm, agents are considered as objects and their performance is measured by their masses. All these objects attract each other by the gravity force, and this force causes a global movement of all objects towards the objects with heavier masses. Hence, masses cooperate using a direct form of communication, through gravitational force. The heavy masses – which correspond to good solutions – move more slowly than lighter ones, this guarantees the exploitation step of the algorithm. The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. The position of the mass corresponds to a solution of the problem, and its gravitational and inertial masses are determined using a fitness function.

Law of gravity: each particle attracts every other particle and the gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the distance between them, R. We use here R instead of R^2 , because according to our experiment results, R provides better results than R^2 in all experimental cases.

Law of motion: the current velocity of any mass is equal to the sum of the fraction of its previous velocity and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the force acted on the system divided by mass of inertia.

For a minimization problem:

$$\text{best}(t) = \min_{j \in \{1, \dots, N\}} \text{fit}_j(t)$$

$$\text{worst}(t) = \max_{j \in \{1, \dots, N\}} \text{fit}_j(t)$$

For a maximization problem:

$$\text{best}(t) = \max_{j \in \{1, \dots, N\}} \text{fit}_j(t)$$

$$\text{worst}(t) = \min_{j \in \{1, \dots, N\}} \text{fit}_j(t)$$

FLOW CHART OF GSA:

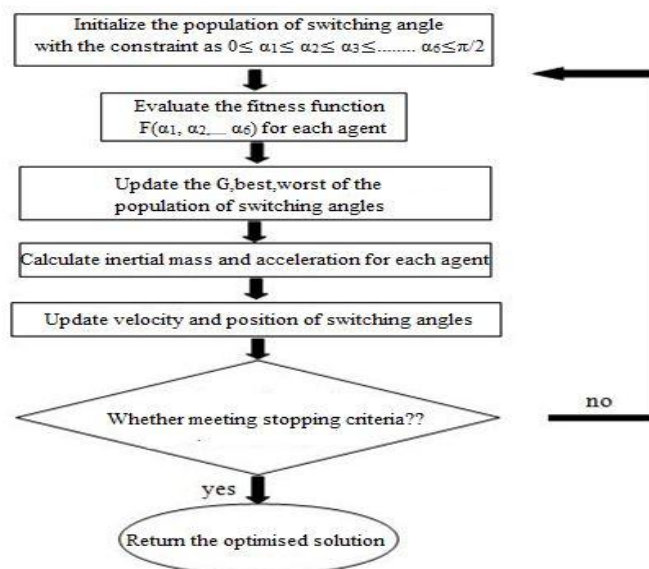


Fig 4 . General principle of GSA

V. RESULTS AND DISCUSSION

➤ ANALYTICAL RESULT

Case I: EQUAL SOURCE VOLTAGES

The following table 1. shows the variation of switching angles (in rad) and $V_{THD}(\%)$ with modulation index.

m_i	Switching Angles in rad						$V_{THD}(\%)$
	α_1	α_2	α_3	α_4	α_5	α_6	
1.2	0.1467	0.41265	0.42254	0.47382	0.60952	0.67949	0.1408
1.1	0.05019	0.07675	0.16639	0.49623	0.62251	0.69282	0.283
1	0.241	0.3156	0.3688	0.729	0.8172	0.9816	0.0012
0.9	0.3222	0.4309	0.5043	0.8988	0.9319	1.04	0.075
0.8	0.525	0.6273	0.7531	1.0218	1.0826	1.1768	0.393
0.7	0.7124	0.8828	0.9282	1.0734	1.1709	1.2892	0.0742
0.6	0.677	0.7554	0.8521	1.2475	1.3524	1.4667	0.155
0.5	0.7246	0.8323	0.9263	1.3209	1.3831	1.5097	0.059
0.45	0.7332	0.8439	0.944	1.3609	1.4173	1.528	0.296

Table 1. Multiple set of switching angles (in rad) at different modulation index for equal source voltage

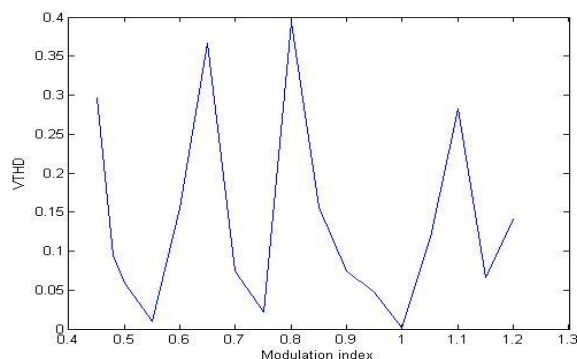
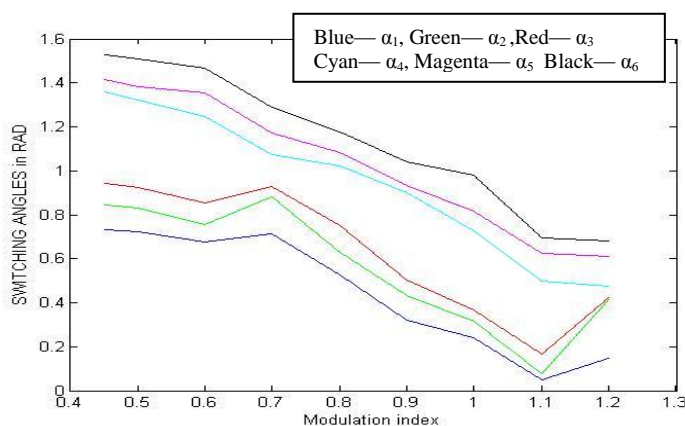


Fig 6. Variation of $V_{THD}(\%)$ with modulation index for equal source voltage (first approach)

The following table 2. shows comparison in between $V_{THD(31)}(\%)$ obtained by two different approaches for equal source voltages at particular modulation index,

m_i	$V_{THD(31)}(\%)$ (1 st approach)	$V_{THD(31)}(\%)$ (2 nd approach)
1.2	48.796	4.2251
1.1	23.923	5.2876
1	12.781	9.6336
0.9	44.8726	6.0771
0.8	19.6954	11.679
0.7	85.8726	13.144
0.6	33.6249	10.672

Table 2. Comparison of $V_{THD(31)}(\%)$ by two different approaches for equal source voltage

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

The variation of $V_{THD(31)}(\%)$ with modulation index in first and second approach for equal source voltage is shown in fig 7.

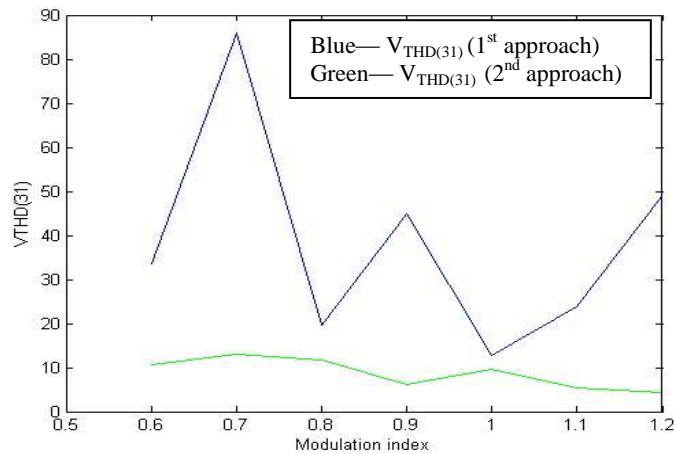


Fig7. Comparison between $V_{THD(31)}(\%)$ by first and second approach (equal source voltage)

Case II: UN-EQUAL SOURCE VOLTAGES

The following table 3. shows the best solution set of switching angles (in rad) and corresponding variation of $V_{THD}(\%)$ with modulation index.

Best Set of Solution								
m_i	ρ	α_1	α_2	α_3	α_4	α_5	α_6	$V_{THD}(\%)$
1.3	1.2	0.5566	0.63611	0.77792	1.1069	1.1781	1.2379	0.0040
1.2	1.4	0.71012	0.80946	0.89634	1.2531	1.3493	1.4331	0.0021
1.1	1.4	0.72772	0.83752	0.93294	1.3206	1.3991	1.4878	0.0144
1	1.2	0.71556	0.818	0.90765	1.2833	1.3675	1.4763	0.0033
0.9	1.1	0.71955	0.82446	0.91578	1.2998	1.3736	1.4931	0.0083
0.8	1.1	0.73589	0.84726	0.94941	1.3767	1.4417	1.5343	0.3431

Table 3. Best set of solution for un-equal source voltage (first approach)

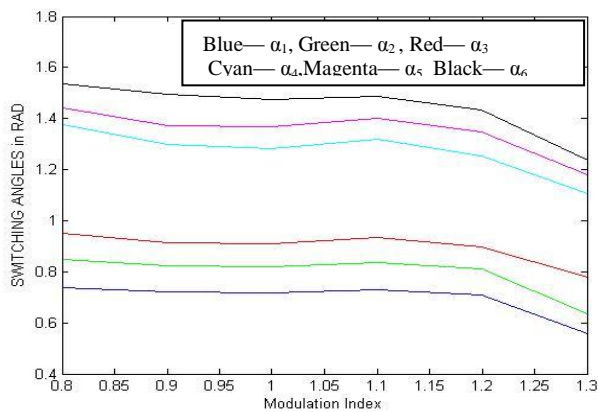


Fig 8. Variation of switching angles (in rad) with modulation index at a particular voltage ratio for un-equal source voltage (first approach)

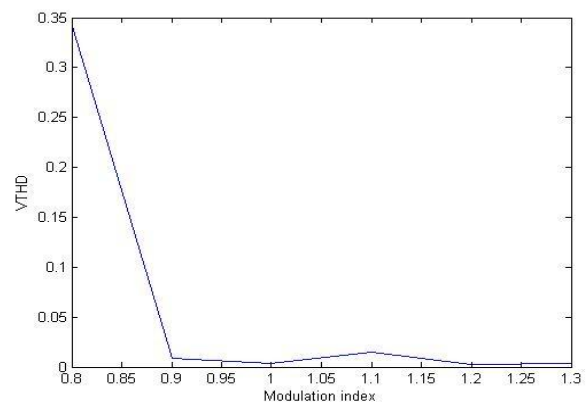


Fig 9. Variation of $V_{THD}(\%)$ with modulation index at a particular voltage ratio for un-equal source voltage (first approach)

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

The following table 4.shows comparison in between $V_{THD(31)}$ (%) obtained by two different approaches at particular modulation index and voltage ratio.

m_i	ρ	$V_{THD(31)}$ (%) 1 st approach	$V_{THD(31)}$ (%) 2 nd approach
1.3	1.2	15.90	11.23
1.2	1.4	17.74	8.44
1.1	1.4	28.68	19.49
1	1.2	27.19	9.19
0.9	1.1	31.06	16.28
0.8	1.1	25.00	17.56

Table 4. Comparison of $V_{THD(31)}$ (%) by two different approaches for unequal source voltage

The variation of $V_{THD(31)}$ (%) with modulation index by first and second approach for un-equal source voltage is shown in fig 10.

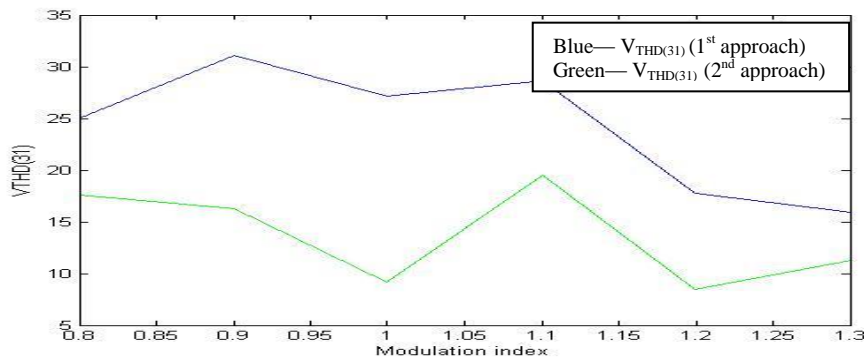


Fig 10. Comparison between $V_{THD(31)}$ (%) by first and second approach for unequal source voltage

From the above analytical data and its graphical representation, it can be concluded that in between two approaches, the second approach considering up to 31st order of harmonics in the objective function is better than the first approach for both equal and unequal source voltages for maintaining lower system THD.

➤ SIMULATION RESULTS

The simulation output waveform for equal source voltage along with harmonic spectrum at modulation index ($m_i=1$) is shown in fig(11-14):

➤ EQUAL SOURCE VOLTAGE (FIRST APPROACH)

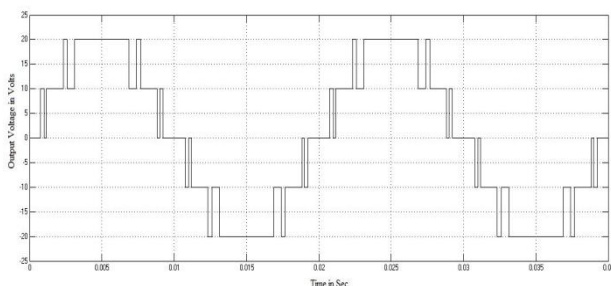


Fig 11. Per phase Output voltage waveform with equal source voltage (first approach) at $m_i=1$

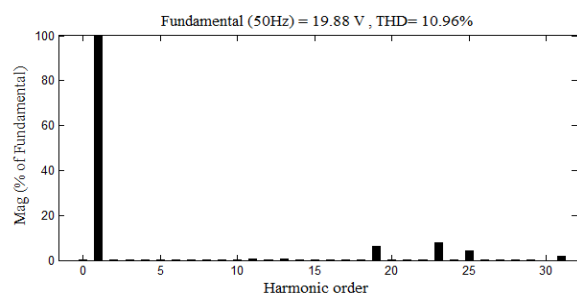


Fig 12. FFT of Output voltage wave form with equal source voltage (first approach) at $m_i=1$

➤ **EQUAL SOURCE VOLTAGE(SECOND APPROACH)**

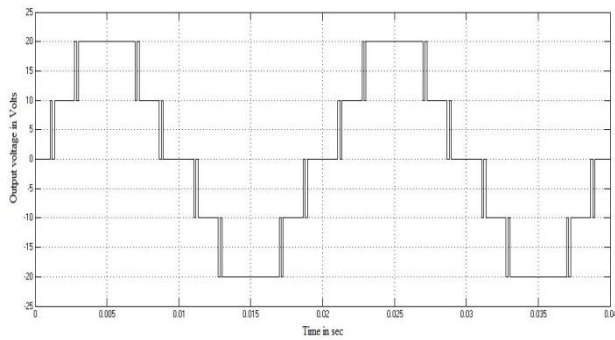


Fig 13. Per phase Output voltage waveform with equal source voltage (Second approach) at $m_i=1$

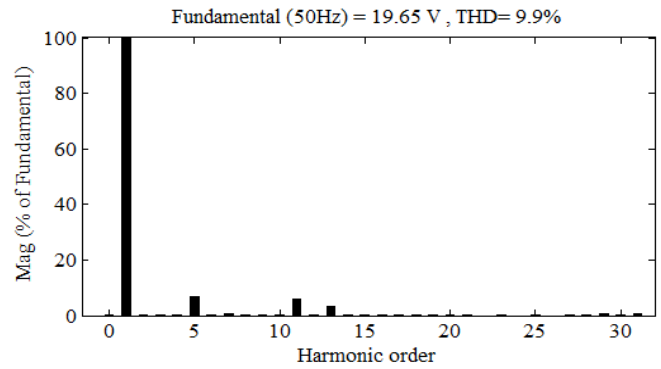


Fig 14. FFT of Output voltage wave form with equal source voltage (Second approach) at $m_i=1$

The simulation output waveform for un-equal source voltage along with harmonic spectrum at modulation index ($m_i=1.1, \rho=1.4$) is shown in fig(15-18):

➤ **UN-EQUAL SOURCE VOLTAGE(FIRST APPROACH)**

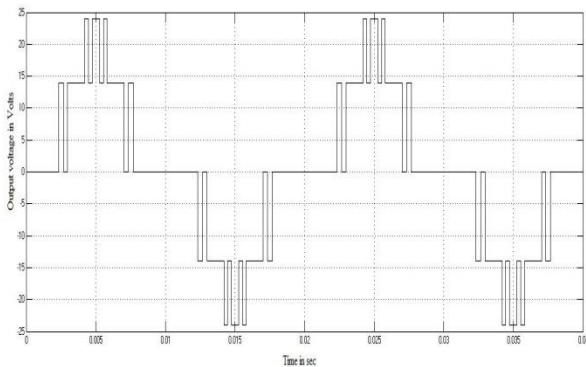


Fig 15. Per phase Output voltage waveform with un-equal source voltage (First approach) at $m_i=1.1, \rho=1.4$

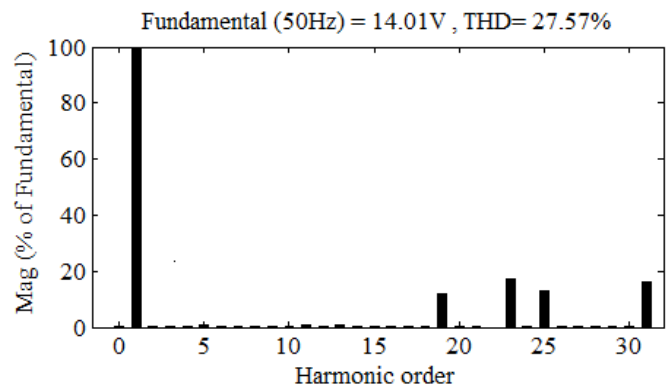


Fig 16. FFT of Output voltage wave form with un-equal source voltage (First approach) at $m_i=1.1, \rho=1.4$

➤ **UN-EQUAL SOURCE VOLTAGE(SECOND APPROACH)**

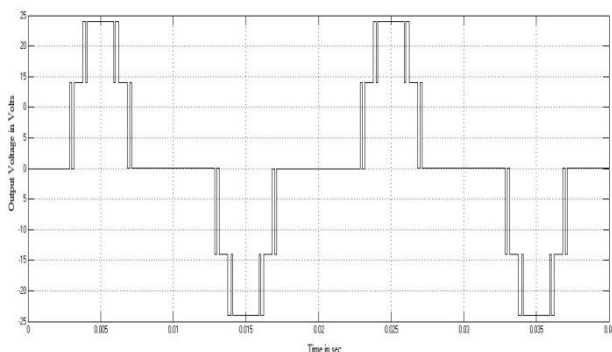


Fig 17. Per phase Output voltage waveform with un-equal source voltage (Second approach) at $m_i=1.1, \rho=1.4$

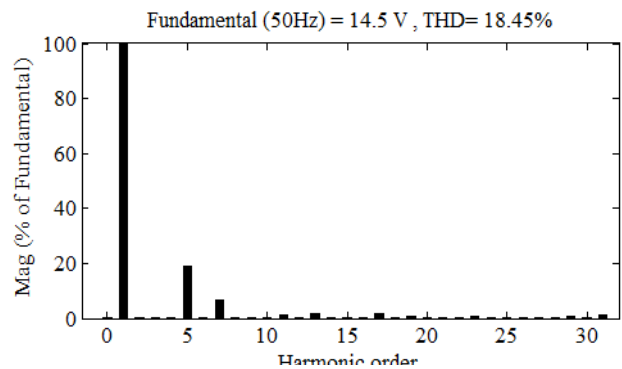


Fig 18. FFT of Output voltage wave form with un-equal source voltage (Second Approach) at $m_i=1.1, \rho=1.4$



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(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

➤ COMPARISON BETWEEN $V_{THD(31)}(\%)$ IN BOTH THE CASE OF EQUAL AND UNEQUAL SOURCE VOLTAGE BY TWO APPROACHES FROM SIMULATION RESULTS

Source type	Modulation Index	Voltage ratio	$V_{THD(31)}(\%)$ by First Approach	$V_{THD(31)}(\%)$ by Second Approach
Equal	1	1.0	10.96%	9.90%
Unequal	1.1	1.4	27.57%	18.45%

Table 5. Comparison between $V_{THD(31)}(\%)$ by two approaches from simulation result

From the above simulation results it is concluded that the output voltage THD considering second approach is superior compare to first one. The same was also maintained in case of analytical results.

VI.CONCLUSION

In this study, Gravitational Search Algorithm has been implemented to eliminate lower order harmonics besides maintaining fundamental output voltage component of a cascaded multilevel inverter by using Selective Harmonic Elimination-Pulse Width Modulation technique. A 3 phase five-level cascaded multilevel inverter with quarter wave symmetry has been considered with both equal and unequal input DC link voltages and 5 low order dominant harmonics 5th, 7th, 11th, 13th and 17th was possible to eliminate with maintaining fundamental component. With the help of GSA, it was possible to find out the switching angles from nonlinear transcendental equation which exhibits multiple set of solutions. Advantage of proposed Gravitational Search Algorithm is its fast convergence in less time. This method is advantageous because after eliminating the low order harmonics, THD was maintained within the range of (0-1) % for both the cases. In between two approaches as mentioned earlier, second approach is found to be more efficient than first approach to maintain an overall low system THD. This also leads to reduce system switching loss maintaining an overall low THD without increasing the number of switching angle. In case of unequal source voltage, with higher modulation index, it was possible to vary voltage ratio more widely.

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