Lower Order Harmonics Minimisation in CHB Inverter Using GA and Decomposition by WT

V. Joshi Manohar, P. Sujatha, and K. S. R. Anjaneyulu

Abstract—Nowadays Multilevel inverters are widely using in various applications. Modulation strategy at fundamental switching frequency like, SHEPWM is prominent technique to eliminate lower order of harmonics with less switching losses and better harmonic profile. The equations which are formed by SHE are highly nonlinear transcendental in nature, there may exist single, multiple or even no solutions for a particular M_I. However, some loads such as electrical drives, it is required to operate in whole range of M_I. In order to solve SHE equations for whole range of M_I intelligent techniques are well suited to solve equations so as to produce lest %THD$_V$. Hence, this paper uses Continuous genetic algorithm for minimising harmonics. This paper also presents wavelet based analysis of harmonics. The developed algorithm is simulated and %THD from FFT analysis and Wavelet analysis are compared. MATLAB programming environment and SIMULINK models are used whenever necessary.

Keywords—Cascade H-Bridge Inverter (CHB), Continuous Genetic Algorithm(C-GA), Selective Harmonic Elimination Pulse Width Modulation (SHEPWM), Total Harmonic Distortion (%THD$_v$), Wavelet Transform (WT).

I. INTRODUCTION

NOWADAYS there is great demand in industrial sector for higher power devices which converts electrical energy. Multilevel converters are able to control and to supply diverse equipment working in power range up to hundreds of MW. These converters are widely used in chemical, oil, and liquefied natural gas (LNG) plants, marine propulsion and power-quality improvement techniques. One important application of multilevel converters is focused on medium voltage and high power applications because it provides high quality output voltage, high converter efficiency and reduced electromagnetic Interference (EMI) [1].

There are three well established topologies of multilevel inverters neutral point clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) inverters [2]. Among all topologies cascade multilevel inverters are capable of reaching medium voltage and high power applications levels using cascaded connection of several single phase inverters at low voltage level with better harmonic spectrum of output voltage [3]. In high power applications, high converter efficiency is an

important requirement. Hence, switching losses have been an active subject of research. These switching losses are majorly dependent on the modulation strategy used to control multilevel inverters. As the switching frequency is high for carrier based PWM methods and space vector modulations, they cannot be used for high power applications. If so, it leads to poor converter efficiency and side bands around carrier frequency appears as lower order harmonics producing high distortion in the output voltage [4].

Hence for high power applications, low switching frequency technique is preferred. This switching technique produces lower order of harmonics. Thus this has been an interesting research area to eliminate harmonics. Among all the switching techniques, Selective harmonic elimination PWM switching technique is widely used technique at fundamental switching frequency to eliminate specific lower order of harmonics in output voltage. SHE has several advantages compared to traditional modulation methods such as: low switching frequency to fundamental frequency ratio and direct control over output voltage harmonics [5].

However, the equations formed by SHE technique are highly non-linear transcendental in nature and there may exist single, multiple or even no solutions for a particular modulation index [6]. Solving SHE equations has been a research topic since from several decades. The solution of non linear transcendental equations is obtained by using an iterative method like Newton-Raphson method. This method is derivative dependant and it needs good initial guess [7]. Another approach to solve equations is resultant theory method. In this method as the number of levels of inverter increases, degree of polynomials of equations increases which increases the computational difficulty [8].

In order to overcome above mentioned problems, Genetic Algorithm has been proposed in [9]. Therefore in this paper, by using optimising methods like GA, an attempt is made to solve SHE equations during whole range of modulation index and %THD$_v$ is observed. In this paper three phase cascaded H-bridge 11-level inverter is chosen for analysis. This paper also presents wavelet based harmonic analysis.

This paper is organized as follows: Section II presents brief review on Selective Harmonic Elimination switching technique. Section III presents the implementation of C-GA to the given problem. Results and analysis are presented in Section IV.

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II. SELECTIVE HARMONIC ELIMINATION TECHNIQUE

Converter efficiency is one of the important requirements in

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multilevel converters and it is considerably affected by device switching losses. Switching losses are in direct relation with modulation techniques used in converters. For this reason in megawatt range drives average switching frequency (f_{sw}) over 1 kHz are considered inconvenient due to high thermal losses [10]. Minimization of switching losses can lead to a reduction in operating cost, cooling requirements and physical size which further reduces manufacturing cost of the drive. Hence modulation strategy at high switching frequency cannot be used instead, SHE modulation technique at low switching (fundamental) frequencies is one of the preferred modulation technique which gives better harmonic profile. SHE has been a research topic since early 1960's and developed into mature form during 1970's, advantages of SHE are listed in [11]-[12].
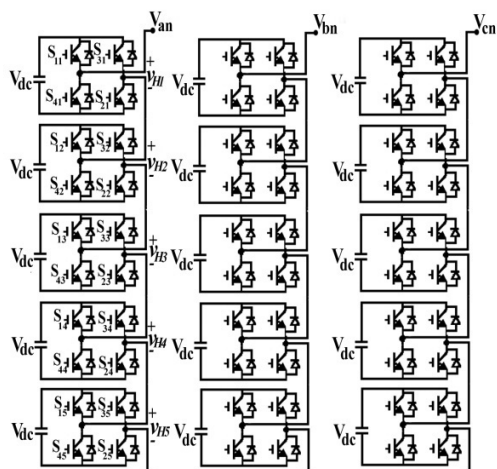

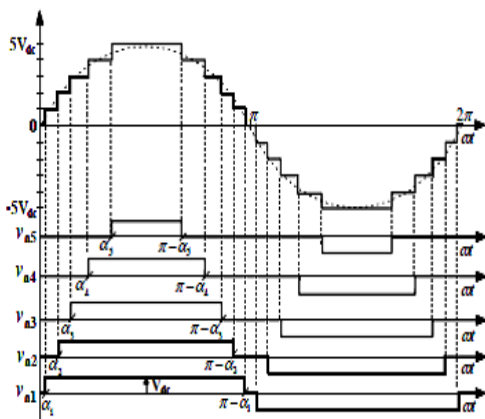Fig. 1 Three phase cascade H- bridge 11- level inverter

Fig. 2 Output phase voltage waveform of CHB 11-level inverter

The CHB inverter can synthesizes its output nearly sinusoidal voltage waveforms by combining many isolated voltage levels. The general rule for the number of levels in the output phase - to - neutral voltage in cascaded single - phase H - bridge multilevel inverter is 2s+1, where s is the number of H- bridges used per phase. A three-phase CHB inverter is made up of three identical phase legs of the series-chain of H-bridge converters, which can possibly generate different output voltage waveforms and offers the potential for AC

system phase-balancing. For a three-phase system, the output voltage of the three cascaded converters can be connected in either wye (Y) or delta (Δ) configurations. Fig. 1 represents three phase wye(Y) connected CHB 11-level inverter and Fig. 2 shows its output phase voltage waveform which has eleven steps. The magnitude of the ac output phase voltage is sum of output voltages of all H bridges in phase. Therefore

$$V_{an} = V_{H1} + V_{H2} + V_{H3} + V_{H4} + V_{H5} \qquad (1)$$

Using Fourier series, the expression for Fig. 2 can be written as

$$V(\omega t) = \sum_{n=1}^{\infty} V_n Sin(n\,\omega t) \qquad (2)$$

V_n is the amplitude of the harmonics. The angles are limited in between 0^0 and 90^0. As the waveform has an odd quarter-wave symmetric characteristic, all the even order harmonics becomes zero. For odd values of 'n', V_n becomes

$$V_n = \frac{4V_{dc}}{n\pi}\sum_{i=1}^{S} Cos(n\alpha_i) \qquad (3)$$

As there are five sources per phase in case study (i.e s=5), there are five angles as degrees of freedom. Hence, it is possible to satisfy fundamental component and to eliminate four lower order of harmonics i.e 5th, 7th, 11th and 13th respectively. It is not required to eliminate triplen harmonics because they will be eliminated automatically in the line to line output voltage in the Y connection.

For an 11-level inverter, the SHE equations are

$$[\,Cos(\alpha_1) + Cos(\alpha_2) + \cdots + Cos(\alpha_5)]/5 = m_I$$
$$Cos(5\alpha_1) + Cos(5\alpha_2) + \cdots + Cos(5\alpha_5) = 0$$
$$Cos(7\alpha_1) + Cos(7\alpha_2) + \cdots + Cos(7\alpha_5) = 0$$
$$Cos(11\alpha_1) + Cos(11\alpha_2) + \cdots + Cos(11\alpha_5) = 0$$
$$Cos(13\alpha_1) + Cos(13\alpha_2) + \cdots + Cos(13\alpha_5) = 0 \qquad (4)$$

where M_I is modulation index and defined as

$$M_I = \frac{\pi V_1}{4sV_{dc}} \ (0 \le m_I \le 1) \qquad (5)$$

Equations set (4) are called non linear transcendental trigonometric equations. The main challenge associated with SHE technique is to obtain the analytical solutions of non linear transcendental trigonometric equations which naturally exhibit multiple solutions and during some range of M_I (4) does not have any feasible solution. However, in some drive applications it is required to operate during whole range of M_I. Hence it is necessary to calculate α_1, α_2, α_3, α_4 and α_5, such that (4) is satisfied. This paper deals with the problem of finding solution during whole range of M_I from 0 to 1. Modern Stochastic search technique such as genetic algorithm (GA) is applied to the given problem to find solution.

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III. CONTINUOUS GENETIC ALGORITHM

As mentioned in Section II, SHE equations are non linear transcendental in nature. In order to solve these equations modern stochastic technique like C- GA is used to calculate switching angles during whole range of M_I from 0 to 1. Genetic Algorithm (GA) replaces the difficulty associated in numerical algorithms, because of its intrinsic ability to begin searching randomly, handle large amount data simultaneously and "jump" out of local optimum automatically.

GA's are a subclass of Evolutionary Computing and are random search algorithms. GA's are based on Darwin's theory of evolution Genetic Algorithms are inspired by the study of genetics. Evolutionary computing has evolved in 1950's and GA's developed by John Holland over the course of the 1960's and 1970's and finally popularized by one of his students, David Goldberg, who was able to solve a difficult problem involving the control of gas-pipeline transmission for his dissertation. This algorithm is used to reach a near global optimum solution. Using genetic operators, in each iteration of C-GA, a new set of strings, which are called chromosomes with improved fitness, is produced. The fitness function is the function responsible for evaluation of the solution at each step. The objective here is determination of the switching angles such that some selected harmonics are minimized or made equal to zero.

When the variables are continuous, it is more logical to represent them by floating point numbers (alphabet GAs).This continuous GA has advantage of: less storage requirement, inherently faster than binary GA. In C-GA all decision variables are expressed as real numbers. The complete discussion of GA is found in [13]-[16]. The flow chart in Fig. 3 represents overview of process of C-GA and it is briefly explained in this section.
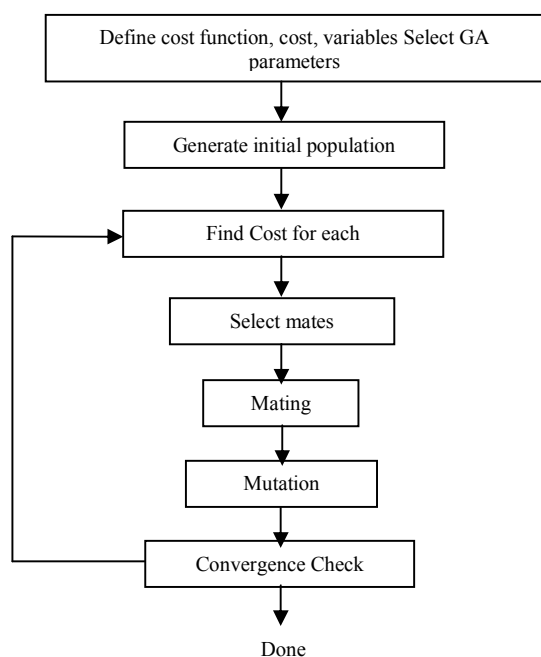

Fig. 3 Flow chart of continuous Genetic Algorithm

A. Variables

Main objective here is to solve optimization problem, means search for an optimal (minimum) solution in terms of variables of the problem. In this study, each chromosome is taken as a possible solution for the problem. Chromosome is defined as an array of variable values to be optimized. If the chromosome has N_{var} variables given by $p_1, p_2, p_3, \ldots \ldots p_{N_{var}}$ then chromosome is written as an array with $1 \times N_{var}$ elements so that

$$\text{Chromosome} = [p_1, p_2, p_3, \ldots \ldots p_{N_{var}}] \qquad (6)$$

In this paper variables are switching angles and the number of switching angles is five. In this case, the variable values are represented as floating-point number

B. Initialisation of the Population

To begin the GA, it is required to define an initial population. Then initialise the chromosome values randomly. The most common method is to generate solutions for the entire population. The population size is defined by conserving nature of problem, time complexity and the search space measure. In this paper, the population size is set at 300.

C. Natural Selection

It is required to decide which chromosomes in the initial population are fit enough to survive and reproduce offspring in the next generation. Chromosomes are ranked from lowest cost to highest cost and the rest dies off. This process of natural selection must occur at each iteration of the algorithm to allow the population of chromosomes to evolve over the generations to the fit members as defined by the cost function. Among all the survivors only the top are kept for mating and rest are discarded. The selection rate, Xrate, is the fraction of total selected population size that survives for the next step of mating.

D. Mating

Mating is the most significant operation in GA. Mating is the creation one or more offspring from the selected mates in pairing process. The simplest method is choosing one or more points in the chromosome to mark as the crossover points and then the variables are merely swapped between the two parents. Crossover points are randomly selected, and then the variables are exchanged, thus new creation is produced.

E. Mutation

Mutation is another vita operation which works after mating. Mutations alter a certain percentage of the bits in the list of chromosomes. That percentage is called mutation rate. Multiplying the mutation rate by the total number of variables that can be muted in the population gives mutations. This process is repeated until desired optimum of objective function is reached.

F. Evaluation of Fitness function

Main objective of this study is to minimise lower order of harmonics. The fitness value is a measure of the

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appropriateness of a solution with respect to the original objective and the amount of infeasibility.

For each solution (or each chromosome), the fitness function is calculated as follows.

$$f = \theta_i^{min} \left\{ \left(100 \frac{V^*_1 - V_1}{V^*_1}\right)^4 + \sum_{s=2}^{s} \frac{1}{h_s} \left(50 \frac{V_{h_s}}{V_1}\right)^2 \right\}$$

$$i = 1, 2, \ldots, S \tag{7}$$

Subject to: $\quad 0 \le \theta_i \le \pi/2 \tag{8}$

where, V^*_1 is the desired fundamental harmonic, S is the number of switching angles and h_s is the order of sth viable harmonic at the output of a three phase multi-level inverter e.g $h_2 = 5$ and $h_5 = 13$.

The main objective is to find a set of switching angles such that the magnitude of fundamental harmonic reaches a desired value, i.e V^*_1. Detail working of fitness function is present in [17].

IV. RESULTS AND ANALYSIS

The proposed technique is simulated on a three phase cascaded H-bridge 11-level inverter. A code based on the continuous genetic algorithm is written in MATLAB software and Simulink model is developed to calculate %THD$_v$ from FFT analysis. Wavelet based harmonic analysis algorithm is used to evaluate distortion contributions from decomposed components of output voltage signal and %THD$_v$ is calculated. Thus, %THD$_v$ in both the cases is compared.

A. Continuous Genetic Algorithm Analysis

The developed Genetic algorithm is run 10 times, because it may fall into local minima. By increasing the number of runs, the probability of reaching the global minimum increases.
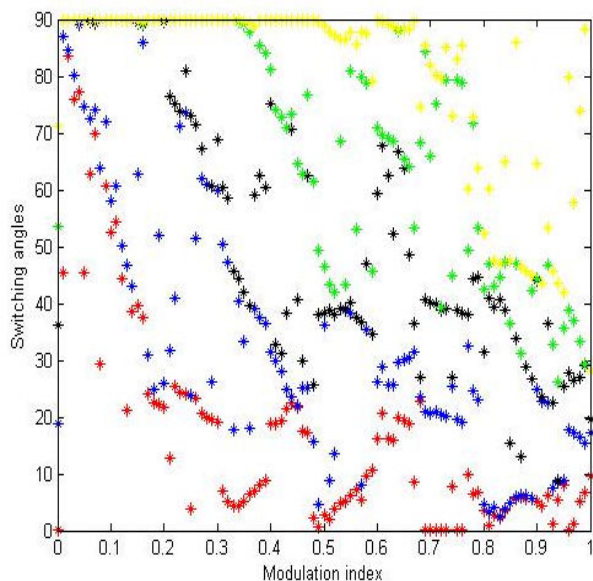
The least cost function (%THD$_v$) between all runs is chosen and the following results are extracted from developed code. In Fig. 4, switching angles at various modulation indices are represented. Firing angles α_1, α_2, α_3, α_4 and α_5 are represented by red, blue, black, green and yellow colours respectively. Here M_I varies from 0 to 1 in steps of 0.01.

It is observed in Fig. 4, whenever there are more than one solution exists for set of equations (4), the developed C-GA algorithm randomly selects the solution which results less %THD.The values of %THD$_v$, and firing angles at various modulation indices are tabulated in Table I. It is observed that the developed algorithm runs for all of the range of modulation index i.e 0 to 1 for minimising harmonics and least %THD$_v$ is obtained at $M_I=0.97$. Fig. 5(a) represents output phase voltage of 11 level CHB Inverter and FFT analysis of output line to line voltage signal at modulation index of 0.97 is represented in Fig. 5 (b).

TABLE I
%THD$_V$ & SWITCHING ANGLES AT VARIOUS M_I

S.No	M_I	α_1	α_2	α_3	α_4	α_5	%THD$_V$
1.	0.1	38.17	57.89	89.99	89.99	90	19.67
2.	0.2	10.57	21.68	89.77	89.84	89.84	12.81%
3.	0.3	19.16	38.61	59.91	89.98	89.99	11.33%
4.	0.4	6.840	18.79	31.41	75.18	89.99	11.93%
5.	0.5	4.671	30.83	37.44	48.55	89.42	11.12%
6.	0.6	11.64	33.58	33.74	56.79	78.11	10.67%
7.	0.7	0.001	11.45	20.78	40.12	82.00	9.17%
8.	0.8	6.62	23.10	44.42	54.37	63.57	8.59%
9.	0.9	4.85	5.243	24.95	34.12	44.23	7.30%
10.	0.97	4.82	12.69	23.32	24.46	37.27	6.19%
11.	1	3.24	9.496	17.17	28.03	28.14	6.85%
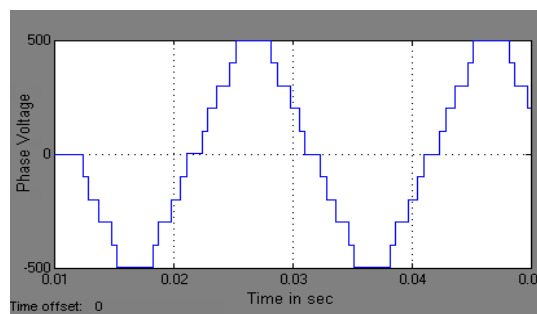
Fig. 5 (a) Output phase voltage of 11 level CHB inverter

Fig. 4 Switching angles vs. Modulation index

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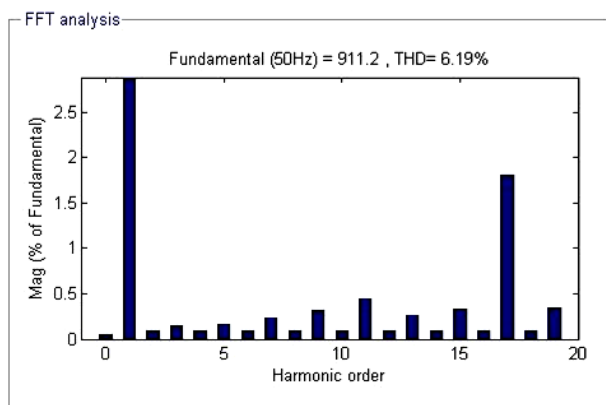Vol:7, No:5, 2013

Fig. 5(b) FFT analysis representing order of voltage harmonics at M_I 0.97

From FFT analysis in Fig. 5 (b), It is observed that, all the lower order of the harmonics are minimised to a greater extent and the value of %THD$_v$ is 6.19%, which is a better value even without using filter. This value satisfies the IEEE 519-1992 harmonic guidelines too.

B. Wavelet Analysis

The developed wavelet based algorithm is run in MATLAB, results obtained are tabulated in Table II. The developed algorithm evaluates distortion contributions of different frequency sub-bands and %THD$_v$ is estimated. The details of the distortions caused by each sub-band harmonics and %THD$_v$ at various modulation index are present in Table II. Fig. 6 represents details of output voltage decomposition at level five. By comparing the %THD$_v$ by FFT analysis and WT analysis, it is observed that %THD$_V$ values are almost equal.

TABLE II
DISTORTION ESTIMATION USING WT TRANSFORM COEFFICIENTS

| M_I	Sub-band Distortion					%THD$_V$
	d_1	d_2	d_3	d_4	d_5	
0.1	8.1695	7.4202	7.8707	7.6677	7.2921	19.774
0.2	5.5371	5.3357	4.7788	4.3295	6.6801	13.722
0.3	3.9283	3.5937	3.8148	7.2478	2.8724	11.043
0.4	3.2241	2.8441	4.2622	4.8259	7.9976	11.917
0.5	2.3351	3.2863	3.0884	5.7248	3.5486	9.2985
0.6	3.0003	3.2636	4.6707	6.4253	5.1086	11.563
0.7	2.1096	2.7951	4.5265	4.5265	3.1817	8.6203
0.8	2.2035	2.6397	3.8767	3.1005	5.114	8.715
0.9	1.8205	2.4939	3.9039	2.8631	3.5928	7.5518
0.97	**1.6555**	**2.655**	**2.5465**	**3.658**	**2.8876**	**6.8974**
1	2.2538	2.0927	3.4447	2.697	3.8375	7.3725
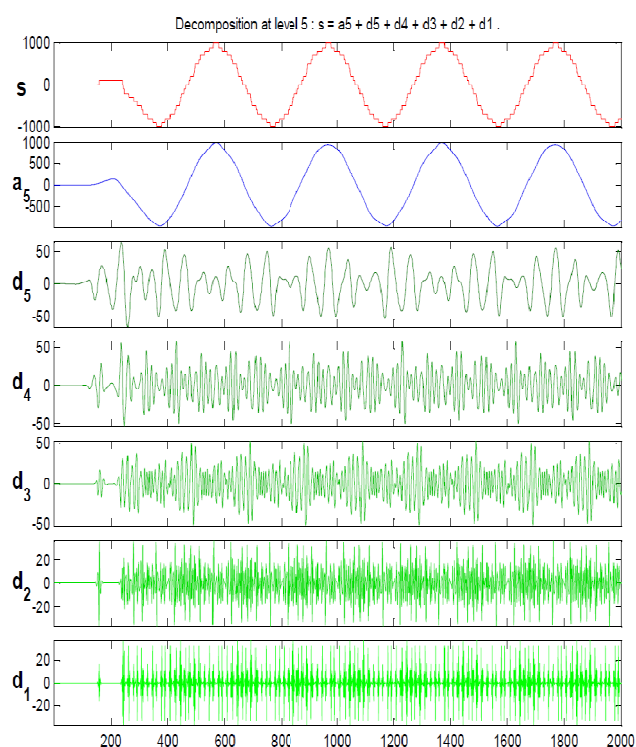
Fig. 6 Details of output voltage decomposition at level five

The mother wavelet used here is biorthogonal spline (BIOR 3.9) which is most suitable for symmetry and exact reconstruction by using FIR filters [18], [19].

V. CONCLUSION

Selective harmonic elimination PWM technique is widely used in medium voltage and high power drives. Solving of highly non linear transcendental equations formed by SHEPWM technique during entire range of modulation index is a big challenge. In this paper C- GA is used to solve the equations during whole range of modulation index i.e from 0 to 1. Table I shows the results that over a range of modulation index from 0 to 1, least %THD$_v$ i.e 6.19% is observed at M_I = 0.97, which is nearer to IEEE 519-1992 harmonic guidelines. FFT analysis also represents minimisation of magnitudes of the lower order harmonics i.e 5th, 7th, 11th and 13th are minimised to a greater extent. Wavelet based harmonic analysis is presented in section IV. An algorithm is developed to calculate percentage distortions due to different sub-band harmonics and %THD$_v$ are tabulated in Table II at each modulation index. It is observed that %THD$_v$ obtained from WT approach is close to that FFT approach during whole range of modulation index. However, in order to analyze steady-state periodic signals FFT approach is suitable, whereas WT approach is more suitable when time and frequency information is required simultaneously, especially for analyzing non-periodic signals (Transients).

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