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Design of Fuzzy Logic Controlled and PSO Optimized 7-level Inverter having non-Ideal DC Sources

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ABSTRACT: Due to continuously increasing electricity demand and continuous depletion of fossil fuels, worlds interest is shifting towards non-conventional sources of energy such as wind, tidal and photovoltaic (PV) for the generation of electricity. Among those sources photovoltaic is considered as the most emerging one. Solar energy is clean energy and can be easily available but it cannot be obtained continuously. The inconsistency of solar energy is inevitable. So while considering PV as the input voltage source for multilevel level inverter, Variations in the input voltage has to be taken care off in the analysis. Until now most of the researches have been done by considering input voltage sources as a constant source of power. In this paper analysis is done on 7-level inverter by considering ideal and non-ideal DC sources and the same has been implemented in hardware. A comparative study is done and results are presented in result section. Fuzzy logic control is used as a control technique for controlling the variations in the input voltage.

KEYWORDS: Multilevel inverter, Particle Swarm Optimization, Fuzzy Logic, MATLAB

I.INTRODUCTION

Multilevel inverters are gaining popularity from past few years because of their undeniable contribution in field of energy conversion. Multilevel inverters are one of the main blocks in energy conversion for non-conventional sources of energy [1]. The voltage generated by non-conventional energy sources is dc in nature, to make it suitable for the grid connection and usable for household purposes, it should be converted into Ac [3]. To connect this strand multilevel inverter is must require. Multilevel inverters are the power devices which are capable of generating sinusoidal output voltage levels by using different dc voltages present at the input side. The required dc sources can be chosen from any of the sources such as batteries, photovoltaic, fuel cells, capacitors and other similar dc sources [11]. Multilevel inverters are of three types [3];

1. Diode-clamped inverter (neutral-point clamped)
2. Capacitor clamped inverter
3. Cascaded H-bridge inverter.

In the given above three types, diode clamped and capacitor clamped are used in application where less levels in output voltage is required, whereas cascaded h-bridge inverter are used for high levels. In diode clamped and capacitor clamped inverters the number of devices used in circuit gets significantly increased as the levels in output voltage increases and which is a drawback. There are various new hybrid topologies have been proposed on cascaded H-bridge multilevel inverter, to achieve more efficiency [2] [3].

Several time harmonics gets generated at the output voltage in addition to the fundamental component in multilevel inverter due to different factors such as: switching transitions, input voltage variations etc. Presence of harmonics reduces the quality of the output and increases the total harmonic distortion (THD) of the output voltage.

One of the main challenges in multilevel inverter is to reduce the percentage THD (total harmonic distortion) of the output. This can be done by adjusting the switching angles in order to eliminate the lower order harmonics. As per the IEEE-519 [2] the THD content in the output should be less than 5%. There are various methods available to reduce the THD of the output voltage by reducing the lower order harmonic content of the output, so the quality of output increases. Many methods are available to reduce lower order harmonics content in the output such as: PWM,

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Vol. 5, Issue 11, November 2016

SHE PWM, SVM (Space Vector Modulation) and sinusoidal pulse width modulation [6] [3]. Here in this paper SHE (selective harmonic elimination) PWM technique has been implemented to do the same. With the help of SHE selectively harmonics can be removed. Here in this paper with the help of SHE PWM 3^{rd} and 5^{th} order harmonics are being removed. Implementation of SHE leads to the generation of some non-linear transcendental equations. By expressing the generalized stepped output voltage waveform of multilevel inverter through Fourier series expansion and taking into consideration the values of pre-specified desired fundamental component of output voltage and low order harmonics elimination, some nonlinear transcendental equation are obtained. The solution of these equation leads to the determination of switching angles. There are various ways to solve the nonlinear transcendental equations such as newton raphson, Genetic algorithm, Particle swarm optimization and etc. Newton raphson is an iterative repetitive method and may lead to local minima but it is highly dependent on initial guessing [2]. Genetic algorithm and particle swarm optimization has proved to be good optimization methods so far. Genetic algorithm has been used in some previous researches for constant input voltage sources [11] [12]. Here in this paper we are using particle swarm optimization (PSO) technique to optimize our circuit, by generating the angles with minimization of 3^{rd} and 5^{th} harmonics, optimization can be done. In many of the researches done in this area have not considered input voltage sources variations and switching angles are generated by varying the modulation index and taking constant voltage sources [2]. Input to the multilevel inverter is taken from dc/dc converter and any variations in the parameters of the dc/dc converters leads to the failure of optimization technique. As the input of dc/dc converters are through photovoltaic cells so the change in dc/dc converters parameters are likely to occur. In this paper Fuzzy logic control strategy is used to monitor the changes in input voltage side and generating the switching angles in order to minimize the percentage THD of the output. With combined effect of both fuzzy logic and PSO a highly stable and efficient 7 level multilevel inverter for practical applications is presented.
Here in this paper firstly a description of topology is given which has been implemented in the circuit and then the calculation of switching angles with the help of optimization techniques and control strategies by solving non-linear transcendental equations is done. Simulation results of the circuit are shown and a satisfactory conclusion is made. MATLAB/*Simulink* software is used to perform the simulation.

II.CASCADED H-BRIDGE MULTILEVEL INVERTER

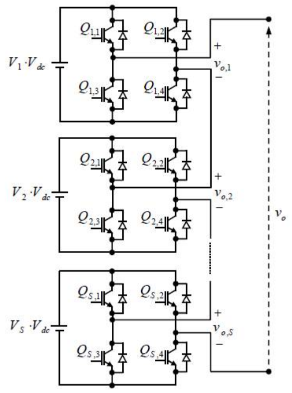

Fig.1. single phase H-Bridge multilevel inverter

The basic single phase H-bridge inverter topology is shown in figure (1). Number of H-Bridges can be arbitrary chosen according to the output voltage levels, here it is ‘s’. Each H-Bridge is having its own dc source and 4 bidirectional switches. With various switches combinations different voltage levels can be obtained at the output and summing all the individual output of the H-Bridges gives the overall output of the circuit [2].
There are several methods to generate the switching angles for the multilevel inverter, but the general scheme of generating the switching angles is the fundamental frequency switching scheme. The output voltage waveform obtained from fundamental switching scheme is shown in figure (2).

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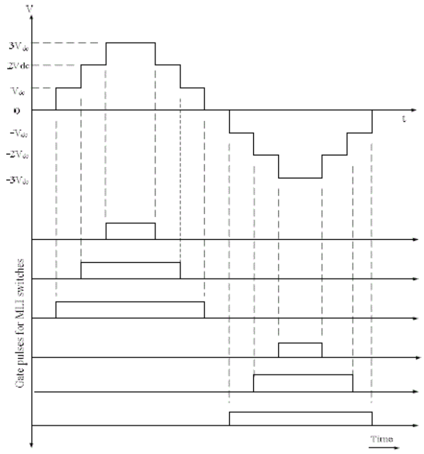

Fig.2. output voltage waveform of 7-level inverter.

Whenever a waveform is not sinusoidal in nature it can be expressed as a Fourier series expansion containing fundamental frequency component and the components of multiples of the fundamental frequency. Its depend on the application of the system that which harmonics is to considered and which to remove. In most of the cases where the load is critical such as drives, motors, switch mains, Ups requires the supply free from lower order harmonics. Fourier series expansion of the waveform obtained from fundamental switching scheme can be expressed as follows [2] [5].

$$V_0(wt) = \sum_{n=1,3....}^{\infty} \frac{4V_{dc}}{n\pi} [V_1.\cos(n\theta_1)+V_2.\cos(n\theta_2) + V_3.\cos(n\theta_3)+..+V_s\cos(n\theta_s)]\sin(nwt) \quad ....[1]$$

Equation (1) shows that the overall output voltage is the summation of the fundamental component and the different order of harmonics. Our main aim is to reduce the different order of harmonics while keeping the fundamental component to a pre specified value. By implementing SHE different order harmonics are equated to zero and the fundamental component to modulation index. General implementation of SHE is given in the equation (2).

$$V_1\cos(\theta_1) + V_2\cos(\theta_2) + \cdots + V_s\cos(\theta_s) = \frac{V_f.\pi}{4V_{dc}}$$

$$V_1\cos(3\theta_1) + V_2\cos(3\theta_2) + \cdots + V_s\cos(3\theta_s) = 0$$

$$V_1\cos(5\theta_1) + V_2\cos(5\theta_2) + \cdots + V_s\cos(5\theta_s)=0 \qquad [2]$$

$$V_1\cos(n\theta_1) + V_2\cos(n\theta_2) + \cdots + V_s\cos(n\theta_s) = 0$$

In the above equation V_f represents the amplitude of fundamental voltage. The modulation index can be defined as;

$$M = \frac{V_f}{s.V_{dc}} \quad [3]$$

In the above equation s is the number of H-Bridges connected in series.

$$M = \frac{4V_{dc}}{\pi}.\frac{V_1\cos\theta_1 + V_1\cos\theta_2 + \cdots + V_1\cos\theta_1}{sV_{dc}}$$

$$= \frac{V_f}{s.V_{dc}} \quad [4]$$

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III. PROPOSED CONTROL METHOD

In practical and theoretical approaches there is a huge gap, to fill the existing gap between the approaches, a new control strategy based on fuzzy logic has been used in the paper. In most of the industrial applications fuzzy logic control is used to approximate the system behavior. Here in this paper fuzzy logic has been used to remove the lower order harmonics from the output and to generate the switching angles to yield a low THD output from multilevel inverter. In this paper for all possible input voltage combination fuzzy rule base has been made, so according to the possible input voltage variations output voltage would be generated automatically. But for making the fuzzy rule base considering all the voltage variations some initial information is required [4].

1. Input output voltage pairs.
2. Switching angles corresponding to the input output voltage pairs.
3. Minimization Function.
4. Expert Knowledge for creating fuzzy rule base.

1. Input output voltage pairs

To make fuzzy rule base, input output pairs are required. Input output pairs can be made with any expert knowledge or with any logic. The number of membership function can be chosen arbitrary according to accuracy requirement. Membership function and system accuracy have a close relationship, i.e. more the membership functions more would be the accuracy. Here in this paper three membership functions for input voltage has been taken and output membership functions are randomly chosen. Binary logic has been used to make the input combinations. For 7-level inverter 3 H-Bridges are used and every H-Bridge is having separate dc source. The number of membership functions for each input is three, (1.) Low voltage (2.)Nominal voltage (3.)High voltage. System is designed for 10% tolerance in input voltages and according to those variations low voltage and high voltage is designed corresponding to nominal voltage. The total number of input combinations is given byn^N. n= number of inputs, N= number of membership functions. According to the above mentioned relation 3^3 yields 27 input voltages pairs. 14 membership functions are taken for the output pairs.

2. Switching angles corresponding to input output voltage pairs

For all 27 combinations of the input voltages switching angles, has to be calculated. For getting switching angles for various voltage combinations require non-linear transcendental equations has to be solved. Here in this paper we are using Particle Swarm Optimization (PSO) technique to minimize the low order harmonics and getting the switching angles. Switching angles obtained from this method generates an output voltage waveform which is having low total harmonic distortion (THD).

Particle Swarm optimization algorithm (PSO) is particle based search technique [4]. PSO was introduced in 1995 by Kennedy and Eberhart. PSO is inspired by the social behaviour of the swarms of birds and flocks or group of ants and insects. Each bird or insect of the group is called as particle. Each particle is the potential solution of the optimization problem and tries to find the optimal solution by changing its position and velocity. Every particle traces its path according to the position and velocity of the other particle. Each particle is determined by two vectors in D-dimensional search space: Position vector $X_i = [x_{i1}, x_{i2}, \dots\dots, x_{iD}]$ and the velocity vector V_i=$[v_{i1}, v_{i2}, \dots\dots, v_{iD}]$. Best position obtained so far byi^{th} particle is given as personal best denoted as P_i =$[P_{i1}, P_{i2}, \dots\dots, P_{iD}]$ and the best position obtained by entire swarm is called global best denoted by$P_g = [P_{g1}, P_{g2}, \dots\dots, P_{gD}]$. Updating equations for particles are given as:

$\vec{v}(t+1) = w\vec{v}(t) + c_1 r_1(\vec{p}(t) - \vec{x}(t)) + c_2 r_2(\vec{g}(t) - \vec{x}(t))$.................... [5]

$\vec{x}(t+1) = \vec{x}(t) + \vec{v}(t+1)$.. [6]

Where,

C_1andC_2 are the constants values ranging from [0 to 2.5].

r_1 *and* $r_2$are the random numbers ranging from 0 to 1.

W is inertial weight.

3. Minimization function

$f(\theta_1, \theta_2, \dots\dots, \theta_n) = [\sum_{n=1}^{s} V_1 \cos(\theta_n) - \frac{V_f \cdot \pi}{4 \cdot V_{dc}}]^2 + \cdots + [\sum_{m=2}^{s} (\sum_{n=1}^{s} V_n \cos((2m-1)\theta_n))^2]$... [7]

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Vol. 5, Issue 11, November 2016

The fitness function given in equation (7) is used to calculate the switching angles $(\theta_1, \theta_2, \theta_3)$ [2]. Above equation is derived from equation (1) and equation (2). The randomly generated particle values $(\theta_1, \theta_2, \theta_3)$ are supplied to the above function and systems fitness function is tested. According to the obtained fitness value particles are assigned as P_{Best} andG_{best}.

4. Expert Knowledge for creating Fuzzy Rule Base

Creating fuzzy rule base requires some expertise knowledge. It is a known fact that more the number of membership function, more would be the system accuracy, considering this point one has to select the membership function according to his accuracy constraint. Here in this paper 3 membership function for input voltage variations and 14 membership functions for getting output switching angles is been taken. According to the obtained switching angles for different input output voltage combinations from particle swarm optimization technique, fuzzy logic rule base is designed to get the approximation for switching angles for different voltage variations so that output voltage always has less percentage of lower order harmonic content with a pre specified fundamental component. Aligning membership functions to meet the output constraint is a repetitive task and manual tuning is required with the available tool in MATLAB. Expertise knowledge is explicitly required while designing the fuzzy rule base.

IV. SIMULATION RESULTS

In this section simulation result of 7-level multilevel inverter having non-ideal input voltage sources simulated with the proposed technique is presented. 10% input voltage variations are considered with the following voltage values.

$$V_1 = 18 \pm 1.8, V_2 = 17 \pm 1.7, V_3 = 16 \pm 1.6$$

Input voltage sources are varying independently with respect to each other. Nominal values for input dc voltage sources are$V_1 = 18, V_2 = 17$, $V_3 = 16$. Modulation index for the system is M= .8063 [4] [2]. 3^3 Input output voltage combinations are made, switching angles and fitness function for respective voltage combination has been calculated. Some approximation is made to reduce the system complexity, as 14 membership functions are taken rather than particular membership function for each input voltage. With 14 membership function each angle is achieved with fulfilling the system constraint. As of result of this, system complexity is reduced and less calculation is required for making the fuzzy rule base. The following obtained results are tabulated in respective tables Table-1 and Table-2.

TABLE-1: angles obtained for different input voltages

DIFFERENT INPUT VOLTAGE LEVELS			**OBTAINED ANGLES THROUGH PSO ALGORITHM**		
V1	V2	V3	Theta 1	Theta 2	Theta 3
16.2	15.3	14.4	18.706	25.206	63.7342
16.2	15.3	16	20.132	23.738	63.712
16.2	15.3	17.4	23.175	24.117	76.387
16.2	17	14.4	18.759	27.774	71.2873
16.2	17	16	18.337	28.751	74.0375
16.2	17	17.4	21.523	25.83	75.9751
16.2	18.7	14.4	14.188	33.616	75.2716
16.2	18.7	16	14.117	34.455	78.2374
16.2	18.7	17.4	17.039	30.132	76.2616
18	15.3	14.4	18.861	28.376	70.2117
18	15.3	16	23.124	23.408	73.512
18	15.3	17.4	22.991	24.118	75.4249

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18	17	14.4	15.938	33.104	74.8447
18	17	16	17.574	30.424	76.1476
18	17	17.4	19.678	28.269	75.4917
18	18.7	14.4	12.854	38.82	80.6153
18	18.7	16	13.315	37.753	80.7875
18	18.7	17.4	13.349	38.491	82.1648
19.8	15.3	14.4	16.755	35.078	75.361
19.8	15.3	16	16.428	36.35	78.7187
19.8	15.3	17.4	18.612	30.928	76.0805
19.8	17	14.4	15.371	39.013	78.9848
19.8	17	16	14.079	41.247	83.0301
19.8	17	17.4	15.218	39.366	82.3176
19.8	18.7	14.4	14.197	41.144	80.5424
19.8	18.7	16	13.824	41.126	82.2862
19.8	18.7	17.4	13.063	43.865	86.3161

Table-1 shows the different obtained angles $\theta_1, \theta_2, \theta_3$ for different input voltage combinations of V_1, V_2, V_3. Different membership functions for input and output variables are showed from figure (3) to figure (8).

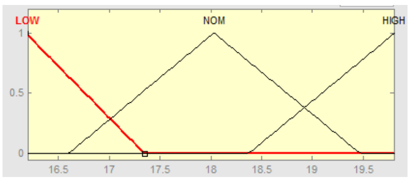

Fig.3. Input voltage membership function for V_1

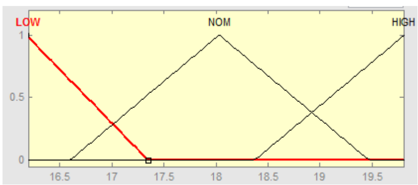

Fig.4. Input voltage membership function for V_2

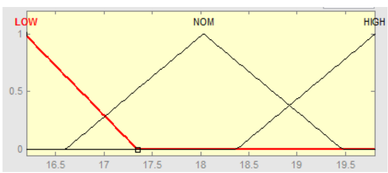

Fig.5. Input voltage membership function for V_3

ISSN (Print) : 2320 – 3765
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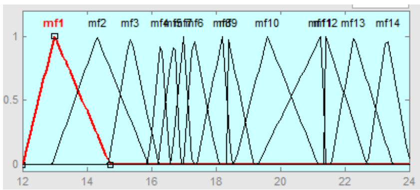

Fig.6. membership function for θ_1

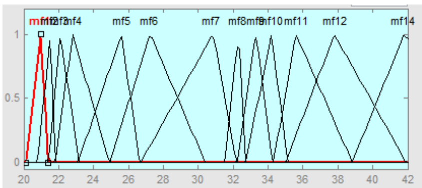

Fig.7. membership function for θ_2

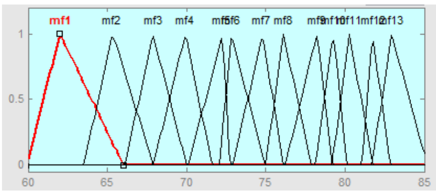

Fig.8. Membership function for θ_3

TABLE-2: Considered Fuzzy Rule Base

Rule Base						
	Membership functions					
S.No	Input membership functions			Output membership functions		
	V1	V2	V3	Theta1	Theta 2	Theta 3
1	Low	Low	Low	MF2	Mf4	MF5
2	Low	Nom	Nom	MF4	MF3	MF5
3	Low	Low	High	MF7	MF6	MF8
4	Low	Nom	Low	MF3	MF2	MF1
5	Low	Nom	Nom	MF5	MF6	MF1
6	Low	Nom	High	MF1	MF2	MF3
7	Low	High	Low	MF2	MF5	MF6
8	Low	High	Nom	MF3	MF1	MF8
9	Low	High	High	MF4	MF2	MF6
10	Nom	Low	Low	MF4	MF2	MF2
11	Nom	Low	Nom	MF7	MF6	MF5
12	Nom	Low	High	MF7	MF6	MF8
13	Nom	Nom	Low	MF4	MF3	MF4
14	Nom	Nom	Nom	MF4	MF3	MF5
15	Nom	Nom	High	MF4	MF3	MF8
16	Nom	High	Low	MF1	MF1	MF1
17	Nom	High	High	MF1	MF1	MF5
18	Nom	Low	Low	MF9	MF9	MF6
19	High	Low	Nom	MF9	MF9	MF8
20	High	Low	High	MF9	MF9	MF9
21	High	Nom	Low	MF6	MF6	MF6
22	High	Low	High	MF9	MF9	MF9
23	High	Nom	Low	MF6	MF6	MF6
24	High	Nom	Nom	MF6	MF6	MF4
25	High	Nom	High	MF6	MF6	MF7
26	High	High	Low	MF4	MF3	MF6
27	High	High	Nom	MF4	MF3	MF1

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Vol. 5, Issue 11, November 2016

To check the capability of suggested system, 5 random input voltage variations from each voltage source are supplied to the system. Designed fuzzy rule base will automatically adjust the switching angles to generate the output voltage with less content of lower order harmonics and maintaining the desired fundamental component.

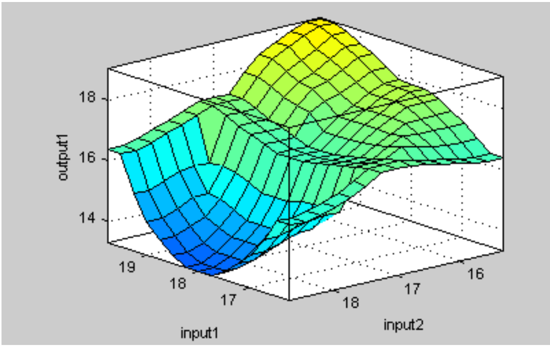

Fig.9. Surface view for constructed rule base

Above surface view shows that system is converging for different input voltage values. Minimization function is designed in such a way that generated switching angles are minimizing lower order harmonics in output voltage while maintaining the fundamental component at a pre-specified value. From figure (9) it can be seen that the output angles are coming after minimizing the system function.

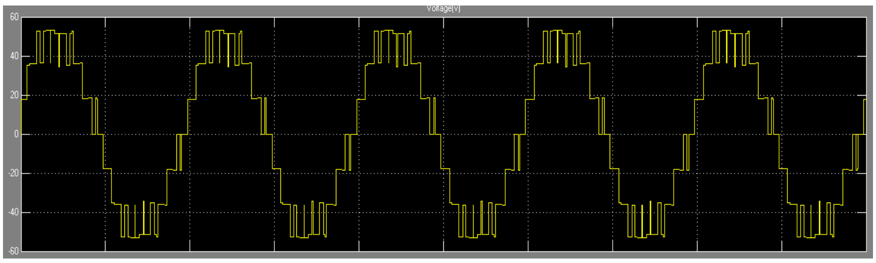

Fig.10. Output Voltage Waveform

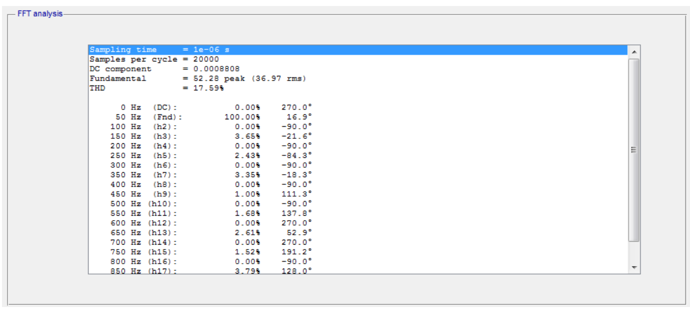

Fig.11. Harmonic analysis of the output voltage waveform

System overall obtained THD is 17.59% and remaining all harmonics are significantly low, specially 3rd and 5th order harmonics with respect to fundamental are very less.

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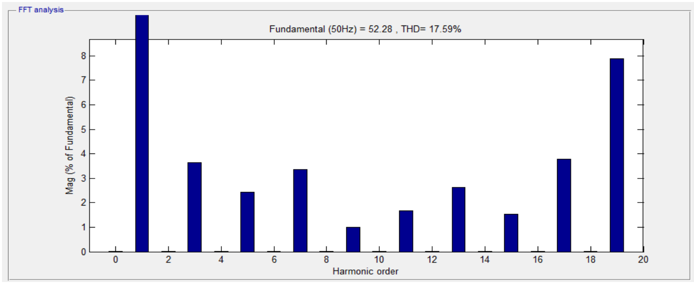


Fig.12. Harmonic analysis of output voltage waveform

In figure (8), a comparison between different odd order harmonics can be seen with respect to the fundamental component in the output voltage.

Table (3) gives the comparative analysis of 7-Level multilevel inverter with ideal and non-ideal sources.

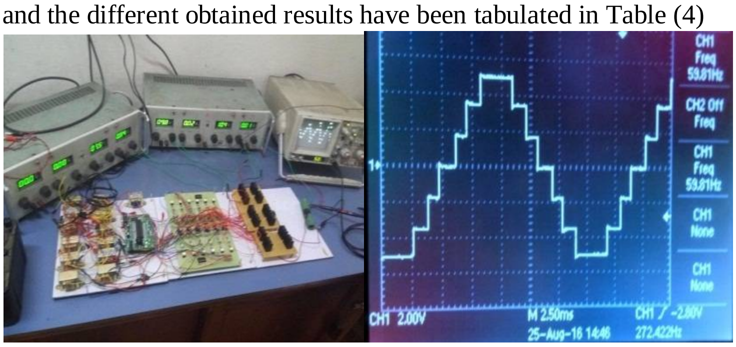
TABLE 3: Comparative analysis of 7 level inverter having ideal and non-ideal input voltage sources

		7-Level multilevel inverter with ideal source	7 level multilevel inverter with non - ideal source
voltages	I/P voltage	51 volts	v1=[17.9, 18.5, 18.6, 18.9, 18] v2=[17.8, 18.4, 18.5, 18.2, 17.1] v3=[16.9, 17, 16.8, 17.1, 17.4]
	rms o/p voltage	33.88	36.97
	peak to peak o/p voltage	47.92	52.28
Total Harmonic distortion	THD	20.10%	17.59%
Different order harmonics present in output voltage	3rd	3.04%	2.89%
	5th	4.87%	2.43%
	7th	14.03%	3.35%
	9th	7.31%	1.00%
	11th	3.00%	1.68/%
	13th	3.30%	2.61%
	15th	4.73%	1.52%

V. HARDWARE DESCRIPTION AND EXPERIMENTAL RESULTS

Using simulation results, hardware model has been made with input voltage sources having values as $V_1 = 18$, $V_2 = 17$, $V_3 = 16$.

Working model of hardware and the output voltage waveform from the hardware circuit with 100 ohm resistive load is shown in figure 13(a) (b) and the different obtained results have been tabulated in Table (4)



(a) (b)

Fig.13. (a) Working Hardware Model, (b) Output voltage waveform from hardware circuit with 100 ohm resistive load

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

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(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

Table (4) shows the results obtained from hardware corresponding to different loads. With different loads hardware is tested for its efficiency and regulation.

TABLE 4: Hardware Output Results for different loads

Load (Ohms)	V_{in} (Volts)	V_{op} (Volts)	V_{orms} (Volts)	I_o (mAmps)	P_o (watts)	P_{in} (watts)	Regulation in R%	Efficiency %
1000	51	50.5	34.125	36.2	1.23	1.447	-	85.01
500	51	49.86	34.67	73.34	2.54	3.209	1.22	79.2
250	51	49.2	34.20	144.8	4.95	6.504	2.49	76.1
100	51	48.90	34.992	356	17.408	23.91	3.05	72.8
50	51	48.82	34.93	718.6	25.100	35.57	3.21	70.56
33	51	48.6	34.77	1000	34.77	50.29	3.65	69.13

VI. CONCLUSION

Many factors affect the operation of multilevel inverter; voltage variation is one of them. In the proposed paper considering input voltage variations, lower order harmonics are eliminated with maintaining the fundamental component at a desired value Using fuzzy logic in the system also justifies the practicality of the proposed system. Proposed method is applied on 7-level H-bridge inverter and the obtained results are presented. Obtained simulation results effectively demonstrate the efficacy of the system. A comparison between the simulation results of 7-level inverter with ideal and non-ideal dc sources is done. From the results it can be concluded that proposed technology is reducing the lower order harmonics content in the output more effectively. Hardware results are also presented to check the system usefulness in practical applications. The proposed circuit is able to deliver an output of around 50W, making it suitable for stand-alone house hold applications.

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