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A Novel Approach to GSA, GA and Wavelet Transform to Design Fuzzy Logic Controller for 1ϕ Multilevel Inverter

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ABSTRACT

This paper proposes a novel approach for obtaining a closed loop control scheme based on Fuzzy Logic Controller to regulate the output voltage waveform of multilevel inverter. Fuzzy Logic Controller is used to guide and control the inverter to synthesize a stepped output voltage waveform with reduced harmonics. In this paper, three different intelligent soft-computing methods are used to design a fuzzy system to be used as a closed loop control system for regulating the inverter output. Gravitational Search Algorithm and Genetic Algorithm are used as optimization methods to evaluate switching angles for different combination of input voltages applied to MLI. Wavelet Transform is used as synthesizing technique to shape stepped output waveform of inverter using orthogonal wavelet sets. The proposed FLC controlled method is carried out for a wider range of input dc voltages by considering ±10% variations in nominal voltage value. A 7-level inverter is used to validate the results of proposed control methods. The three proposed methods are then compared in terms of various parameters like computational time, switching angles and THD to justify the performance and system flexibility. Finally, hardware based results are also obtained to verify the viability of the proposed method.

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1. INTRODUCTION

In recent years, interest in power electronic has surged due to increase in deployment of electrical and electronic equipment in industrial, commercial as well as residential applications. The growing demand has accelerated the pace of development in modulation techniques and power conversion topologies (especially in multilevel inverters). In a traditional multilevel inverter ‘n’ separate dc sources are used to produce (2n-1) levels at the output waveform, by employing power switches and switching them such that the step or staircase output is as close to a sine wave as possible [1]-[2]. The dc source can be a battery, fuel cells, photovoltaic cells or a rectified output of a wind turbine [3]. MLI is gradually gaining wide acceptance in high power applications, especially in industrial use like AC motor drives, electric vehicle drive and static VAR compensators owing to its advantages of offering lower switching losses, higher efficiency, better electromagnetic compatibility, smaller common mode voltage and Less Total Harmonic Distortion (THD) over the usual two level inverter [4]-[6]. While designing an inverter, stress is given on elimination of harmonics from output voltage of MLI inverter so that THD can be reduced as specified by Duffey et al [7]. In designing MLI importance is given to restrict the no of switches and dc sources to minimum this can be achieved by the use of hybrid topology and advanced hardware implementation techniques like, digital signal controller, FPGA [8]-[9].

Modulation techniques play an important role in the operation of MLI, the prime aim of modulation techniques is minimization of THD, different topologies might use one of the modulation techniques that suits best. From a gamut of available modulation techniques, Selective Harmonic Elimination (SHE) method is commonly used to minimize THD by eliminating some per-selected harmonics in output waveform [10]. The main challenge with SHE technique is to solve non-linear transcendental equations resulting from Fourier series expansion of output half wave symmetrical waveform. Prior to the advent of optimization methods, Resultant theory and walsh functions were widely accepted methods for solving these equations, especially walsh function was used to solve linear equations [11]-[12]. The strategy to reduce preselected harmonic content using SHE technique involves optimization method to calculate the accurate switching angles in complex topology, this is done by using Fourier series for a stepped inverter wave form.

Commonly used optimization techniques are genetic algorithm (GA) and Particle swarm optimization (PSO) [13]-[14]. GA is based on the concept of natural selection and uses genetic operators like reproduction, crossover and mutation and PSO is [Russell Eberhart et.al (1995)] inspired by social behavior of birds flocking or fish schooling has proven to be very fast and effective when applied to a diverse set of optimization problem. Researches are also working on some new optimization techniques such as evolutionary algorithm, Differential Evolution Algorithm (DE) and an all new optimization theory based on Minority Charge Carrier (MCI) to generate optimal switching angles in MLI [15]-[17]. These all are optimization techniques are producing encouraging results when applied to the problems at hand. In this paper an innovative approach in optimization method, Gravitational search algorithm (GSA) has been used to minimize the harmonics at the output voltage of multilevel inverter. GSA is a heuristic optimization technique inspired by Newton’s law of gravity and motion; it has four specifications for each of its agents viz. Active Gravitational Mass, Passive Gravitational Mass, Inertial Mass and Position. Over a period of time, GSA has undergone major changes in the basic algorithm and has been adapted for specific applications in varied fields of science [18]-[19]. Another approach used in this paper for harmonic reduction is Waveform synthesis, which is based on wavelets transform, it is a useful mathematical tool for designing multilevel inverter structures and control strategies, features of wavelets such as dilation and translation allow them to be used not only for analysis of processes consisting in decomposition but also in composition of signals and structures in power electronics [20]-[21].

Today more and more researchers are, working with Fuzzy Logic system along with conventional controllers (a hybrid system) to accurately control the operations of induction motor drives, dc motors and many other applications [22]-[23]. Fuzzy controller when used with optimization based soft computing techniques for parameters optimization have given better performance than conventional PI controller in non linear system [24]-[25]. In fuzzy system, the number of membership functions and system accuracy has a very close relation, the more the membership function the greater is the system complexity and the less the membership functions, lesser the system accuracy, hence the number of ‘mfs’ needs to be carefully chosen. A desired inverter output voltage can be obtained by regulating various parameters like modulation index, switching angles, input voltage of the inverter.In the presented work, fuzzy logic has been used as closed loop system to generate inverter output for variation in switching angles (GA and GSA based FLC controller) and modulation index (Wavelet based FLC controller). For each value of modulation index or set of switching angles, fuzzy system varies the output voltage for minimal THD. Hence, fuzzy controller serves as a voltage regulator corresponds to minimum THD in an inverter.

For the purpose of this paper, it is assumed that the input dc voltages to the multilevel inverter are fed from renewable energy sources such as fuel cells, photovoltaic cell, wind energy system etc. and accordingly a variation of ±10% in nominal dc voltage source has been taken into consideration for all calculation purposes, resulting in respective input dc values V_1=(1±10%)p.u., V_2=(0.9±10%)p.u., V_3=(0.8±10%)p.u. by considering all possible combination i.e. 3^3=27 different input sets [25]. GSA and GA are then used to calculate switching angles for all these 27 input sets. Study shows that performance of GA is better than PSO in terms of THD minimization and computational time [26]. Hence, the paper introduces other optimization methods such as GA and GSA to compute optimal switching angles. Wavelet transform has been used to synthesize stepped waveform using sets of orthogonal wavelets and then fed to design variables and rule-base for fuzzy system.

The paper is arranged as follows; Section 2 presents an introduction to Cascaded H-bridge multilevel inverter and a set of derived equations for SHE method. Section 3, 4 and 5 introduces and implements Genetic algorithm, Gravitational search algorithm and Wavelet Transform techniques for proposed fuzzy logic controller to control inverter output. Section 6 verifies the performance of proposed control methods by simulation of 7-level MLIs. Performance validation is done in section 7 and conclusions are made in 8.

2. CASCADED H-BRIDGE MULTILEVEL INVERTER (PROBLEM FORMULATION)

A single phase 7-level cascaded H-bridge multilevel inverter consists of three series connected H–bridge inverter units as shown in (Figure 1). Output voltage of MLI which is in the form of periodic staircase waveform can be expressed by Fourier series expansion as:

$$V_{out}(wt)=\sum_{n=1,3,5}^{\infty} b_n sin(nwt) \quad (1)$$

Amplitude of fundamental component b_1 and odd harmonics components b_n are given as:

$$b_1=\sum_{k=1}^{s}\frac{4V_s}{\pi}cos(n\theta_k) \ \ and \ \ \ b_n=\sum_{k=1}^{s}\frac{4V_s}{n\pi}cos(n\theta_k)$$

Now, Equation (1) is rewritten as:

$$V_{out}(wt) = \sum_{n=1}^{\infty}[\frac{4}{n\pi}\sum_{k=1}^{s} V_s \cos(n\theta_k)] \sin(nwt) \quad (2)$$

s is no. of switching angles to be calculated and let 'l' be the no. of inverter levels, then s and l are related by:

$$s= (l-1)/2 \quad (3)$$

Finally, based on Equation (3), three angles (s=3) are to be calculated for 7-level inverter such that these are limited as $0\leq \theta_1 \leq \theta_2 \leq \theta_3 \leq \frac{\pi}{2}$. Based on SHE method, minimizing (s-1) harmonics results 5th and 7th harmonics to be minimized and fundamental component is maintained for 7-level cascaded inverter as: In this paper, modulation index M is given by $M= \frac{b_1}{sV}$

$$V_1cos(\theta_1)+V_2cos(\theta_2)+V_3cos(\theta_3) = \frac{s\pi M}{4}$$
$$V_1cos(3\theta_1)+V_2cos(3\theta_2)+V_3cos(3\theta_3) = 0$$
$$V_1cos(5\theta_1)+V_2cos(5\theta_2)+V_3cos(5\theta_3) = 0$$
$$V_1cos(7\theta_1)+V_2cos(7\theta_2)+V_3cos(7\theta_3) = 0$$

Minimization of harmonics reduced total harmonic distortion (THD) of inverter which is given by Equation (4).

$$\%THD=\sqrt{\frac{V_2^2+V_3^2+.....+V_n^2}{V_1^2}}\times 100 \quad (4)$$

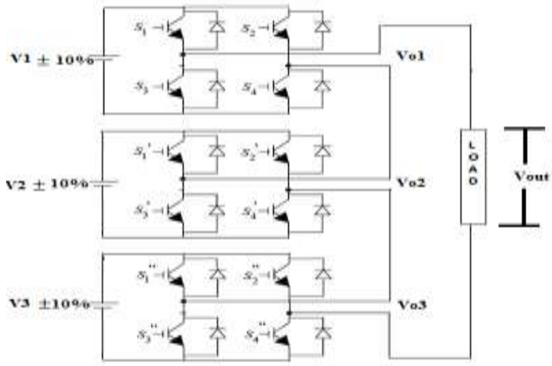

Figure 1. Seven level cascaded H-bridge MLI

3. PROPOSED GA BASED FUZZY LOGIC CONTROLLER

In this approach the aim is to obtain dataset for input-output pairs of FLC system based on calculation of optimal switching angles ($\theta_1, \theta_2, \theta_3$) for 7-level inverter. In literature review, PSO algorithm has been employed to calculate switching angles and also as discussed by authors, GA performance is rated better than PSO in terms of THD minimization and computational time [25]-[26]. Hence in this paper presents GA has been used to calculate the optimal values of switching angles, the approach requires considering input voltage valuesat V_1=1p.u., V_2=0.9p.u. and V_3= 0.8p.u., and applying $\pm$10% variations in each voltage value, this results in a set of total 27 input voltage values at different modulation index. At M=0.791, GA algorithm gives the best values of THD. The approach to calculate switching agles using GA is shown in the form of a flow chart in Figure 2. The result of GA algorithm for some of these input combinations is tabulated in Table 1.

Table 1. Result of GA algorithm for Switching Angle calculation

V_1 (volt)	V_2 (volt)	V_3 (volt)	θ_1(degree)	θ_2(degree)	θ_3(degree)
1.1	0.81	0.72	19.3586	47.13822	89.96561
1.1	0.81	0.8	20.73439	54.72229	89.99732
1.1	0.81	0.88	17.83376	46.22102	84.22739
……..	……	……..	……	……	…..
1.1	0.99	0.8	18.31529	43.96815	89.99702
1.1	0.99	0.88	21.01529	55.79427	89.20318
1	0.81	0.72	16.92229	40.21338	66.70318
1	0.81	0.8	17.17452	43.77325	86.65223
…….	…….	…….	…….	……	…….
1	0.99	0.8	17.26624	42.58089	89.71338
1	0.99	0.88	17.57006	46.46178	84.08981
0.9	0.81	0.72	19.1293	46.04904	64.6051
0.9	0.81	0.8	15.45478	42.18535	83.72293
…….	……	…..	……	……	……
0.9	0.99	.	15.08217	41.72675	84.13567
0.9	0.99	0.88	19.24395	51.24841	86.25096

3.1 Fuzzy Logic Controller

The obtained input-output datasets of GA (Table 1) are implemented over fuzzy system using different membership functions and Rule-Based Input voltages V_1, V_2, V_3 are represented by 3 triangular MFs (Low, Nom, High) covering the entire range of input variable as shown in Figure 3(a). For output switching angles θ_1, θ_2, θ_3, instead of using single membership function for each value, values that are close to each other are merged within the same membership functions. This leads to 7 membership functions for θ_1, 9 for θ_2 and 9 for $\theta_3$as shown in Figure 3(b). IF-THEN rule is used to write 27 rules for designing a complete rule-base for fuzzy system which is given in Table 2. An example to write if-thenrule is as: If (v_1 is high) and (v_2 is nom) and) (v_3 is nom) then (θ_1 is mf7) and (θ_2 is mf9) and (θ_3 is mf9)

Table 2. Rule Base of Fuzzy Data Base

INPUT MFs			OUT PUT MFs		
V_1	V_2	V_3	θ_1	θ_2	θ_3
high	low	low	mf5	mf5	mf8
high	low	nom	mf6	mf8	mf9
…	…	….	…	…	…
high	high	nom	mf5	mf3	mf9
high	high	high	mf7	mf9	mf9
nom	low	low	mf3	mf1	mf3
nom	low	nom	mf4	mf3	mf8
…	…	….	…	…	…
nom	high	nom	mf4	mf2	mf9
nom	high	high	mf4	mf5	mf7
low	low	low	mf5	mf4	mf2
low	low	nom	mf3	mf3	mf8
…	…	….	…	…	…
low	high	low	mf4	mf5	mf3
low	high	nom	mf1	mf1	mf7

In this manner, rule-based database is obtained for fuzzy logic controller to provide control mechanism for 7-level inverter to generate desired output waveform with reduced harmonics. Also to evaluate the performance of proposed GA optimized fuzzy logic controller, simulation is carried out in Section 6 and the result obtained are compared with other techniques for validation.

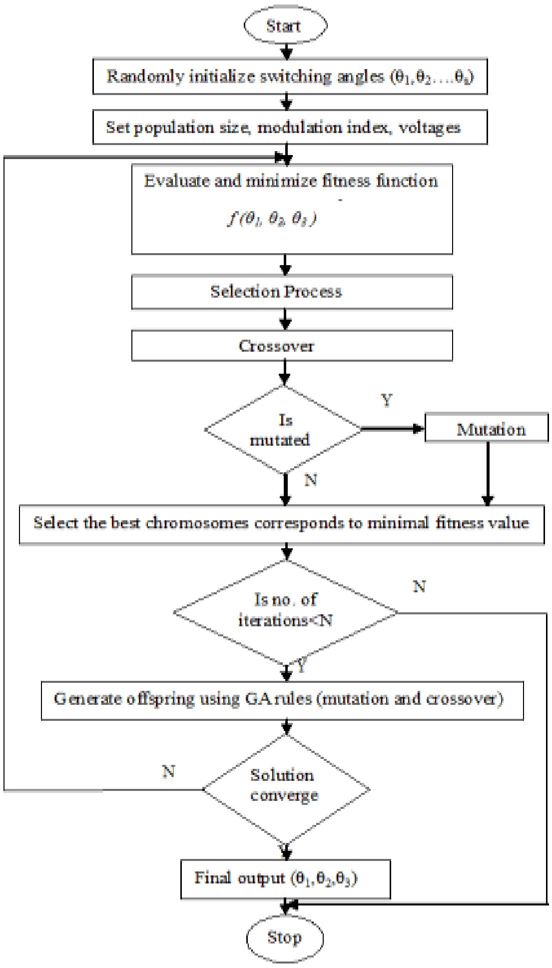

Figure 2. Flow chart for GA algorithm for Optimal Switching angle calculation

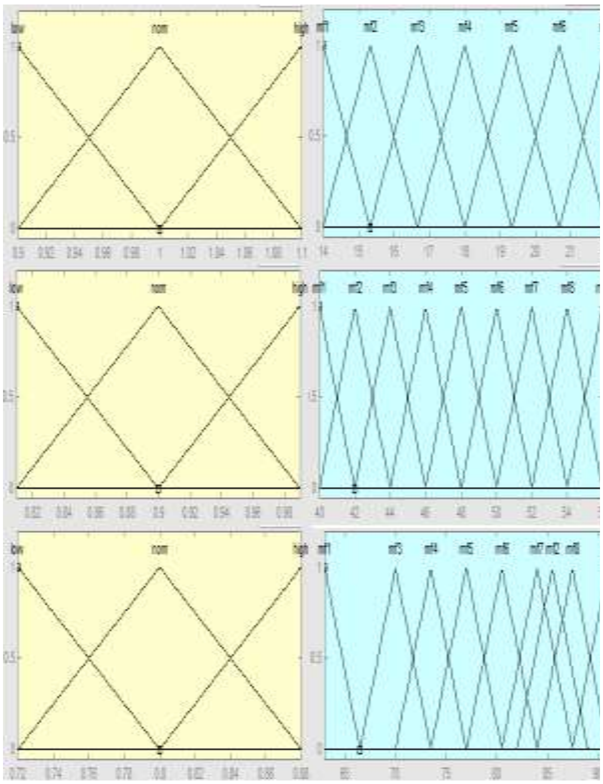

Figure 3. (a) and (b) Membership Functions for input voltages V_1,V_2,V_3(b) Membership Functions for Output angles θ_1,θ_2,θ_3

4. PROPOSED GRAVITATIONAL SEARCH ALGORITHM BASED FUZZY LOGIC CONTROLLER

In the proposed method of the second approach to calculate optimal switching angles GSA algorithm has been used for angle optimization over a wide range of input dc sources. The two proposed methods, i.e. GSA and GA based FLC controller have the same approach to design fuzzy logic system and this is done in order to compare the complexity and smoothness of the two optimization techniques. For 7-level inverter, GSA calculates 3 optimal switching angles (θ_1, θ_2, θ_3) for each of 27 input combinations and hence generates input-output pair datasets for FLC system.

4.1 Gravitational Search Algorithm

In GSA, an agent is characterized by 4 parameters which are to be calculated and updated until the stopping criterion is reached. These four parameters are- position (X_j^d), Inertial Mass (M_{ij}), Active Gravitational Mass (M_{aj}) and Passive Mass (M_{pj}). GSA algorithm for optimizing switching angles is formulated as given in the flow-chart, Figure 4. The input voltage and output switching angles datasets so obtained is shown in table 3, further from the dataset generated, FLC system is designed using the 8 membership functions for $\boldsymbol{\theta_1}$, 10 for $\boldsymbol{\theta_2}$ and 8 for $\boldsymbol{\theta_3}$ are generated from total 27 fuzzy rules as shown in Figure 5(a) and 5(b).

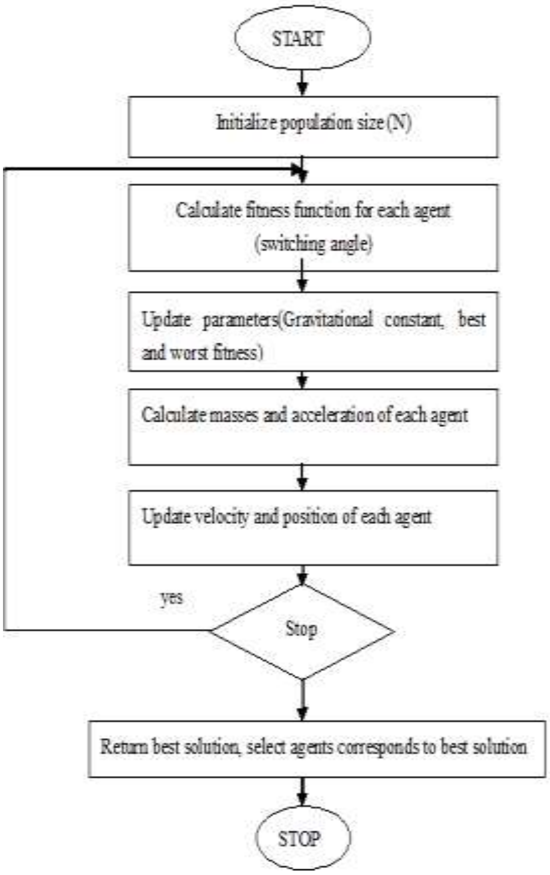

Figure 4. Flowchart of GSA algorithm for Optimal Switching Angle Calculation

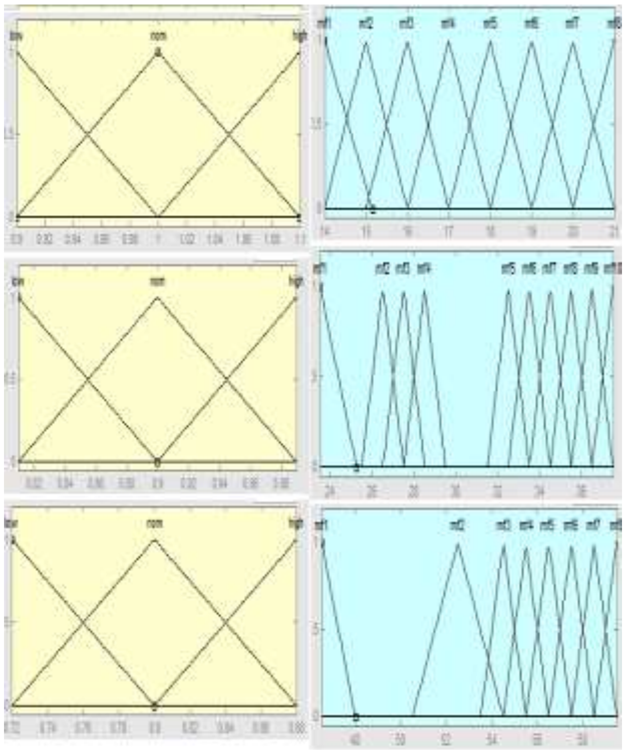

Figure 5. (a) Membership Functions for input Voltages V_1,V_2,V_3 (b) Membership Functions for Output Angles θ_1,θ_2,θ_3

Table 3. Result of GSA algorithm for Switching Angle Calculation

V1	V2	V3	ϴ1	ϴ2	ϴ3
1.1	0.81	0.72	19.17398	36.61871	53.23892
1.1	0.81	0.8	16.32547	28.20019	56.92725
---	---	---	---	---	---
1	0.81	0.72	17.64677	34.16058	58.21732
1	0.81	0.8	18.05846	28.07518	54.10266
---	---	---	---	---	---
0.9	0.81	0.72	18.91299	34.93328	52.03527
0.9	0.81	0.8	17.86655	26.15981	58.00402
---	---	---	---	---	---
0.9	0.99	0.88	18.67791	33.32681	56.72099

5. WAVELET TRANSFORM

The term wavelet is derived from French term ondelettes, which means little waves. Wavelet Transform is based on these small wavelets and allows to analyze the signals in different time scale, with different resolutions [20], [21]. It provides both time and frequency analysis of signal simultaneously. Wavelet is defined as a mathematical function or waveform that has finite time period and zero average value.

$$\int_{-\infty}^{\infty} \psi(t) = 0 \qquad (5)$$

Where, $\psi(t) = \varphi(2t) - \varphi(2t-1)$
In proposed work, Haar fundamental scaling function and wavelet function are used for waveform synthesis.

Hereinput function f(x) =sin(x) is selected in the interval 0<x<0.02 to generate approximation function $f_\psi(x)$ which is a composition of successive wavelets. In this paper, wavelet transform is applied to generate approximation function $f_\psi(x)$ for 7-level inverter output. Waveform synthesis $f_\psi(x)$ is represented as a composition of following wavelets given in Equation (6) and Equation (7).

$$f\psi(x) = f(x) = \sum_{r=ro} \sum_{s} b_{r,s}\, \psi\, r,s(x) \quad (6)$$

For 7-level waveform,

$$f\psi(x) = \sum_{r=0}^{3} \sum_{s=0}^{2^r-1} b_{r,s}\ \psi\, r,s\,(x) = b0{,}0\ \psi\ 0{,}0\ (x) + \sum_{s=0}^{3} b_{r,s}\ \psi\, r,s\,(x) + \sum_{s=0}^{7} b_{r,s}\ \psi\, r,s\,(x)$$

$$f\psi(x) = f\psi00\,(x) + f\psi2s(x) + f\psi3s(x) \quad (7)$$

Wavelet families $\psi_{0,0}(x)$, $\psi_{2,s}(x)$ and $\psi_{3,s}(x)$ and corresponding approximation functions $f_{\psi00}$ (x), $f_{\psi2s}(x)$ and $f_{\psi3s}(x)$ are presented in Figure 6. Values of wavelet coefficients $b_{r,s}$ are calculated from $f_\psi(x)$.

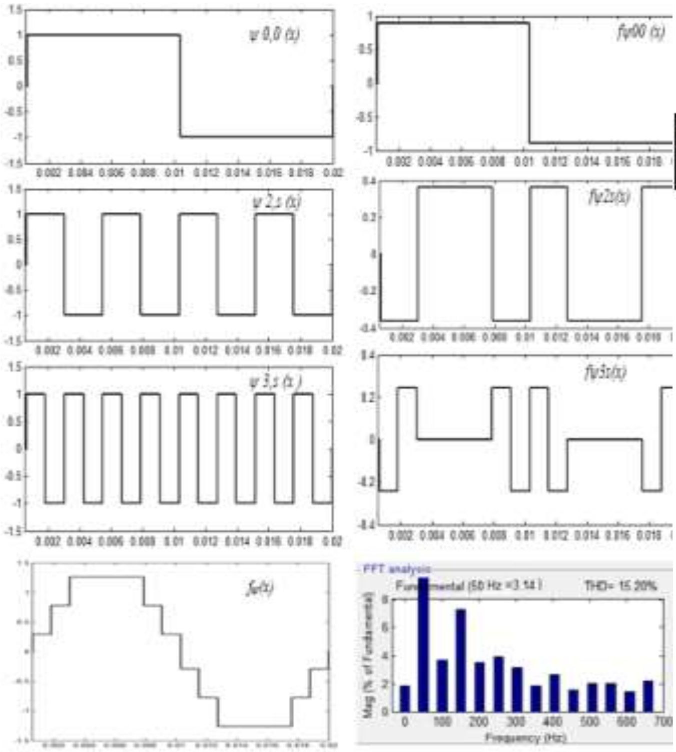

Figure 6. Wavelet approximation function $f_\psi(x)$ and frequency spectrum of approximation function $f_\psi(x)$

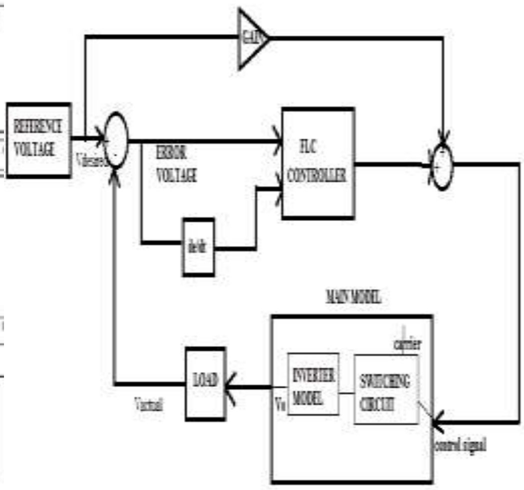

Figure 7. Block diagram representation of closed loop FLC controller inverter

5.1 Fuzzy Logic Controller Implementation

Synthesized $f_\psi(x)$ in Figure 6 has proved to present a better possibility to control fundamental voltage and frequency of output waveform and hence is used as reference waveform in fuzzy logic controller. Figure 6(a) and Figure 6(b) isa family of wavelets ψ 0,0 (x), ψ 2,s (x) and ψ 3,s (x) and Wavelet approximation functions fψ00 (x), fψ2s(x) and fψ3s(x) respectively Figure 7 shows the mechanism of FLC embedded to inverter module and to control the inverter. Output voltage of inverter V_{actual} is compared to reference voltage $V_{desired}$ to obtain error voltage e. Two inputs to fuzzy system are ‘e ‘and ‘de’which invoke fuzzy rule-base and results in output value that is used as a controlled parameter for switching circuit of inverter. For this 7 triangular membership functions are used to cover entire range of input-output variables namely: (NH) negative high, (NN) negative normal, (NL) negative low, (ZZ) zero, (PL) positive low, (PN) positive normal, (PH) positive high. IF-THEN rule is used to form fuzzy rule base and results in 49 rules are formed. An example of if-then rule is: if (e is NH) and (de is NN) then (V is NH).

For de-fuzzyfication centroid method is used. Simulation is carried out for 7-level inverter in (Section 6) to verify the results of proposed Wavelet Transform based fuzzy logic controller. But this model can be generalized to control output waveform of any level inverter.

6. RESULTS AND ANALYSIS

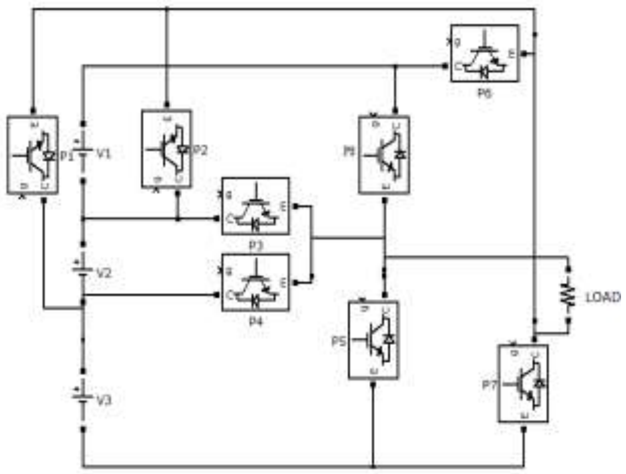

Figure 8(a). seven level inverter using 8-switches

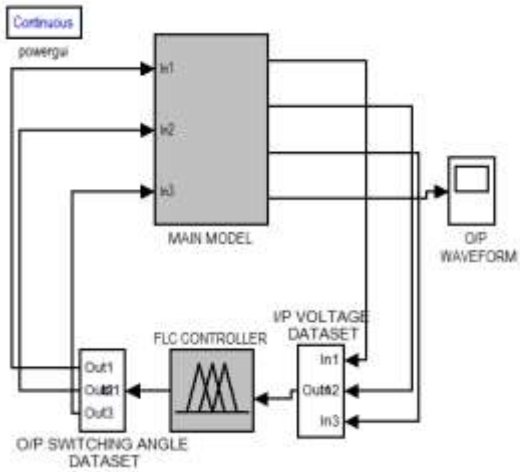

Figure 8(b). Closed loop control system of GSA/GA based fuzzy logic controller

6.1 Simulation Results for GA and GSA Based Fuzzy Logic Controller

Simulation is performed with MATLAB/SIMULINK on 7-level inverter to verify the performance of proposed closed loop control methods using fuzzy logic controller the same control methods can be extended to any level of inverter and for any defined topology. To validate the results, two different topologies are designed one using FLC for a 7-level cascaded H-bridge inverter and the other 7-level hybrid inverter topology with 8 switches as shown in Figure 8(a). Closed loop FLC controlled model using (GA and GSA) as shown in Figure 8(b) feeds the output voltage of inverter (MAIN MODEL) to fuzzy logic controller which then activates fuzzy decision rule and suitable switching angles are generated to control switching circuit of inverter.

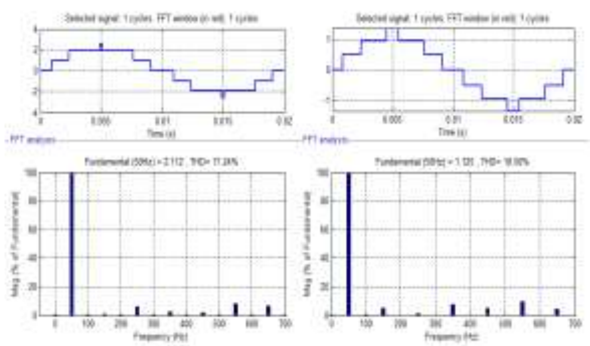

Figure 9(a)

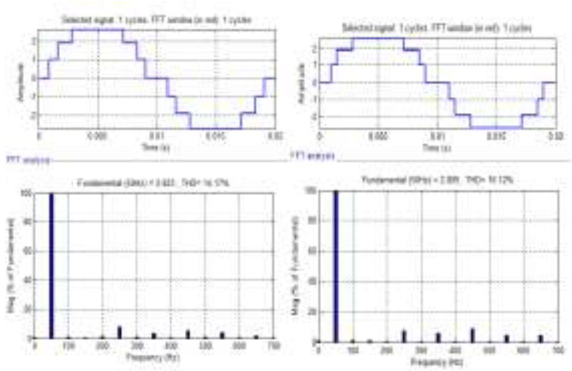

Figure 9(b)

Figure 9(a) & 9(b). Output voltage waveform and FFT spectrum of GAand GSA based FLC for 7-level inverter with 8 switches& 7-level cascaded H bridge inverter

This closed loop simulink model is then used to control the MAIN MODEL module by defined inverter module. Finally, FLC controlled model is used to generate desired 7-level output voltage waveform for all defined 27 combinations of input voltage. In this paper, 7-level inverter is simulated for input voltage set [V_1=1pu, V_2=0.9pu, V_3=0.8pu] and corresponding output voltage waveform and frequency spectrum for both 7-level inverter topologies are shown in Figure 9(a) and Figure 9(b). From the Figure 9(a) it can be seen that the frequency spectrum of output waveforms obtained by GA based FLC for Hybrid Inverter has reduced lower order harmonic as compared to cascade H-bridge by 1.32% and Figure 9(b) gives the output voltage waveform for GSA based FLC which shows that the THD for hybrid 7-level inverter is reduced over cascaded inverter by1.95%.

6.2 Simulation Results for Wavelet Transform Based Fuzzy Logic Controller

Unlike the approach used to design FLC in GA and GSA a different approach is adopted to design wavelet Transform based FLC. This can be seen from Figure 10(a) that the feedback of 7-level output voltage is compared with generated wavelet approximation function $f\psi(x)$ obtained in (Section 5) to produce error voltage.

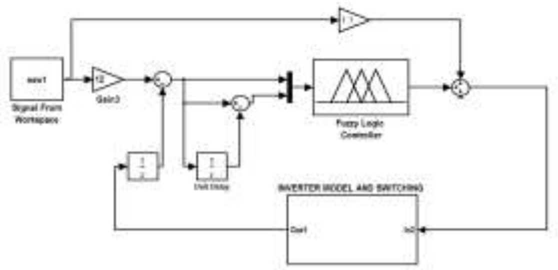

Figure 10(a). Simulink model of FLC controlled wavelet modulation

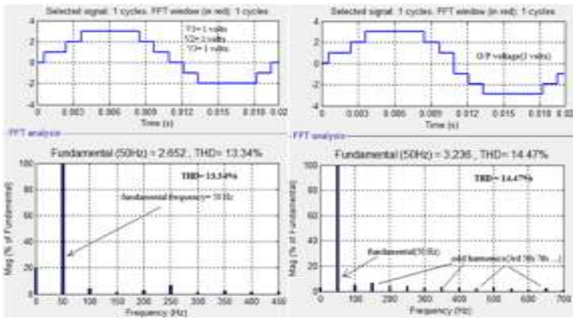

Figure 10(b). Output voltage waveform and FFT spectrum of WT based FLC 7-level hybrid inverter and 7-level cascaded H bridge inverter

The two inputs to FLC controller are error voltage (e) and derivative of error (de/dt) and output obtained is applied to switching circuit of inverter. The output of fuzzy logic controller is then fed to control PWM switching circuit of inverter where it is compared with triangular waveform to generate switching pulses. Figure 10(b) shows frequency spectrum of output voltage results in elimination of 5^{th} and 7^{th} harmonics. THD for hybrid 7-level inverter is reduced by 1.13% over cascaded inverter.

6.3 Experiment Results

A prototype model of proposed topologies has been fabricated and tested in Arduino Due (54 I/0, 14 PWM pins). The experiment is performed for 10 V input dc values for hybrid 7 level inverter and the output voltage waveform and frequency spectrum of GA based FLC system and GSA based FLC system are shown in Figure 11(a) and Figure 11(b) respectively. FFT results of GA, GSA and Wavelet for 7 level hybrid inverter are given in Figure 12 (a, b, c) respectively. The results using Hardware setup are in agreement with those obtained by simulation.

Figure 11(a)

Figure 11(b)

Figure 11(c)

Figure 11. (a), (b) Hardware results of 7 level inverter (GA) & (GSA)

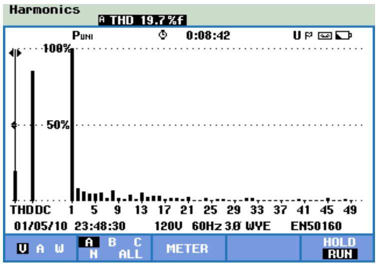

Figure 12 (a)

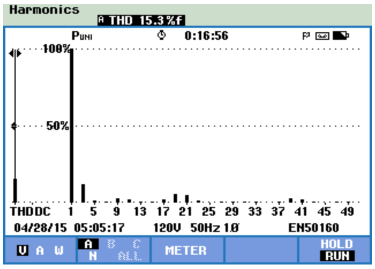

Figure 12 (b)

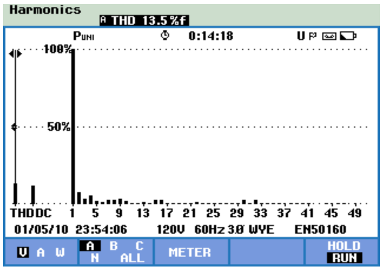

Figure 12 (c)

Figure 12 (a), (b), (c). FFT results of GA, GSA and wavelet for 7 level inverter

6.4 Performance Comparison Of Proposed Methods

In this section, the results obtained by optimization techniques as discussed in section 3 and section 4 are compared for parameters such as THD, Switching Angles and complexity. Figure 13 (a, b, c) illustrates different parameter comparison between GSA and GA for angle optimization at modulation index M=0.7901. As discussed earlier GSA has more computational time than GA due to slow convergence in last iterations which can also be seen in Figure 13(a). In GA much of the step parameters must be fine tuned for a particular problem, making much of it just hit and trial. These drawback of the GAare very easily overcome by the GSA which is a deterministic technique as opposed to the scohastic GA, hence Figure 13(b) shows that GSA has better parameter approach than GA. Even though, GSA has inherent computational delay but this can be contained by use of faster processors widely available, however the overall performance of GSA is better than GA when number of inverter level increases which is clear from the simulation results.

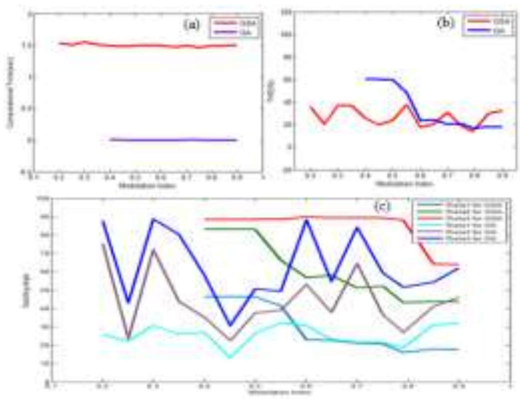

Figure 13. Comparison plots between GA and GSA (a) Modulation index versus Computational time (b) Modulation index versus THD (c) Modulation index versus switching angles

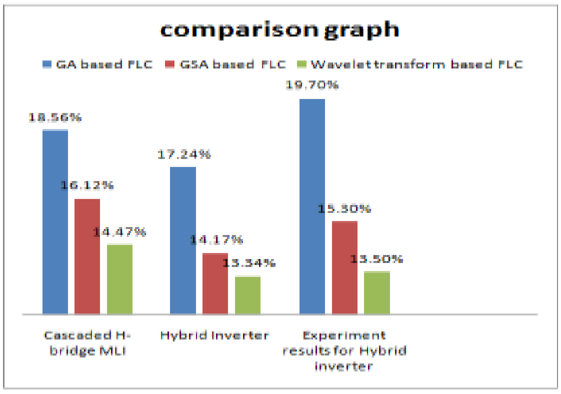

Figure 14. Performance comparison on the basis of THD for GA, GSA and wavelet transform

Finally, the results for % THD values obtained by each of the three techniques-GA, GSA and WT for 7-level inverter are compared by means of graphical representation as shown in Figure 14. From the performance comparison graph it can be seen that for 7 level inverters (cascade H Bridge and Hybrid MLI) the minimum THD occurs in experiment results for hybrid inverter whereas, wavelet based FLC gives approximately 11% less THD than GSA based FLC and 31 %less than GA based FLC. However, It is seen that optimization techniques-GA and GSA are better than Wavelet Transform techniques when higher level of inverter output is considered because in wavelet transform, as the number of levels in output waveform increases, more approximation functions $b_{r,\ s}$ and wavelet family $\psi_{\ r,s}$ (x) are needed to be generated in the order 2^r and the harmonic distortion in GSA based FLC is less than GA based FLC for both considerd topologies.

7. CONCLUSION

A complete analysis of closed loop control of multilevel inverter with Fuzzy Logic Controller has been presented for generating desired output voltage waveform with reduced lower order harmonics and ultimately for better THD performance. All the three techniques that have been proposed to design FLC for closed loop inverter control have proved to be relevant and satisfactory in terms of THD minimization. Considering the overall performance of proposed methods, it can be concluded that GSA based FLC controller is superior to GA based FLC in terms of THD and other parameters. Even though the results of Wavelet based fuzzy logic controller gives minimum THD but as the number of levels increases the wavelet approximation functions increases resulting in higher complexity in terms of more calculations and increased waveforms. Considering all three proposed methods, it can be concluded that, GSA based FLC appears to be a relatively better technique to control hybrid 7-level inverter this is further corroborated by the hardware results too.

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