THD Optimization in 13 level photovoltaic inverter using Genetic Algorithm

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ABSTRACT
Minimum Total Harmonic Distortion (THD) is one of the most important requirements from multilevel inverter concerning good Power Quality. This paper presents the optimization of THD in 13 level Cascaded Multilevel Inverter with unequal dc source using Genetic Algorithm (GA). THD minimization is taken as an optimization problem derived from Selective Harmonic Elimination Pulse width Modulation (SHE-PWM). Results give all possible solutions at each modulation index. Switching strategy, FFT analysis and computational time has been analyzed using MATLAB simulation environment.

Keywords **– Multilevel Inverter, SHE-PWM, Genetic Algorithm**

I. INTRODUCTION
In recent years, there has been an increase in the use of renewable energy due to growing concern for the shortage of conventional energy resources and environment pollution. With the rapid progress of the power electronic techniques, solar energy as an alternative energy source has been put to use such as Photovoltaic (PV) arrays. A key component in photovoltaic generation systems is the DC-AC converter [1]. Multilevel inverters are widely used in solar energy generation systems consist of various photovoltaic generators. There are mainly three topologies in multilevel inverter. These are Diode Clamped, Capacitor Clamped and Cascaded multilevel inverter. Multilevel Inverter gives an AC voltage from several DC sources, that is, from the photovoltaic generators. Cascaded H-Bridge structure takes no dc to dc boost converter and takes no additional transformer connection. For that reason it is 25% cheaper in cost compared with transformer combined structure [7]. Adding a transformer (corresponding to the grid frequency) will add to the bulk and cost of the system, besides adding losses. The superior performance in cascaded multilevel Inverter compared with other multilevel topology has been given in ref. [12]. PV array with large dc voltage suffers from drawbacks such as hot-spots during partial shading of the array, reduced safety and increased probability of leakage current through the parasitic capacitance between the panel and the system ground [3, 4]. On this regards the Multilevel Inverter is taken with unequal dc source so that different magnitude of dc input voltage can be added to get required output voltage. Harmonic elimination methods applied in multilevel inverter reported in literature are Sine-triangle PWM (SPWM), Optimal Minimization of Total Harmonic Distortion (OMTHD), Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) etc. Among them Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) offers a tight control of the harmonic spectrum of a given voltage waveform generated by a power electronic converter along with a low number of switching transitions [5, 9]. It involves the solution of non-linear transcendental equation sets representing the relation between the amplitude of the fundamental wave, harmonic components and the switching angles. There are many optimization methods applied to minimize Total Harmonic Distortion (THD) like Particle Swarm optimization (PSO) [2], Genetic algorithm (GA) [9] and Harmony Search algorithm (HSA) [10] in literature. GA gives better performance in THD minimization and takes less computational time compared with PSO [11]. In this paper Genetic Algorithm (GA) is applied for the minimization of THD of a 13 level cascaded multilevel inverter with unequal dc source. The objective function derived from the SHE problem is minimized, to compute the switching angles while lower order harmonics are controlled within allowable limits.

This paper is organized as follows. The proposed scheme is described in Section 2. Simulation results and comparison are presented in Section 3 and finally conclusion in Section 4.

II. PROPOSED SCHEME
The general function of a multilevel inverter is to synthesize a desired output voltage from several levels of dc voltages as inputs. A single-phase structure of a 13 level cascaded multilevel inverter with unequal dc source obtained from photovoltaic sources is shown in Fig. 1. This structure can be used as off-grid application. When sunlight's are unavailable (at night or in bad weather conditions), battery provide necessary dc input. It is assume that there are z number of dc source, $(V_{dc1}, V_{dc2} \dots\ V_{dcz})$ for general convenience. The synthesized ac output voltage waveform is the sum of all the individual inverter outputs. The number of output phase voltage levels of cascade multilevel inverter is 2N + 1, where N is the number of dc sources. An output voltage waveform of a 13-level cascade multilevel inverter with three dc sources is shown in Fig. 2.

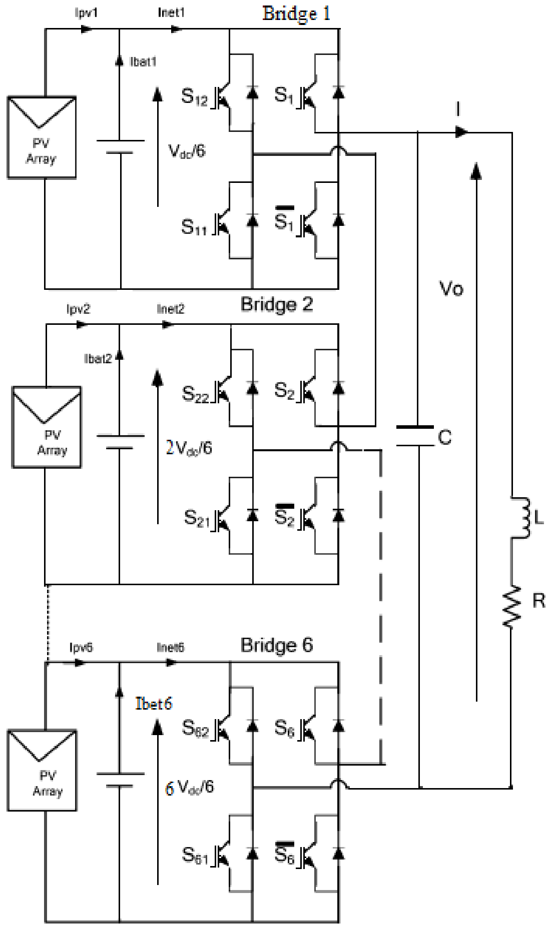

Fig. 1. Single-phase configuration of a multilevel inverter

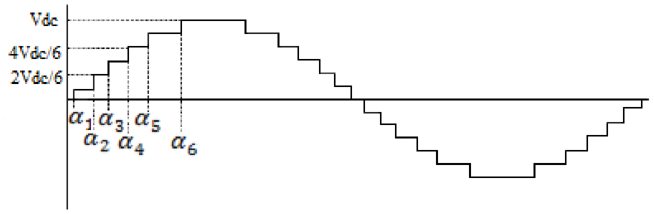

Fig. 2. Output voltage waveform of a 13-level multilevel inverter

A. Conventional Method

The output voltage waveform V(t) of the multilevel inverter as shown in Fig. 2 can be represented by (1)

$$V(t) = \sum_{n=1}^{\infty}(a_n \sin n\alpha_n + b_n \cos n\alpha_n) \quad (1)$$

The even harmonics are absent (bn = 0) due to quarter wave symmetry of the output voltage. The n-th harmonic an is expressed with the first quadrant switching angles $\alpha_1,\alpha_2,...\alpha_m$.

$$an = \left(\frac{4}{n\pi}\right)\sum_{k=1}^{m}(V_{dc1}\cos(n\alpha_1) + (V_{dc2}\cos(n\alpha_2) + \cdots + (V_{dcz}\cos(n\alpha_k))) \quad (2)$$

and

$$0 < \alpha_1 < \alpha_2 < ...\alpha_k < \left(\frac{\pi}{2}\right) \quad (3)$$

For any odd harmonics, (2) can be expanded up to the k-th term where m is the number of variables corresponding to switching angles α_1 through α_m of the first quadrant. In selected harmonic elimination, an is assigned the desired value for fundamental component and equated to zero for the harmonics to be eliminated [6].

$$a1 = \left(\frac{4}{\pi}\right)\sum_{k=1}^{m}(V_{dc1}\cos(\alpha_1) + \ldots + (V_{dcz}\cos(\alpha_k)))$$

$$a5 = \left(\frac{4}{5\pi}\right)\sum_{k=1}^{m}(V_{dc1}\cos(5\alpha_1) + \ldots + (V_{dcz}\cos(5\alpha_k)))$$

$$\vdots \quad (4)$$

$$an = \left(\frac{4}{n\pi}\right)\sum_{k=1}^{m}(V_{dc1}\cos(n\alpha_1) + \ldots + (V_{dcz}\cos(n\alpha_k)))$$

where M is the amplitude of the fundamental component.

Nonlinear transcendental equations are thus formed and after solving these equations, α_1 through α_k are computed. Triplen harmonics are eliminated in three-phase balanced system and these are not considered in (4). It is evident that $(m-1)$ harmonics can be eliminated with m number of switching angles. These nonlinear equations show multiple solutions and the main difficulty is its discontinuity at certain points where no set of solution is available [2]. This limitation is addressed in the present method to ease the online application at these points of discontinuity.

B. Proposed GA Method

Genetic Algorithm (GA) is a method used for solving both constrained and unconstrained optimization problems based on natural selection, the process that drives biological evolution [8, 9]. GA is inspired by Darwin's theory about evolution-"The survible of the fittest". In nature, competition among individuals for scanty resources results in the fittest individuals dominating over the weaker ones. The GA repeatedly modifies population of individual solutions. At each step, the GA selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" towards an optimal solution. A flowchart of the Genetic algorithm is shown in Fig. 3. GA uses three main rules at each step to create the next generation from the current population:

• *Selection rules* select the individuals, called *parents* that contribute to the population at the next generation.

• *Crossover rules* combine two parents to form children for the next generation.

• *Mutation rules* apply random changes to individual parents

Some advantage of GA compared with other optimization technique are as follows [8]:

1. GA is better then conventional Artificial Intelligence (AI); it is more robust.

2. Unlike older AI systems, the GA's do not break easily even if the input changed slightly, or in the presence of reasonable noise.

3. While performing search in large state space, or multi modle state space, or n-dimentional surface, a genetic algorithms offer significant benifits over many other typical search optimization techniques like- linear programming, heuristic, depth-first, breath- first.

The conventional SHE technique for multilevel inverter has the disadvantage of complexity to solve the nonlinear transcendental equations that have multiple solutions [2]. Moreover, at certain points, no solutions are available to satisfy these equations. In the proposed Genetic Algorithm (GA) method, the complexity of finding the solution of these nonlinear equations is avoided by converting the SHE problem to an optimization problem. The %THD of the output voltage can be computed using (5).

$$\%THD = \left[\left(\frac{1}{{a_1}^2}\right)\sum_{n=5}^{\infty}(an)^2\right]^{1/2} \times 100 \qquad (5)$$

Where $n = 6i \pm 1\ (i = 1,2,3,\dots)$

In the method, the same expression of the voltage THD is considered as the objective function $F(\alpha)$ and minimized with the constraints of individual harmonics limits and minimal variations of switching angles. The formulation of the problem will be as follows:

Minimize

$$F(\alpha) = F(\alpha_1, \alpha_2, \dots \alpha_m) \qquad (6)$$

Subjected to:

$$0 < \alpha_1 < \alpha_2 < \dots \alpha_k < \left(\frac{\pi}{2}\right);$$

$$a1 = M$$

$$a5 = \varepsilon 1$$

$$a7 = \varepsilon 2$$

$$\vdots \qquad (7)$$

$$an \le \varepsilon n$$

where $\varepsilon 1$, $\varepsilon 2$,.... εn are the allowable limits of individual harmonics.

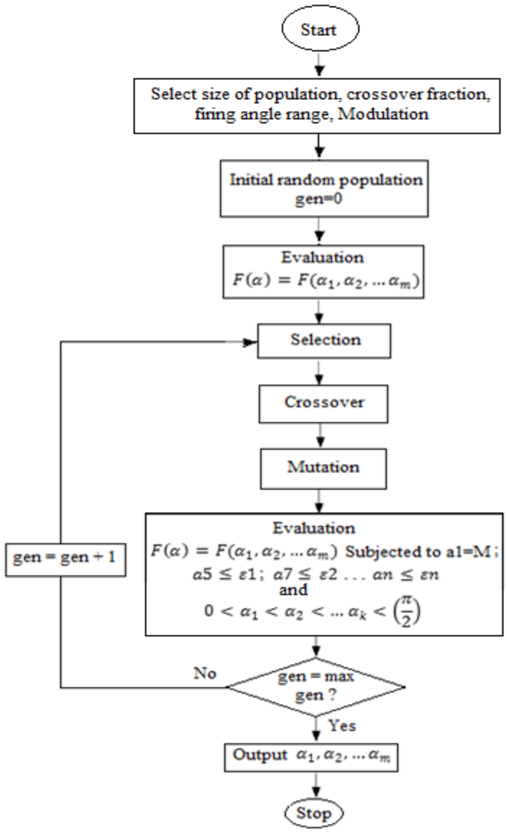

Fig. 3. Flowchart of proposed Genetic algorithm

III. Simulation Results and Discussion

The proposed scheme has been simulated in MATLAB/Simulink environment. For six dc sources, the multiple sets of angles present within the modulation index range of 0.20–1.10. For present case problem is formulated that way such that input dc voltage $V_{dc1}=V_{dc}/6$, $V_{dc2}=(2\times V_{dc})/6$, $V_{dc3}=(3\times V_{dc})/6$, $V_{dc4}=(4\times V_{dc})/6$, $V_{dc5}=(5\times V_{dc})/6$, $V_{dc6}=V_{dc}$. The Switching angle against Modulation Index is shown in Fig 8. The voltage THD against modulation index is shown in Figs. 7. The THD is being optimized up to 49^{th} order. Harmonic Spectrum for output phase voltage at 1 Modulation Index is shown in Fig. 9. The time taken for particular THD is shown in table I. In GA optimization tool double vector population type is taken for 20 population sizes with 0.8 crossover fraction of scattered function. **Best fitness** plots the best function value in each generation versus iteration number shown in Fig. 4. **Best individual** plots the vector entries of the individual with the best fitness function value in each generation shown in Fig. 5 at modulation index 1. **Genealogy** plots the genealogy of individuals shown in Fig. 6. Lines from one generation to the next are color-coded as follows:

- Red lines indicate mutation children.
- Blue lines indicate crossover children.
- Black lines indicate elite individuals.

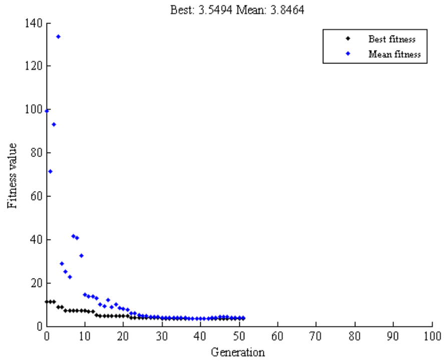

Fig. 4. Best function value in each generation versus iteration number

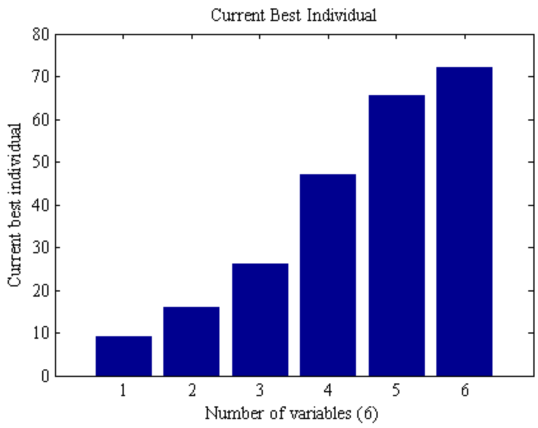

Fig. 5. Best individual plot at Modulation Index 1

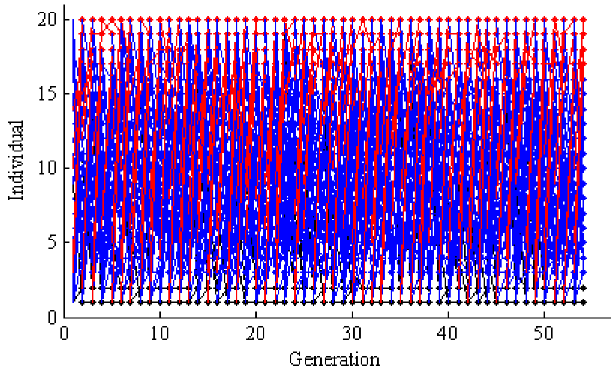

Fig. 6. Genealogy plot

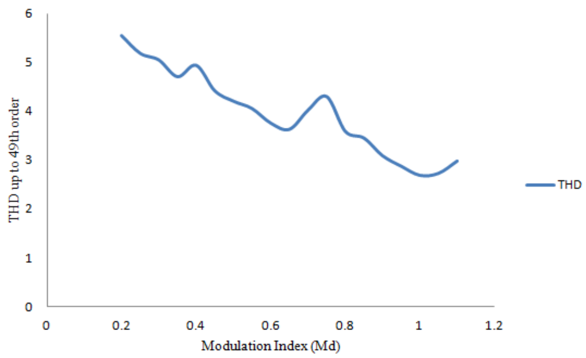

Fig. 7. Voltage THD versus modulation index for 13 level multilevel inverter with unequal dc source considering lowest THD

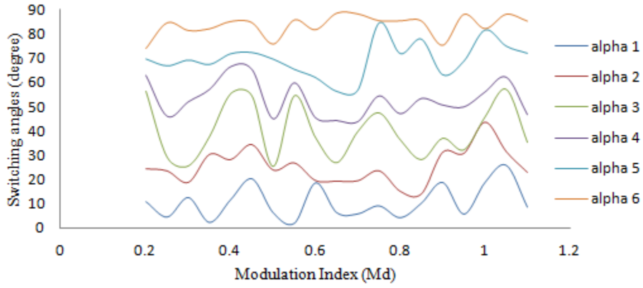

Fig. 8. Switching angles versus modulation index for 13 level multilevel inverter with unequal dc source

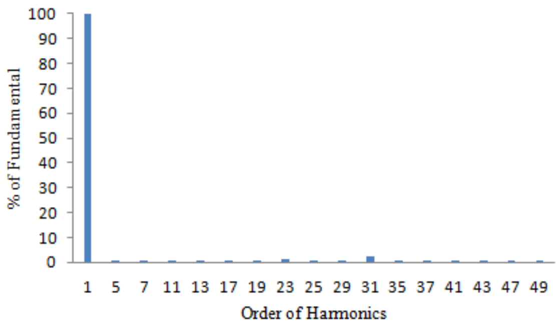

Fig. 9. Harmonic Spectrum of output phase voltage for 13 Level Multilevel inverter at 1 Md up to 49th order having THD 2.693%

TABLE I. Computational time of Genetic Algorithm at certain Modulation Index

Modulation Index	Computational time (sec)	%THD
0.95	0.01413 seconds	2.8018
0.9	0.0208 seconds	3.1814
0.77	0.01029 seconds	4.3082

In this work THD is used to evaluate the performance of Multilevel Inverter. The goal is to find optimum switching angle for the employed modulation index considering lowest THD. The proposed minimization method finds all possible sets of solutions. The result shows that minimized THD meets IEEE 519 standards (below 5%). The time taken for running the algorithm for particular modulation index has been shown in Table I. In GA Toolbox all GA codes are in-built. So it is very easy to use GA Toolbox.

IV. Conclusion

In this paper an efficient way is applied to minimize the Total Harmonic Distortion (THD) of a 13 level Multilevel Inverter with unequal dc source. The selected lower order harmonics are kept within allowable limits. The problem of discontinuity at certain Modulation Index is being addressed by the proposed method.

The result shows that the proposed approach for harmonic optimization of Multilevel Inverter works properly. This method was applied for 13 level Cascaded Multilevel inverter with specific unequal input dc voltage obtainable from photovoltaic sources. This method can be extended to any number of levels of Multilevel Inverter.

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