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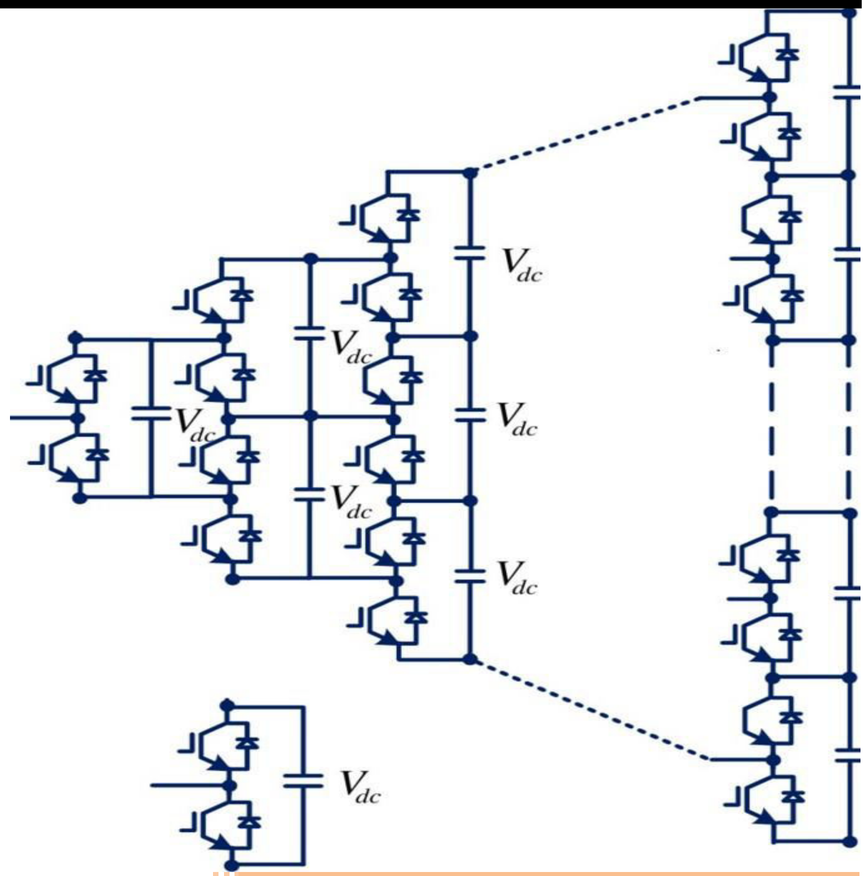

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Preface

Power electronics being a energy efficient devices have major role in power conversion application systems. To guaranteed power quality the significant integration of renewable energy is must in power system. Generally for medium and high power applications multilevel inverters are widely used. But due to harmonics present in the system, the power quality is disturbed usually. In multilevel inverters, switching techniques improve the harmonic profile and ensures its power quality. Mostly selective harmonic elimination techniques are used for lowering harmonics and total harmonic distortion also. Selective harmonic elimination method is a fundamental switching frequency method having lower switching losses and high efficiency. The output obtained from multilevel inverter consists of nonlinear transcendental equations and need specific optimization algorithms. The solution to these equations provides optimized switching angles which further reduces the specific harmonics along with THD for the system. In this monograph, a hybrid optimization algorithm is used for solving these nonlinear transcendental equations and obtaining the desired solution. This hybrid algorithm is a grouping of N-R algorithm with Ant colony algorithm. This algorithm is used whenever there are uncertainties in the system model. This hybrid optimization algorithm proved as a successful algorithm with the help of simulated results.

I precisely mention my sincere thanks for all the members who directly or indirectly helped me, guided me and encouraged me to complete this monograph.

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1. INTRODUCTION

The Multilevel inverters are generally preferred where medium to high voltage drives like electric vehicles, grid-connected systems etc are used. It is widely used for the purpose of increasing power ratings of the devices, improvement for harmonic profile, and reduction for electromagnetic interference. All these advantages can be accomplished with use of several DC voltage levels to obtain output voltage waveform.

In the multilevel inverters, all harmonics cannot be removed with the help of filters. Only few higher order harmonics are removed by the appropriate choice of passive filters. Whereas the lower order harmonics cannot be removed with the help of passive filters. Also when the frequency increases the losses will also increase for high voltages. Hence through optimizations technique, this objective can be achieved which proves the recent contribution of multilevel inverter technology.

So many approaches have made for solving nonlinear equations and getting its approximate solution upto date and again research is going on. The first approach was obtaining solution by resultant theory approach. From this method desired solution sets are achieved by converting nonlinear equations into polynomial sets and then by applying resultant theory. This method was successful to some extent but it was a time consuming algorithm. Also when DC level changes it requires new expressions to solve. To overcome these drwabacks iterative methods came into existence. In iterative methods like Newton Raphson and Gauss Siedal methods, solution to nonlinear transcendental equations can be obtained. But in Newton Raphson algorithm, initial guess closer to approximate solution is required otherwise it may take time to find the possible solution sets and the system may take longer time to converge. In Gauss Siedal method, after successful iterations, it provides solution to nonlinear equations for obtaining desired values but discontinuities in the solution may occur for non-existing solutions.

So, owing to limitations and drawbacks of conventional iterative methods, next approach was based on stochastic search optimization approach. These approaches were mainly nature inspired population-based algorithms. These algorithms include GA, PSO Algorithm, Firefly Algorithm, Bee Algorithm, BBO Algorithm and many more. These algorithms are again proved to be successful for solving nonlinear equations and getting desired solutions. But again these algorithms had some drawbacks and limitations. These algorithms can be implemented to symmetrical design of multilevel inverter with equivalent DC input sources. Secondly, all solution sets cannot be obtained for all modulation indices. Also it requires more computational time. As the number of levels in multilevel inverter increases, complexity in the design of system is also increases.

Other optimization algorithms like Ant Colony Optimization (ACO) were invented by Researcher Marco Dorigo for solving unique traveling salesman problem. Ant Colony algorithm developed applied and verified successfully on typical problems, like battery charging problems, vehicle navigation problems, unit commitment, etc. ACO algorithms have assured convergence but time for convergence may be more depending upon the system parameters and constraints.

From the above discussion, it is obvious that main challenge is to obtain desired solutions for nonlinear transcendental equations derived from fourier series expansion of output of multilevel inverter. Owing to the above drawbacks and limitations of all evolutionary algorithms, need of new improved strong algorithm is to be explored which will maintain all concerns related to selective harmonic elimination issues. In this monograph, a new proposed hybrid algorithm is implemented including combination of optimization algorithm i.e. ACO algorithm and iterative algorithm i.e. Newton Raphson Algorithm. This algorithm proves to be very successful algorithm with less computational burden and faster convergence rate.

2. MODULATION TECHNIQES

2.1 Topologies related to Multilevel Inverter

Generally multilevel inverters are investigated for the purpose of reduction of size as well as price of filters with less harmonic disturbance. VSC i.e. Voltage Source multilevel inverters are very much popular now a days because of its applications in motor drives, UPS systems and FACTS Devices. In multilevel inverter desired output can be obtained with any level using dissimilar DC inputs. This is the most important characteristics of multilevel inverter. For attaining this, the different topologies of multilevel inverter are neutral-point clamped, flying capacitor, cascaded H-Bridge inverter along with different dc levels and modular structures have been proposed by many researchers till date. Figure 2.1 shows the different topologies of inverter.

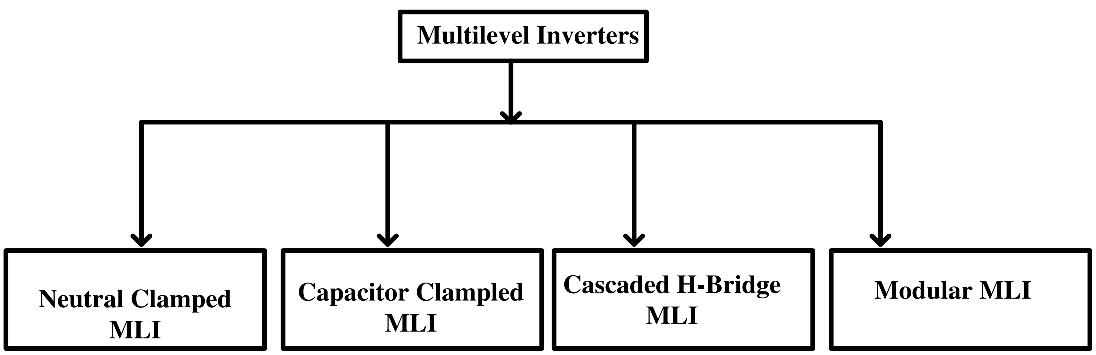

Fig. 2.1: Topologies of MLI

2.2 Modulation Techniques

In multilevel inverter power devices are mainly used. But the drawback of these power devices is-high switching losses and reduced efficiency and thereby reducing the life of the system. This drawback can be overcome by selecting fundamental switching frequency for switching the inverter. It will ensure the less load current disturbances and improvement in the performance dynamically. Hence anew pulse width modulation technique with high performance is introduced to overcome this issue.

Numerous modulation techniques have been suggested for MLI. These techniques are mainly classified as fundamental switching techniques, mixed switching techniques also high switching frequency switching techniques given in Figure 2.2.

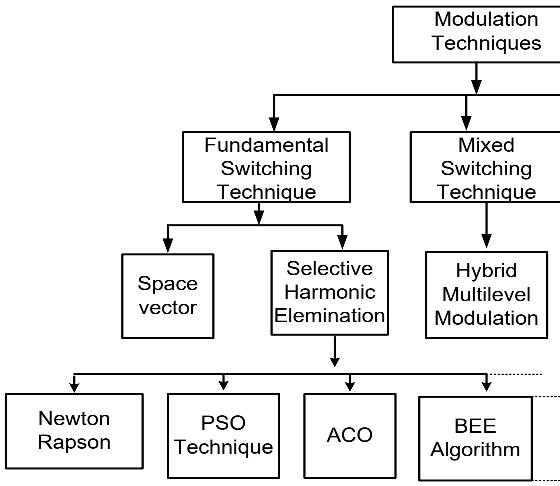

Fig. 2.2: Types of Different Modulation Methods

Another switching technique in inverter is high Switching Frequency scheme. In this scheme sinusoidal pulse width modulation (SPWM) technique and space vector (SVPWM) techniques are included. The average load voltage for every switching interval can be generated by SVPWM method which ensures the suitability of this method in high voltage applications. Pulse width modulation (PWM) technique has a feature of generating train of pulses relative to control. They are mostly used in forced commutated inverters serving variable-speed ac motor drive systems. Whereas I case of sinusoidal PWM (SPWM) technique, the generated control signals are sinusoidal, and the average generated output voltage will also vary sinusoidally.

Low switching scheme includes fundamental switching frequency scheme namely selective-harmonic elimination method and space vector control (SVC) method. In SVC method, a voltage vector (Vc) and reference voltage vector (Vref) are approximately equal so that the space error and designing modulation complexity can be reduced to a great extent. Hence the errors will be small as compared with the reference vector. The SVC method is more suitable for large number of voltage level inverters. Selective Harmonic Elimination is implemented with low frequency i.e. fundamental frequency. It will ensure the elimination of harmonics in the system and maintaining the fundamental component at desired level. In SHE technique, DC sources decide the number of levels of multilevel inverter which will again decide the quantity of eliminated harmonics in the system. In SHE technique, calculation of switching period is done through the preprogrammed angle arrangement fetched from the look-up table. Hence this technique is more attractive and popular day by day as it contains fundamental switching frequency with less switching losses.

3. SELECTIVE HARMONIC ELIMINATION

In selective harmonic elimination technique, both fundamental frequency and the switching frequency is equal. When inverter is switched with fundamental frequency, the switching losses are less and the efficiency of the system increases. To achieve this, the most important thing is to select proper optimized switching angles at the time of switching. Consider a case for cascaded H Bridge seven level multilevel inverter as shown in Figure 3.1and whose output voltage is shown in Figure 3.2.

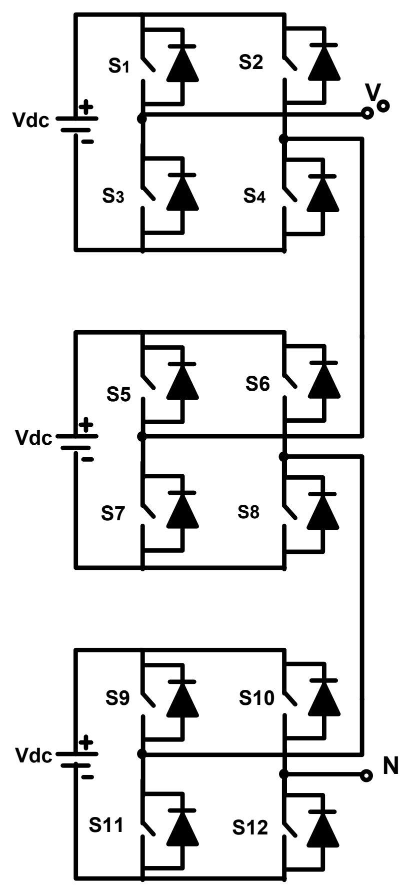

Fig. 3.1: H bridge seven level inverter

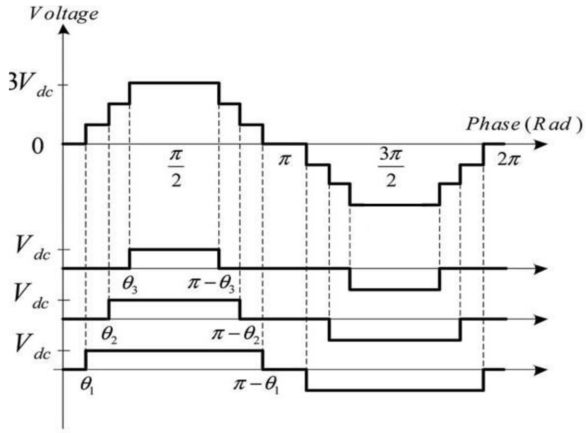

Fig. 3.2: Output waveform

For single phase seven level inverter, the output voltage expression is

$$V(wt) = \sum_{n=1}^{\infty} Vn \sin(nwt)$$

After fourier series, the above equations can be simplified as

$$V_1 = \frac{4Vdc}{\pi}[\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3)] = V_1^*$$
$$V_5 = \frac{4Vdc}{5\pi}[\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3)] = 0$$
$$V_7 = \frac{4Vdc}{7\pi}[\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3)] = 0$$

These equations are called as nonlinear transcendental equations. From the above equations it is clear that, the first equation defines the fundamental voltage component which is to be maintained at desired level. Whereas, second and third equation defines the fifth and seventh harmonic voltage to be reduced to zero. In these equations, switching angles α_1, α_2, $\alpha_3$decides the harmonics to be eliminated. The ratio of output fundamental voltage to maximum output voltage is the modulation index, m_a in multilevel inverters. So in terms of modulation index, all the three nonlinear equations are modified as following.

$$\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) = 3m_a$$
$$\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) = 0$$
$$\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) = 0$$

subject to $0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le \pi/2$

The solution to these nonlinear transcendental equations is determined through optimization methods.

3.1. Newton Raphson Algorithm

Obtaining solutions to nonlinear transcendental equations is very complicated and time consuming. Hence by iterative methods also we can get the solutions but the time of convergence may be more. One of the iterative method is Newton Raphson Algorithm. Only drawback with this method is selection of initial guess which is close to initial guess. It is implemented for obtaining the solutions with the following steps.

1. Assume any initial random angleα_0
2. Fix $m_a = 0$
3.Define objective function F(α_0) , B (m_a), Jacobian J (α_0).
4.Update angle α by small incremental change Δα

$$\Delta\alpha = J^{-1}(\alpha_0)[(B(m_a) - F(\alpha_0)]$$

5. Update angles as α(k+1) = α(k) + Δα(k).
6. Select switching angles in tolerable range.

$$\alpha_{(k+1)} = \cos^{-1}(abs(\cos(\alpha_{(k+1)})))$$

7. Go to steps (3) to (6) again with fixed iterations.
8.Revise modulation index 'm_a'
9. Repeat steps (2) to (8)
10. End of Algorithm and plot the results.

The switching pattern for single phase H-Bridge cascaded multilevel inverter is shown in Figure 3.3 below. So, the firing angles are computed offline by N-R method which fed to the switching devices.

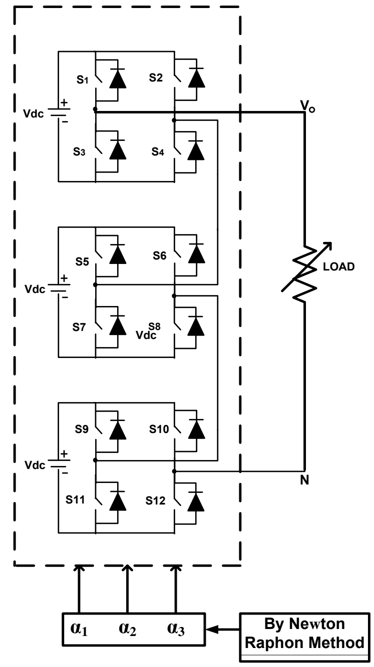

Fig. 3.3: Switching Model for inverter

After implementing N-R algorithm different three switching angles are obtained in case of single phase seven level inverter. Out of three switching angles, one is referred to fundamental voltage and other two angles are referred for elimination of lower order harmonics i.e. fifth and seventh harmonics in the system. The simulated results obtained for three different switching angles as shown in Figure 3.4 and Figure 3.5.

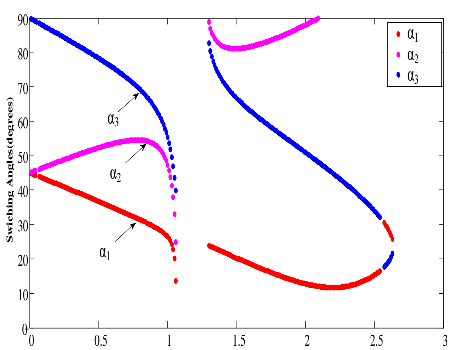

Fig. 3.4: Switching angles Vs '*ma*'

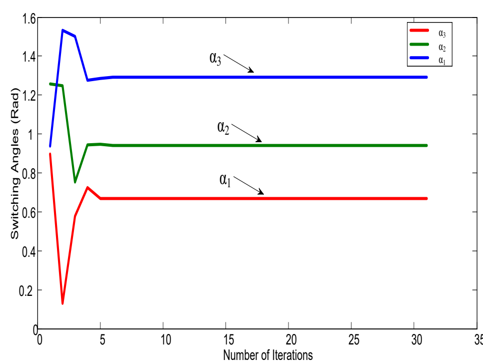

Fig. 3.5: Switching angles Vs iterations

The simulated results are obtained from MATLAB/Simulink environment for single phase 7-Level cascaded H Bridge inverter. H Bridge subsystem and firing system is shown in Figure 3.6 and Figure 3.7.

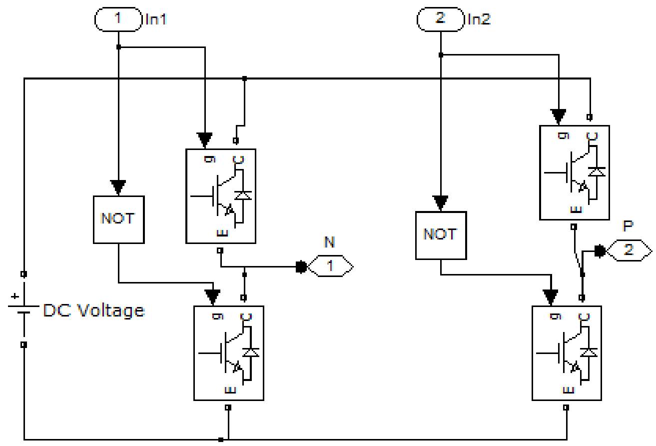

Fig. 3.6: H- Bridge subsystem

The three different switching angles α_1=11.50°, α_2=28.71°, α_3=57.10° are obtained from the iterative N-R algorithm. Switching pulses for respective switches(IGBT) in H-bridge system is given after comparing these constant values of switching angles with sine wave. These pulses are now provided to upper and lower switches of every leg of H bridge inverter without considering the dead band. The switching pulses obtained from simulation are shown in Figure 3.9.

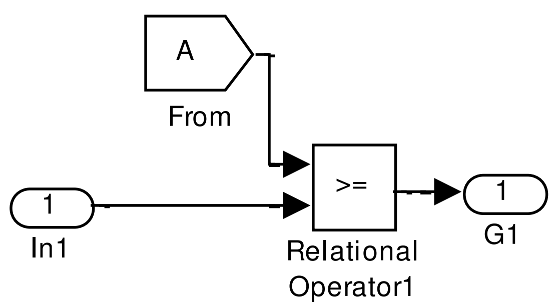

Fig. 3.7: Firing pulses generation

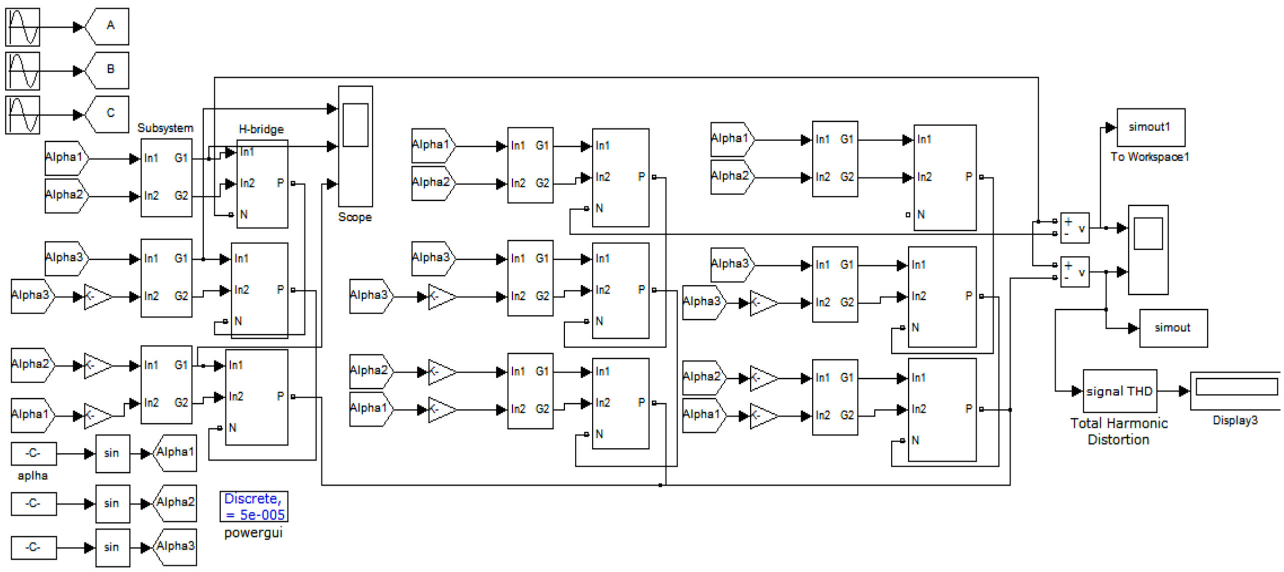

Fig. 3.8: Simulink Model

In Figure. 3.8, three phase inverter using H-Bridge blocks are shown. All are linked in series to build to form a entire three phase seven level multilevel inverter. The equivalent switching as shown in Figure 3.7 in MATLAB Simulink environment. Subsystem shows the total 3 H-Bridges/phase of seven level inverter. The firing pulses to the respective H-Bridges are supplied through switches S_1-S_4. After supplying input, a stepped waveform is received at the output side. Here simulation is done for 7-Level inverter. For more levels, more number of H-Bridge blocks can be further added.

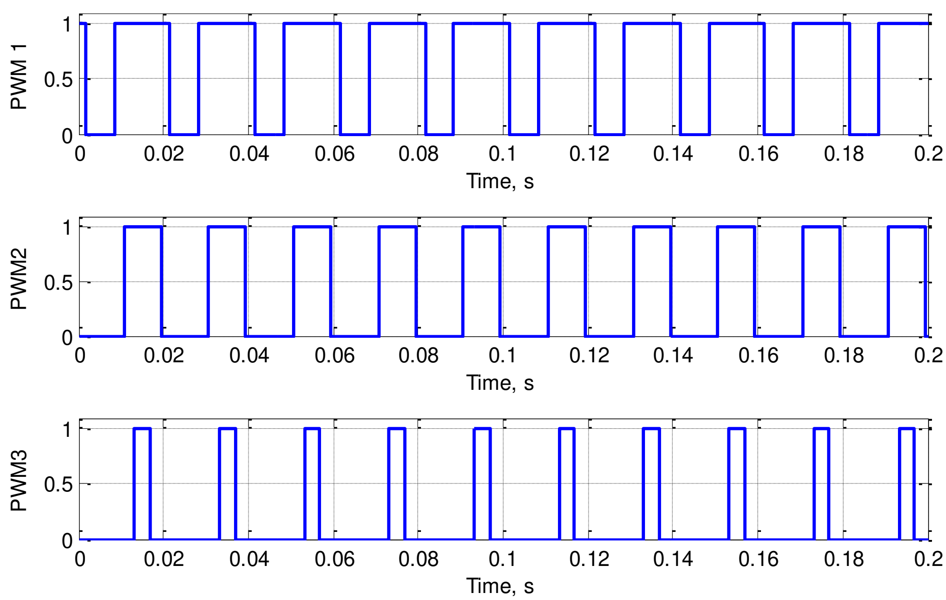

Fig. 3.9: PWM generation

After obtaining switching angles from N-R method, and MATLAB simulation, the phase output voltage and the harmonics and THD plot is shown in Figure 3.10and in Figure 3.11.

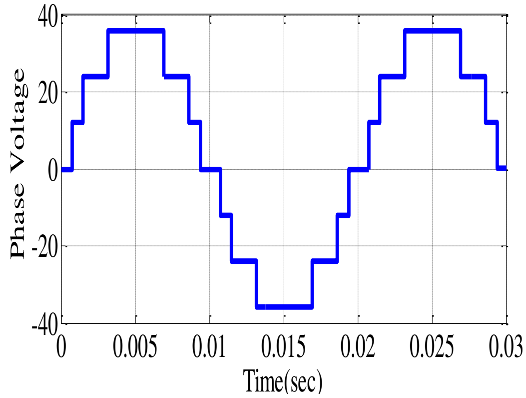

Fig. 3.10: Phase Voltage

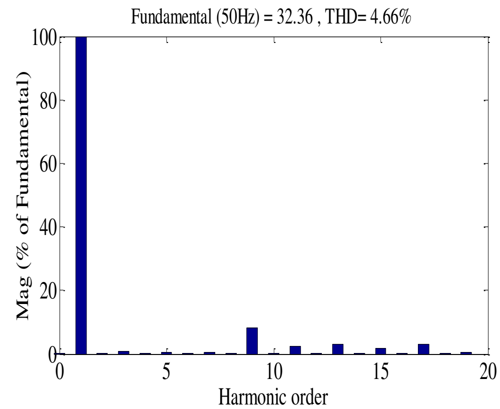

Fig. 3.11: FFT Plot

From the above simulation results, the phase output voltage is obtained for single phase seven level inverter. For this configuration 3- H bridges are constructed with 12V DC supply. Hence phase output voltage is obtained as 36V. But the FFT analysis shows that all the lower order harmonics are not completely eliminated and also the value for Total Harmonic Distortion (THD) is found to be 4.66%. Hence the main objective of SHE Technique is not completely satisfied with the only one algorithm. Hence there is a need of investigation of advanced algorithm to solve nonlinear transcendental equations including minimization of lower order harmonics along with THD respectively. A hybrid optimization algorithm is proposed in this monograph which is a combination of Newton Raphson algorithm and Ant Colony algorithm. Here output of ACO algorithm is fed as a input to the N-R algorithm and results are computed. Hence the dependency of exact initial guess in N-R algorithm is eliminated in Hybrid Optimization algorithm.

4. HYBRID OPTIMIZATION ALGORITHM

In hybrid optimization algorithm, combination of ACO and N-R algorithm is implemented and results are obtained for switching angles. The following steps are to be followed for hybrid optimization algorithm.

Step 1 : Define Objective Function

Step 2 : Define constraints

Step 3 : Find minimum best value

Step 4 :Initially run ACO algorithm for 4iterations

Step 5 :Feed output from ACO algorithm as a input for N-R algorithm.

Step 6 : Run N-R algorithm for convergence.

Step 7 :Obtain solution for switching angles

Step 8 :Stop the algorithm

The following Figure 3.11 shows the flowchart for hybrid algorithm.

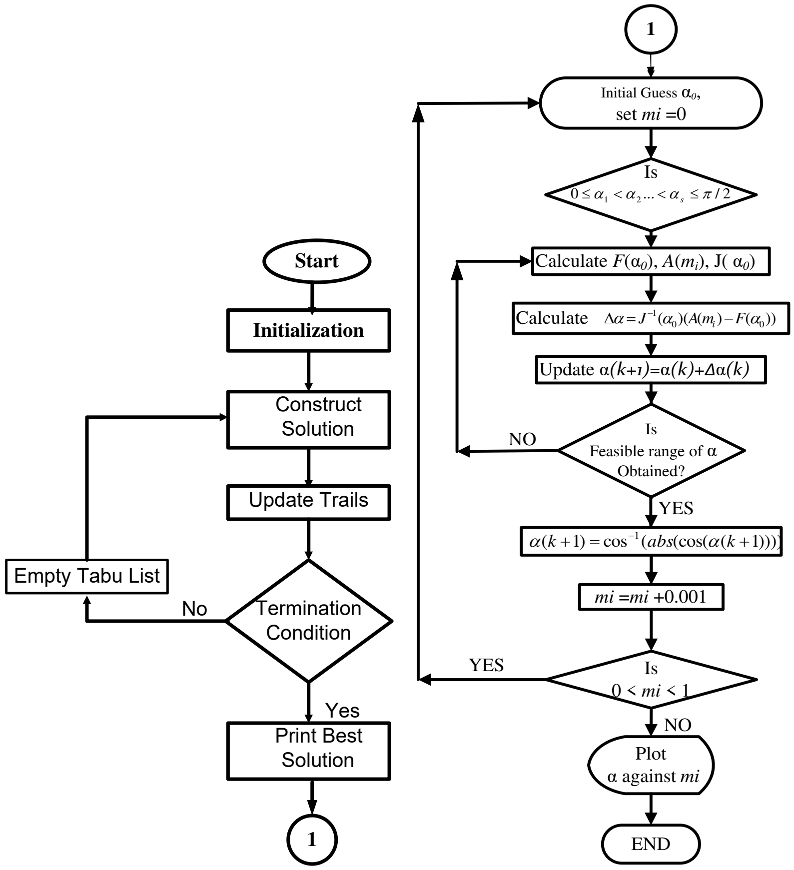

Fig. 3.11: Flowchart for hybrid algorithm

From this flowchart it is clear that the Ant Colony Optimization algorithm is first running for few cycles, then the output obtained from ACO algorithm is given as a input to the N-R algorithm. Hence dependency of random initial guess in N-R algorithm is somewhat eliminated with the proposed hybrid algorithm. These nonlinear equations are now resolved by hybrid algorithm. The different switching angles obtained through proposed hybrid algorithm are found to be $\alpha_1 = 14.26^\circ$, $\alpha_2 = 28.34^\circ$, $\alpha_3 = 41.15^\circ$.These angles are obtained for modulation index '*ma'* = 0.8. The solution set obtained after implementing hybrid algorithm provides the optimized values for switching angles. The different solution sets are obtained after implementing the algorithm as shown in Table 1. Only one solution set is to be selected at a time for simulation purpose which will solve the objective of retaining fundamental component at the desired level and reducing the lower order harmonics and THD simultaneously. Also by using these switching angles the lower order harmonics particularly odd harmonics i.e. fifth and seventh harmonics are comparatively very very less and can be eliminated easily. Also the Total Harmonic Distortion (THD) ratio is reduced greatly.

Table 1: Switching angles with m_a

M.I., m_a	α_1	α_2	α_3
0.61	5.71°	15.55°	21.61°
0.71	24.20°	23.56°	47.42°
0.75	18.49°	22.52°	58.60°
0.8	**14.26°**	**28.34°**	**41.15°**
0.81	19.12°	13.82°	41.15°
0.91	25.55°	27.70°	67.18°
0.95	23.03°	37.34°	59.28°
1.10	21.00°	39.34°	54.09°
1.5	28.89°	51.56°	60.60°

These obtained switching angles are plotted with respect to modulation index *'ma' a*nd as shown in Figure 3.12. Also the objective function is computed as minimum and shown in Figure 3.13. The phase output voltage of single phase seven level inverter is shown in Figure 3.14 and the harmonic profile of the system is shown in Figure 3.15.

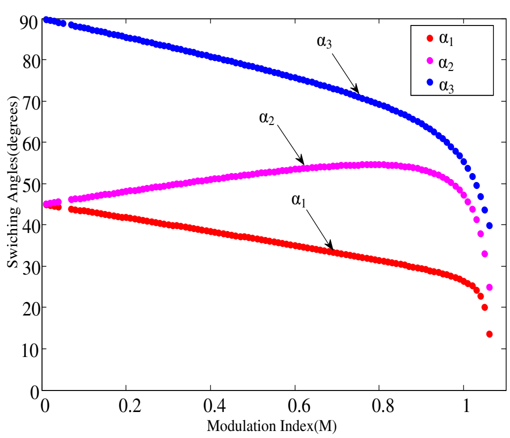

Fig. 3.12: Variation of Switching Angles

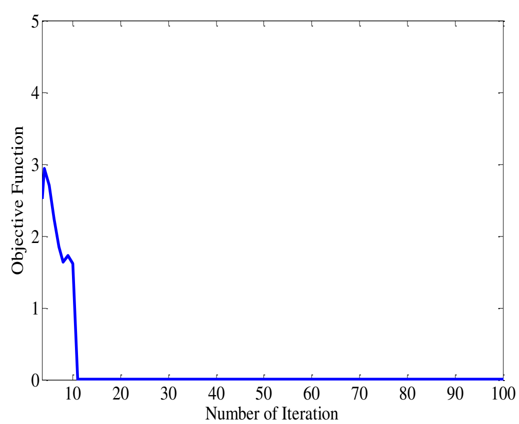

Fig. 3.13: Variation of Objective Function

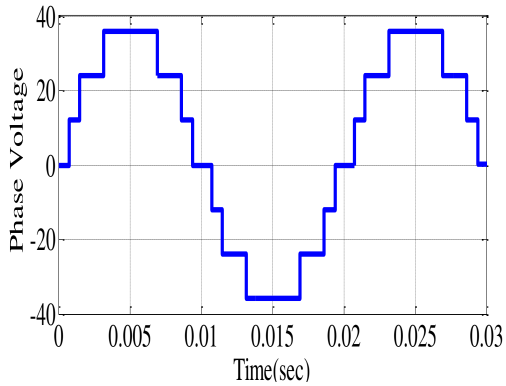

Fig. 3.14: Phase Output Voltage

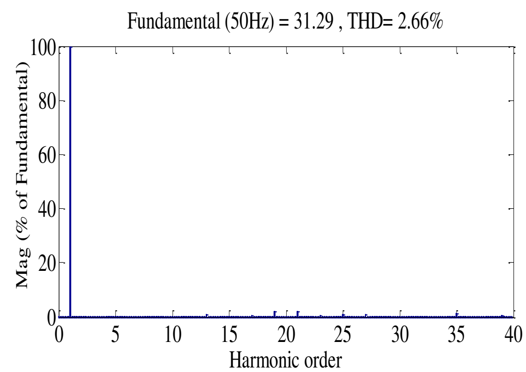

Fig. 3.15: FFT Plot

From the all above results, it is clear that the proposed hybrid algorithm is proved to be the effective algorithm for eliminating lower order harmonics and maintaining the fundamental component at the desired level. The results show the output voltage of single phase 7-level inverter is containing negligible harmonics with the desired output phase voltage. Also FFT analysis shows the fifth harmonic is found to be very less as h_5 = 0.02% and seventh harmonic is found to be h_7 = 0.01%. Also from the harmonic spectra the Total harmonic distortion (THD) is obtained as very less i.e. THD = 2.66% as compared to other iterative method. Also the harmonics are in accordance with IEEE 519 standard i.e. they are within tolerable range.

5. CONCLUSION

Multilevel inverters are proved to be the most significant device in medium power and high power applications. As far as renewable energy sources are concerned, DC to AC conversion is necessary. So multilevel inverters are generally satisfying this requirement which ensures the high efficiency. For obtaining sinusoidal output waveform, modulation techniques are implemented. But all modulation techniques cannot solve the issue of selective harmonic elimination. The high frequency modulation techniques which include generally sinusoidal pulse width modulation (SPWM) technique cannot improve the harmonic profile and gives the more switching losses. Many conventional algorithms cannot find all the solutions to SHE equations. Hence Solution to SHE equations are given by Hybrid algorithm which is investigated in this monograph.

Hybrid Algorithm is applied for obtaining optimized values of switching angles required for switching the power devices of single phase seven level multilevel inverter. Simulation of this cascaded H- Bridge inverter is done in MATLAB/ Simulink environment. This simulation is presented as a systematic approach for single phase seven level multilevel inverter. All the switching angles are computed for modulation index 0.8 and desired values are obtained. Owing to this proposed algorithm, all the lower order harmonics are eliminated easily and the desired fundamental voltage is obtained its value. All the simulated results show the effectiveness of hybrid algorithm. Convergence and finding solutions is very rapid in case of hybrid algorithm.

6. FUTURE SCOPE

In this monograph, analysis of single phase multilevel inverter is carried out with equal DC sources. Further extension of this work can be extended with asymmetrical configuration. Also this work is further extended to three phase multilevel inverter with separate input i.e. separate DC sources and solution to SHE equations can be found out by hybrid algorithm. Here only fifth and seventh harmonics are considered along with THD for elimination. Further study can be extended to eliminate different order harmonics with different modulation indices.

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