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PSO based Harmonic Reduction Technique for Wind Generated Power System

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Abstract - Converters are used in the utility interface of renewable energy system to reduce harmonic contents in line current/voltage and to increase reliability. These converters suffer from high level of Total Harmonic Distortion (THD) in the utility line currents/voltages which creates a lot of problems in the power system. In this paper selective harmonics are eliminated to reduce the THD, that is, the problem is to determine optimal switching angles for eliminate harmonics while maintaining the required fundamental currents/ voltages. The THD reduction is achieved by the help of multilevel inverter with equal separate dc sources using particle swarm optimization technique. This technique can be applied to multilevel inverters with any number of levels; as an example in this paper, an 11-level inverter is considered. Theoretical results are verified by experiments and simulations for an 11-level H-bridge inverter. Results show that the proposed method does effectively eliminate a great number of specific harmonics, and the output voltage is resulted in low total harmonic distortion.

I. INTRODUCTION

Consumption of energy based on fossil fuels is considered to be the major factor for global warming and environment degradation. The utilization of naturally occurring renewable energy sources as an alternative energy supply has been assuming more importance of less power generation utilizing solar rays, geothermal energy, wind force and wave force has become a reality. Research on performance improvement and cost reduction in such non-conventional energy conversion systems is being accorded the highest priority [1]. Wind generation has already been proposed to efficiently utilize the wind power which is prone to fluctuation every moment due to variation of wind speed.

If the wind turbine operates at variable rotational speed, the electric frequency of the generator varies and must therefore be decoupled from the frequency of the grid. This can be achieved by an inverter system. One disadvantage is the production of interharmonics. In general these interharmonics are generated by the inverter in the range of some kHz. Harmonics are a phenomenon associated with the distortion of the fundamental sinewave of the grid voltages, which is purely sinusoidal in the ideal situation. Harmonic disturbances are produced by many types of electrical equipment. Depending on their harmonic order they may cause different types of damage to different types of electrical equipment.

Harmonics must always be limited below threshold level prescribed by standards [2], both in their total harmonics distortion (THD) and in their individual magnitudes. Several techniques have been proposed to cancel out high amplitude harmonics to eliminate or reduce the need for filtering while meeting the standard requirements. The most interesting one includes programmed harmonic elimination and multilevel converters, which do not require high frequency switching as the PWM techniques provided in [3]. Therefore multilevel converters have attracted much attention in high power application. Among the different topologies for multilevel converters, the cascaded multilevel inverter has received special attention due to its modularity and simplicity of control [4]. There are different power circuit topologies for multilevel converters. The most familiar power circuit topology for multilevel converters is based on the cascade connection of an s number of single-phase full-bridge inverters to generate a $(2s + 1)$ number of levels. There are several literature to control the output voltage and to eliminate the undesired harmonics in multilevel converters with equal dc voltages, various modulation methods such as sinusoidal pulse width modulation (PWM), space vector PWM techniques as suggested by [5]-[7]. Another approach is to choose the switching angles so that specific higher order harmonics such as the 5th, 7th, 11th, and 13th are suppressed in the output voltage of the inverter. This method is known as Selective Harmonic Elimination (SHE) or programmed PWM

techniques in technical literature [8]-[9]. Such method solves a set of nonlinear equations by Newton-Raphson method whereas this technique needs a good initial guess. Therefore, the Newton-Raphson method is not feasible to solve the SHE problem for a large number of switching angles if good initial guesses are not available.

In this paper, Particle Swarm Optimization (PSO) technique is developed to deal with the SHE problem with equal dc sources. For a large number of switching angles, the proposed PSO approach reduces the computational burden to find the optimal solution compared with iterative methods. The proposed method solves the asymmetry of the transcendental equation set, which has to be solved in cascade multilevel inverters. Simulation results are provided for an 11-level cascaded multilevel inverter to show the validity of the proposed method.

II. CASCADE MULTILEVEL INVERTER:

The cascaded H-bridge multilevel inverter consists of a series of single-phase H-bridge inverter units, as shown in figure 1.

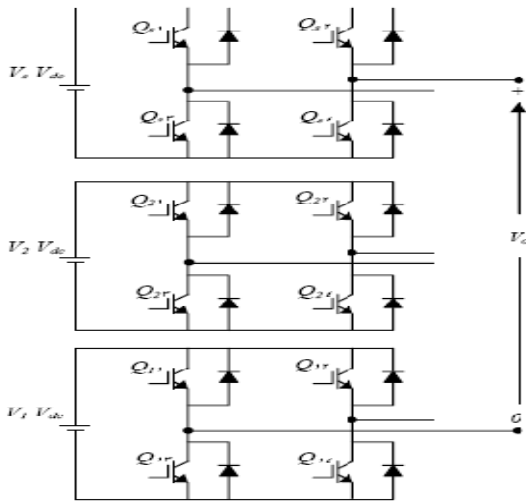


Fig. 1: Cascade H-bridge multilevel inverter

It is modular in nature and can be extended to any required number of levels. It is supplied from several separate dc sources (SDCSs), which may be obtained from batteries, solar cells, fuel cells or ultra-capacitors. Each SDCS is connected to a single-phase H-bridge inverter and can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$. This is accomplished by connecting the dc source to the ac output side by using different combinations of the four switches Q_1 , Q_2 , Q_3 , and Q_4 . The ac outputs of the modular H-bridge inverters are connected in series such that the synthesized voltage

waveform is the sum of all of the individual inverter outputs.

Figure 2 shows the generalized output voltage of cascaded H-bridge multilevel inverter with non-equal dc sources.

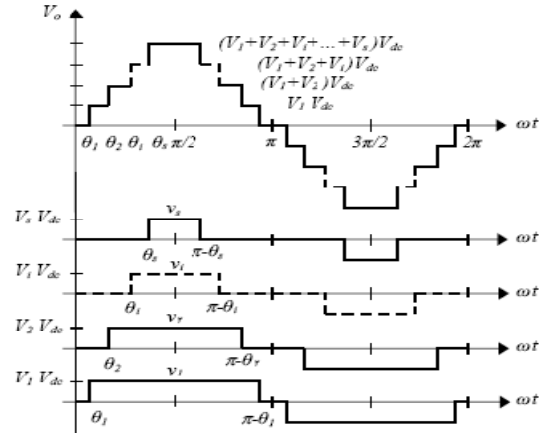


Fig. 2: Output voltage of cascaded H-bridge multilevel inverter

All semiconductor devices of the H-bridges are only switching at the fundamental frequency, and each unit generates a quasi-square waveform by phase-shifting its positive and negative phase legs' switching timings. The number of output voltage levels in a cascaded multilevel inverter is then $2s+1$, where s is the number of dc sources. Three-phase version of this circuit is also available by adding another two phases and connecting their neutral point together. The total output voltage is given by $v_o = v_1 + v_2 + v_3 + \dots + v_s$, with respect to switching angles $\theta_1, \theta_2, \dots, \theta_s$ and θ_s i.e. the multilevel inverter results in an output voltage that is almost sinusoidal with a low THD with each of the active devices subjected to a single dc source. This reduces both the voltage stress and the switching losses of the semiconductor devices, resulting in a better utilization and high overall efficiency.

Problem formulation: Assuming the equal DC source is applied to each of the inverter and taking into consideration the characteristics of the inverter waveform Fourier series expansion of stepped output voltage waveform of the multilevel inverter with equal dc sources can be expressed as:

$$V_o(\omega t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{dc}}{n} \{ \cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \cos(n\theta_4) + \cos(n\theta_5) \} \times \sin(\omega t) \tag{1}$$

Where V_{dc} is the nominal dc voltage and the variables $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ (firing angles) are given as $0 < \theta_1 < \theta_2 < \theta_3 < \theta_4 < \theta_5 < \pi/2$.

A set of solutions is obtainable by equating s - l harmonics to zero and assigning a specific value to the fundamental component, as given below:

$$\begin{aligned} \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5) &= m \\ \cos(3\theta_1) + \cos(3\theta_2) + \cos(3\theta_3) + \cos(3\theta_4) + \cos(3\theta_5) &= 0 \\ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) + \cos(5\theta_5) &= 0 \\ \cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3) + \cos(n\theta_4) + \cos(n\theta_5) &= 0 \end{aligned} \quad (2)$$

Where $m = V_1/(4V_{dc}/\pi)$ and the modulation index $m_a = m/s$.

For 11 level inverter when $s=5$, then 3rd, 5th, 7th, 9th order harmonics will be eliminated if single phase supply is given but if the power supply is in 3 phase then triple harmonics are eliminated automatically.

The main objective is to minimize the THD. The objective function to minimize the THD is given as

$$F(t) = \frac{\sqrt{\sum_{n=3,5,7}^{49} (V_n)^2}}{V_1} \quad (3)$$

Subject to the firing angles $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ are within the limit given as $0 < \theta_1 < \theta_2 < \theta_3 < \theta_4 < \theta_5 < \pi/2$. Where V_1 is the fundamental voltage and V_n is the n th order harmonics voltage.

In this paper the minimum value of THD can be achieved by the Particle Swarm Optimization (PSO) technique.

III. PARTICLE SWARM OPTIMIZATION:

PSO is a simple and efficient population-based optimization method proposed by Kennedy and Eberhart (1995). PSO is motivated by social behavior of organisms such as fish-schooling and bird-flocking. In PSO, potential solutions called particles fly around in a multidimensional problem space. A population of particles is called a swarm. Each particle in a swarm flies in the search space towards the optimum or a quasi-optimum solution based on its own experience, experience of nearby particles, and global best position among particles in the swarm. Let us define a search space S as n -dimension while the swarm consists of N particles. At time ' t ', each particle ' i ' has its position defined by $X_t^i = \{x_1^i, x_2^i, \dots, x_n^i\}$ and a velocity defined

by $V_t^i = \{v_1^i, v_2^i, \dots, v_n^i\}$ in variable space S . The position and velocity of each particle change with time. The velocity and position of each particle in the next generation (time step) can be calculated as

$$V_{k+1}^i = \omega V_k^i + c_1 \times \text{rand}() \times (Pbest_k^i - X_k^i) + c_2 \times \text{rand}() \times (Gbest^i - X_k^i) \quad (4)$$

$$X_{k+1}^i = X_k^i + V_{k+1}^i \quad i = 1, 2, \dots, N \quad (5)$$

The acceleration constant c_1 called cognitive parameter pulls each particle towards local best position whereas constant c_2 (called social parameter) pulls the particle towards a global best position. In the equation $\text{rand}()$ is a random values uniformly distributed within $[0, 1]$. The inertia weight w is an important factor for the PSO's convergence. It is used to control the impact of the previous history of velocities on the current velocity. A large inertia weight factor facilitates global exploration (*ie.* searching of a new area) while a small weight factor facilitates local exploration. Therefore, it is wise to choose a large weight factor for initial iterations and gradually reduce the weight factor in successive iterations. The modified velocity, position and its usage in the PSO search mechanism for individual particle ' i ' is illustrated in Figure 3.

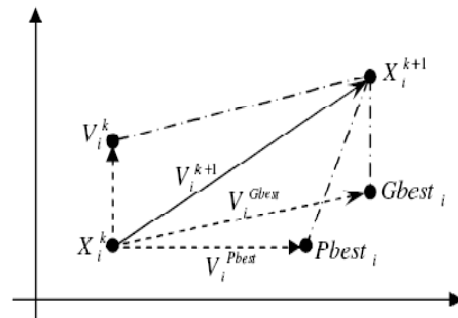


Fig. 3: Concept of modification of a searching point in PSO

- Where X_k : current position of the particle,
 X_{k+1} : modified position of the particle,
 V_k : current velocity of particle,
 V_{k+1} : modified velocity of particle,
 $Pbest$: velocity based on personal best
 $Gbest$: velocity based on global best

PSO Algorithm for minimizing the THD:

Let $\theta^i = [\theta_1^i, \theta_2^i, \dots, \theta_3^i]$ be a trial vector representing the i^{th} particle of the swarm to be evolved.

The elements of θ^i are the solutions of the harmonic minimization problem, and the d^{th} element of that is corresponding to the d^{th} switching angle of the inverter. The step-by-step procedure to solve the SHE problem with equal dc sources to minimize the THD is as follows.

1. At the first step, the required parameters of the algorithm such as population size M , maximum iteration number $intermax$, etc., are determined and the iteration counter is set to 1.
2. Each variable (particles) in the population is randomly initialized between 0 and $\pi/2$; similarly, the velocity vector of each particle has to be generated randomly from $-V_{\max}$ to V_{\max} .
3. Each particle is evaluated to fit in the objective function given in equation (3).
4. In the minimization process of equation (3), if the current position of the i^{th} particle is better than its previous personal best position, replace P_{best}^i with the current position X^i .
5. From the personal best of the particle if the best position of the personal bests of the particles is better than the previous position called global best, then replace the present global best with the previous one.
6. Update the velocity and position vector based on equation (4) and (5) and repeat the process to reach the optimal solution.
7. If the iteration counter reaches maximum set value stop the process to obtain the final result; else, increase the iteration counter and go back to step(3) and repeat the whole process.

IV. SIMULATION RESULT:

The THD minimization problem is solved by PSO technique and the program was developed in MATLAB. For test case the simulation results are presented for a single phase 11-level cascaded H-bridge inverter. The THD of output line voltage upto 49th order harmonics with modulation index $m=0.47$ was calculated and it was around 6% when 10 volt dc supply was given to the inverters. The optimal switching angle for the above THD are $\theta_1 = 5.2338$, $\theta_2 = 16.3852$, $\theta_3 = 30.9033$, $\theta_4 = 42.9065$ and $\theta_5 = 62.6564$. The %THD calculated by proposed approach is better than the result provided in reference [4].

The Fourier transform (FFT) analysis of the above THD calculation is shown in figure 4.

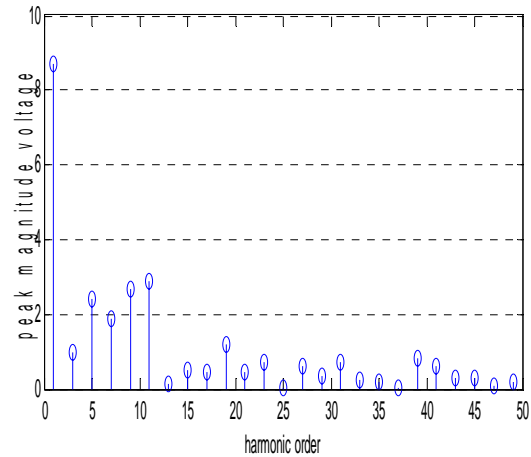


Fig. 4 : FFT analysis of the 11 level cascaded inverter

It has been seen that the magnitude of 3rd, 5th, 7th, 9th and 13th order harmonics are negligible.

The output line voltage waveform of the system is shown in the figure 5.

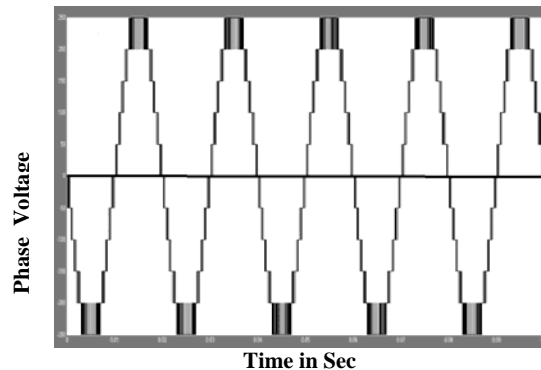


Fig. 5: Output Waveform of line voltage with respect to time

V. CONCLUSION

The PSO technique to minimize the total harmonics distortion (THD) with the help of selected harmonics elimination (SHE) procedure with equal dc sources in H-bridge cascade multilevel inverter is implemented in this paper. The proposed method is able to find the optimum switching angles in a simple manner. The proposed PSO technique minimizes the computational burden and has smooth convergence criteria than other methods. A complete analysis for 11-level inverter has been presented and it is shown that a significant amount of THD reduction can be attained which is within the prescribed IEEE limits.

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