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Elimination of lower order harmonics in Voltage Source Inverter feeding an induction motor drive using Evolutionary Algorithms

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ABSTRACT

Selective Harmonic Elimination technique is one of the control methods applied in Voltage Source Inverters to eliminate the harmonics. However, finding the solutions for the harmonic reduction is a difficult problem to be solved. This paper presents an efficient and reliable Evolutionary Algorithms based solution for Selective Harmonic Elimination (SHE) switching pattern to eliminate the lower order harmonics in Pulse Width Modulation (PWM) inverter. Determination of pulse pattern for the elimination of lower order harmonics of a PWM inverter necessitates solving a system of nonlinear transcendental equations. Evolutionary Algorithms are used to solve nonlinear transcendental equations for PWM–SHE. In this proposed method, harmonics up to 19th are eliminated using Evolutionary Algorithms without using dual transformer. The experimental results are obtained and are validated with simulations using PSIM 6.1 and MATLAB 7.0.

1. Introduction

Elimination of harmonics has been the subject of intensive research in power electronic equipments. The usage of power electronic equipments has increased in recent years in industrial and consumer applications. Such loads draw the nonlinear sinusoidal current and voltage from the source (IEEE Recommended Practices & Requirements for harmonic control in Electrical Power Systems, 1992; Wagner, 1993). These nonlinear loads change the sinusoidal nature of the AC current, thereby resulting in the flow of harmonic currents in the AC power system. These harmonics flow through the power system, where they can distort the supply voltage, over load electrical distribution equipments and resonate with power factor correction capacitors.

The power electronic equipments use Pulse Width Modulation (PWM) and in recent years, most of the applications are dominated by PWM inverters due to their ability of providing both voltage and frequency control at one stage and generating output voltage and current waveform with low harmonic distortion. Different types of feed forward and feedback Pulse Width Modulation schemes having relevance for industrial application have been widely discussed (Holtz, 1992). The Pulse Width Modulated inverter is most favored one for industrial application. The control scheme of PWM inverters are broadly classified as programmed PWM inverter and sinusoidal PWM inverter. Sinusoidal PWM is not suited for microprocessor based implementation because of various sinusoidal voltages and frequencies are required in the system.

Eliminating lower order harmonics using Programmed PWM (Sun & Grotsotollen, 1992) generates high quality output spectra, which in turn results in minimum current ripples, thereby satisfying several performance criteria and contribute to overall improved performance. Performance characteristics of a rectifier/inverter power conversion scheme largely depend on the choice of the particular Pulse Width Modulation strategy employed. Programmed PWM techniques optimize a particular objective function, such as selective elimination of harmonics and therefore are the most effective means of obtaining high performance.

The programming PWM schemes are applied for single and three phase inverters (Enjeti, Ziogas, & Lindsay, 1990), thereby providing the framework and guidelines for the selection of the appropriate technique for each application. Also provide the guidelines for solving nonlinear equations associated with each one of the harmonic elimination PWM's for small and very large degree of freedom. Third harmonic current injection technique (Eltamaly, 2008) is used to reduce the line current harmonic content and increasing the power factor of the controlled and uncontrolled converters.

An optimized PWM technique was proposed in Shi and Li (2005), to reduce harmonic distortion and to spread harmonic energy for high switching frequency inverters. Optimization algorithms are becoming increasingly popular in engineering design activities, where the emphasis is on the maximizing or minimizing certain goal primarily because of the availability and affordability

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of high speed computers. They are extensively used in engineering design problems. The 5th and 7th harmonics are eliminated in the five level SHE PWM converters by optimal switching transition through the Fourier theory (Dohidah, Agelidis, & Rao, 2006).

A direct minimization of nonlinear transcendental trigonometric Fourier function in combination with a random search was illustrated to obtain multiple sets of solution for uni-polar PWM circuits (Agelidis, Balouktsis, & Cossar, 2008). Generalized methods are developed for eliminating a fixed number of harmonics in the half bridge and full bridge inverter (Chiasson, Tolbert, McKenzie, & Du, 2004; Patel & Hoft, 1973, 1974; Wells, Nee, Chapman, & Krein, 2005) output waveforms and solutions are presented for eliminating up to 5th harmonics.

The minimization of objective function used for SHE was done using traditional mathematical techniques such as Conjugate Gradient Descent method (CGD) (Maswood, Wei, & Rahman, 2001) and Newton Raphson method (NR) (Sun, Beineke, & Grotsllen, 1994). These methods need initial values to obtain the objective function and are based on differential information, so they may produce local minimum solution which leads to undesirable pattern.

GA is one of the non-traditional programming which provides solution to nonlinear mathematical problems. GA is inspired by the mechanism of natural selection, in which stronger individuals are likely to survive in a competing environment. GA uses a direct analogy of such selection. EP is a technique in the field of evolutionary computation. It is a powerful and general global optimization method which does not depend on the first and second differentials of the objective function of the problem to be optimized. The EP (Sinha, Chakrabarti, & Chattopadhyay, 2003) technique is based on the mechanism of natural selection.

As demonstrated in Maswood and Wei (2005), GA is applied to eliminate the lower order harmonics in power converter with dual transformer and 12 pulse rectifier. The 3rd and other triplen harmonics can be ignored if the machine has an isolated neutral. A Genetic Algorithm optimization technique is applied to determine the switching angles for a cascaded multilevel inverter (Ozpineci, Tolbert, & Chiasson, 2005) which eliminates specified higher order harmonics while maintaining the required fundamental voltage. A seven level inverter is considered and optimum switching angles are calculated offline to eliminate 5th and 7th harmonics.

Genetic Algorithm based approach is used for the optimal design of passive shunt compensator (Zacharia, Menti, & Zacharias, 2008) when non-ideal, non-sinusoidal voltage source supplies a linear load. No preliminary calculations are necessary to identify compensator parameter values which would create resonant conditions at the harmonic frequencies of the source. GA and CGD methods are used to find the switching pattern for SHE to eliminate rectifier low input current harmonics without having any initial guess for the switching pattern. GA is used to provide the initial values (Shen & Maswood, 2000). A five level PWM–SHE technique for Voltage Source Converters (Maswood, Neo, & Rahman, 2001) has been proposed by finding switching transitions without quarter and half wave symmetry for the input waveform to remove harmonics up to 7th with the help of GA.

NR and GA are adopted to reduce the lower order line current harmonics by developing 'N' number of pulses per half cycle (Sundareswaran & Chandra, 2002). Genetic Algorithm and Particle Swarm Optimization are applied to compute the switching angles in a three phase seven level inverters (Barkati, Baghali, Berkouk, & Boucherit, 2008) to produce the required fundamental voltage, while at the same time, specific harmonics are eliminated. 5th, 7th and multiples of 3rd harmonics are suppressed in line-to-line voltage. The line voltage total harmonic distortion increases slightly when the modulation index decreases.

The power circuit for Voltage Source Converter drive system is given in Fig. 1. DC voltage is obtained using six pulse Voltage Source Rectifier. The rectifier is connected to Voltage Source Inverter through DC link capacitor and DC link Inductor.

This paper presents an Evolutionary Algorithms method for reduction of line voltage harmonics in PWM inverter without dual transformer. The use of dual transformer and 12 pulse rectifier are avoided to eliminate the characteristic harmonics 5th, 7th, 11th, 13th, 17th and 19th for six pulse rectifier. The objective is achieved by determining the switching pattern for the three phase Inverter using Genetic Algorithm and Evolutionary Programming methods. Experimental results and simulation were carried out and validated using MATLAB 7.0 and PSIM 6.1.

2. Problem formulation

The Fourier coefficients of the PWM–SHE switching pattern for a three phase line to neutral voltage are given by Eq. (1).

$$a_n = \frac{4}{n\pi}\left[\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k)\right] \qquad (1)$$
$$b_n = 0$$

Eq. (1) has N variables (α_1 to α_N) and a set of solution are obtained by equating $N-1$ harmonics to zero and assigning a specific value of the fundamental amplitude α_1, through Eq. (2).

$$\begin{aligned}
f_1(\alpha) &= \frac{4}{\pi}\left[\sum_{k=1}^{N}(-1)^{k+1}\cos(\alpha_k)\right] - M = \varepsilon_1\\
f_2(\alpha) &= \frac{4}{5\pi}\left[\sum_{k=1}^{N}(-1)^{k+1}\cos(5\alpha_k)\right] = \varepsilon_2\\
&\cdots\cdots \quad \cdots\cdots \quad \cdots\cdots\\
f_N(\alpha) &= \frac{4}{n\pi}\left[\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k)\right] = \varepsilon_N
\end{aligned} \qquad (2)$$

where the variables $\varepsilon_1 - \varepsilon_N$ are the normalized amplitude of the harmonics to be eliminated. The objective function of PWM–SHE technique is to minimize the harmonic content in the inverter line current and it is given in Eq. (3).

$$F(\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_N) = \varepsilon_1^2 + \varepsilon_2^2 + \cdots + \varepsilon_N^2 \qquad (3)$$

Subjected to the constraint equation (4), $0 < \alpha_1 < \alpha_2 < \alpha_3$

$$< \alpha_4 < \alpha_5 \cdots \alpha_N < \frac{\pi}{2} \qquad (4)$$

for Quarter-wave symmetric pulse pattern. In the proposed method α_1, α_2, α_3, α_4 and α_5 solutions are expected with elimination of 5th, 7th, 11th, 13th, 17th and 19th harmonics.

3. Harmonic elimination using Genetic Algorithm method

Genetic Algorithms are numerical optimization algorithms based on the principles inspired from the genetic and evolution mechanisms observed in natural systems and population of living beings. Binary encoding GA is dealing with binary strings, where the number of bits of each string simulates the genes of an individual chromosome, and the number of individuals constitutes a population. Each parameter set is encoded into a series of a fixed length of string symbols usually from the binary bits, which are then concatenated into a complete string called chromosome. Substrings of specified length are extracted successively from the concatenated string and are then decoded and mapped into the value in the corresponding search space. Generally, GA implementation comprises the procedures of initial population generation, fitness

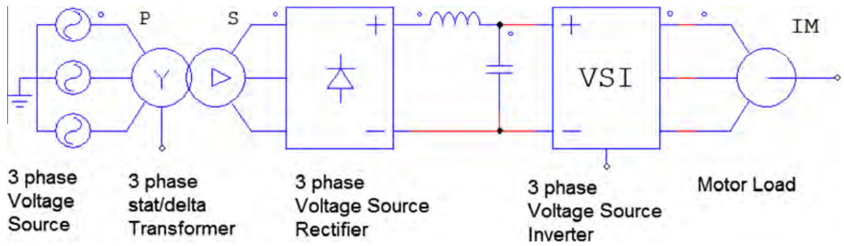

Fig. 1. Power circuit of Voltage Source Converter drive system.

evaluation and genetic operations of selection, crossover and mutation.

In this paper, an attempt has been made to determine the most optimal switching pattern to eliminate the lower order line voltage harmonics in the Voltage Source Inverter. The implementation of GA algorithm is given below.

3.1. Step 1: Initialization

The initial population (P_i) of N chromosomes is generated with randomly selected initial individual switching angles. The generated switching angles are distributed uniformly between their minimum and maximum limits by satisfying Eq. (4). Each chromosome is coded as binary string which is mapped into a real number.

3.2. Step 2: Fitness of the candidate solutions

The Fitness function Value (FV) in this case attempts to minimize the objective function using the given Eq. (5). Fitness function Value can be calculated for each chromosome in the population.

$$FV = \frac{1}{1 + f(\alpha)} \tag{5}$$

where $f(\alpha)$ can be calculated using Eq. (2).

When the switching angles violate the minimum and maximum value, the penalty factor is introduced to avoid violation. The alpha limit violation can be dealt with the violation coefficient value using Eq. (6).

$$Vio\_coeff = (1 + [\alpha_{(i-1)} - \alpha_{(i)}]) \times \rho \tag{6}$$

where ρ is the penalty parameter, $\alpha_{(i)}$ is the ith value of α.

In such cases, the objective function is calculated by multiplying with the *Vio_coeff* value. After computing the Fitness function Value of each individual chromosome, the parents then undergo genetic operation of selection, crossover and mutation. After the evaluation of the initial randomly generated population, GA begins to create new generation. The process of selection and mating of individuals continues until a new generation is reproduced.

3.3. Step 3: Selection

Chromosomes from the parent population are selected in pairs with a probability proportional to their fitness to replicate and form offspring chromosomes. This selection scheme is known as Roulette Wheel selection. Each chromosome selects a percentage of Roulette Wheel equal to its normalized fitness value. The chromosomes that will be copied are selected with rates proportional to their fitness.

3.4. Step 4: Crossover

In accordance with the crossover rate, randomly chosen pairs of parent chromosome from the population produced after reproduction undergo crossover to produce offspring. A random cut point is selected for fixed length chromosomes, the cut point between the first and the last gene of the present chromosomes. For variable length chromosomes, the cut point is between the first and the last gene of the present chromosome with minimum length.

3.5. Step 5: Mutation

In accordance with the mutation rate, some chromosomes from the population produced after crossover will undergo mutation. Random genes are selected and altered from 0 to 1 or vice versa. In this way, the old population is replaced with the improved population generated through steps 2–5.

3.6. Step 6: Elitism

The crossover and mutation for the two chromosomes are repeated until all of the chromosomes of the parent generation are replaced by the newly formed chromosomes. The best chromosome of the parent generation and the best chromosome found in all of the previous generations are copied intact to the next generation, so that the possibility of their destruction through a genetic operator is eliminated.

3.7. Step 7: Termination criterion for GA

The above said procedure from steps 2 to 6 is repeated until the maximum iteration count is reached.

4. Harmonic elimination using Evolutionary Programming method

Evolutionary Programming is powerful global optimization technique, has proved itself effective to handle complex optimization problem. EP starts with a population of randomly generated candidate solution which evolves towards the better solution over a number of iterations. It uses the probabilistic rules to explore the complex search space.

The primary objective of the PWM–SHE technique is to determine the most optimal switching pattern to eliminate the harmonics in the Voltage Source Inverter. Evolutionary Programming is a probabilistic search technique, which generates the initial parent vectors distributed uniformly in intervals within the limits and obtains global optimum solution over number of iterations. The main stages of this technique are initialization, creation of offspring vectors by mutation, competition and selection of best vectors to evaluate best fitness solution. The implementation of EP algorithm is given below.

4.1. Step 1: Initialization

The initial population comprises of combination of all the switching angles generated after satisfying Eq. (4). The elements of parent vectors (P_i) are the various alpha values of generated population distributed uniformly between their minimum and maximum limits.

4.2. Step 2: Fitness of the candidate solutions

The Fitness function Value (*FV*) in this case attempts to minimize the error between the actual angles to the exact values of the same, which is assumed to be the alpha values of the corresponding minimum objective function.

4.3. Step 3: Creation of offspring vector by mutation

An offspring vector P_i' is created from each parent vector by adding Gaussian random variable with zero mean and standard deviation σ_i, denoted as $N(0, \sigma_i^2)$.

$$P_i' = P_i + N(0, \sigma_i^2) \quad \text{for } i = 1, 2, \ldots, N_p - 1 \tag{7}$$

where $\sigma_i = \beta . \frac{f_i}{f_{\min}}(P_{i-\max} - P_{i-\min})$. N_p is the number of population; β is the scaling factor; f_i is the fitness of the ith individual; $f_{\min}$ is the minimum fitness of the entire population.

The created offspring vector must satisfy the minimum and maximum generation limits of the units. After adding a Gaussian random number to the parents, the element of offspring may violate the constraint given by (4).

These violations are dealt as follows:

$$P_i' = \begin{cases} P_{i-\min} & \textit{if } P_i' < P_{i-\min}' \\ P_{i-\max} & \textit{if } P_i' > P_{i-\max}' \end{cases} \tag{8}$$

4.4. Step 4: Selection and competition

In the competition stage, a selection mechanism is used to produce a new population from the existing population and the population is created by mutation. The selection technique used is the Stochastic Tournament method described in the following.

The parent solution P_i along with their corresponding offsprings formed by mutation P_i', each under goes a series of N_t tournaments with randomly selected opponents. Each individual is assigned a score w_s according to:

$$w_s = \sum_{i=1}^{N_t} w_i$$
$$w_t = \begin{cases} 1 \text{ if} & u_1 > \frac{\Delta f_s}{\Delta f_s + \Delta f_r} \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where

$$\Delta f_s = f_s - f_{\min}$$
$$\Delta f_r = f_r - f_{\min}$$

f_s is the objective function of the individual under consideration, f_r is the objective function of randomly selected opponent individual and $f_{\min}$ is the minimum objective function of an individual within the two population. The opponent is chosen at random from $2 * N_p$ individuals based on $r = [2 * N_p * u_2 + 1]$. u_1, u_2 are uniform random numbers in the interval [0,1]. Individuals are ranked in descending order of their corresponding w_s score. The first N_p individuals are selected and transcribed along with their corresponding fitness values to be the parents of the next generation.

4.5. Step 5: Termination criterion for EP

The above procedure from steps 2 to 3 are repeated until maximum iteration count is reached.

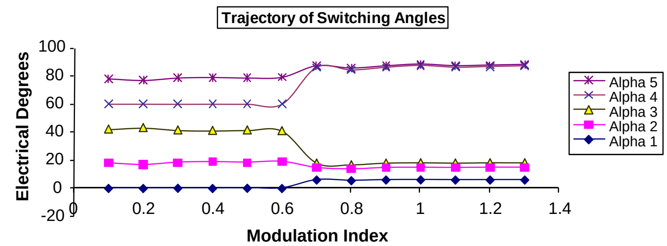

Fig. 2a. Switching angles versus the modulation index (using GA).

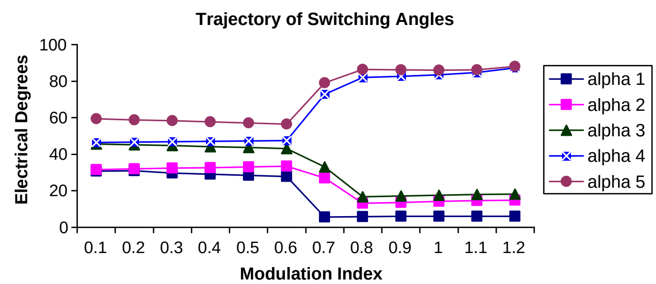

Fig. 2b. Switching angles versus the modulation index (using EP).

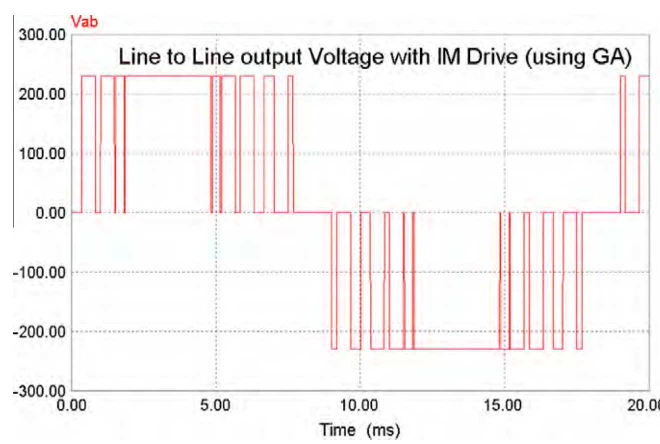

Fig. 3a. Simulated inverter output voltage waveform for induction motor drive (using GA).

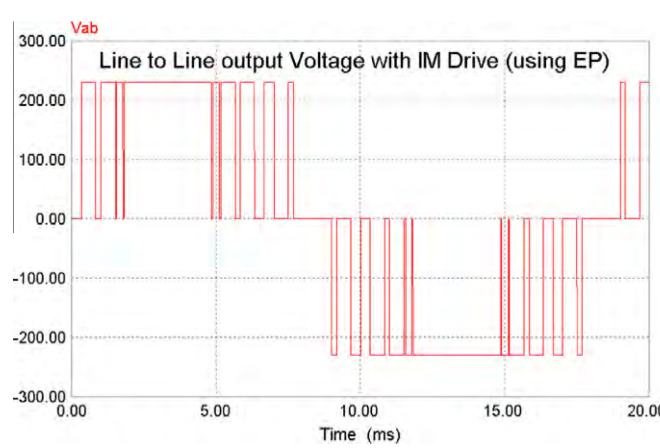

Fig. 3b. Simulated inverter output voltage waveform for induction motor drive (using EP).

5. Optimization results

After solving the five nonlinear functions of Eq. (2) simultaneously using MATLAB 7.0 optimization toolbox, five angles are obtained. This process is repeated for the various modulation indices from 0.1 to 1.3. The trajectory of calculated switching angles of proposed PWM–SHE switching pattern using GA is shown in Fig. 2a.

The trajectories of the switching angles calculated using genetic algorithm are almost smooth for α_1, α_2 and α_5 over the whole range of possible modulation indices. There is an abrupt rise of 25° for α_4 and fall of about 25° for α_3 in the modulation index 0.7. All five angles are smooth after $M = 0.8$.

The trajectory of calculated switching angles of proposed PWM–SHE switching pattern using Evolutionary Programming is shown in Fig. 2b. In this approach, the trajectory of the angles are smooth from $M = 0.1$ to $M = 0.6$ and from $M = 0.8$ to $M = 1.3$. We can find in the trajectory that there is a sudden change in the path of trajectory at $M = 0.7$.

All these characteristics bring unpredictability to traditional algorithms that require precise initial values to guarantee convergence. In this paper both Genetic Algorithm and Evolutionary Programming are used because of discrete nature of harmonics to be eliminated.

6. Simulation and experimental results

After obtaining the switching angles through the MATLAB using Evolutionary Algorithms, the proposed system is developed using PSIM 6.1. The circuit uses three 230 V single phase AC supply source which are connected to the star connected primary winding of the three phase star/delta transformer. The six pulse Voltage

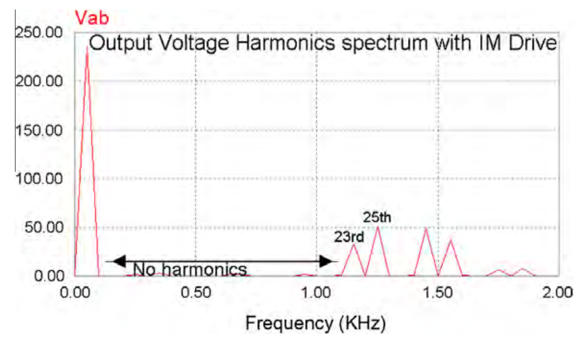

Fig. 5a. Harmonics spectrum for inverter output voltage for induction motor drive (after eliminating 5th, 7th, 11th, 13th, 17th and 19th harmonics using GA) at $M = 0.9$.

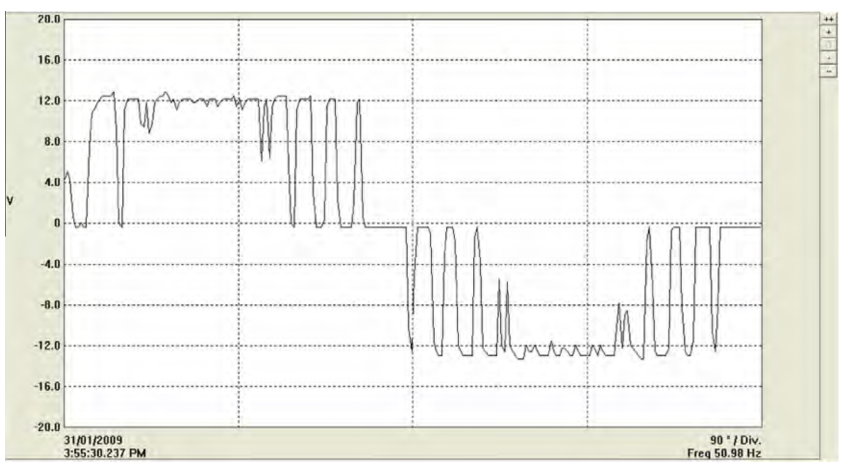

Fig. 4a. Experimental inverter output voltage waveform for induction motor drive (using GA).

Fig. 4b. Experimental inverter output voltage waveform for induction motor drive (using EP).

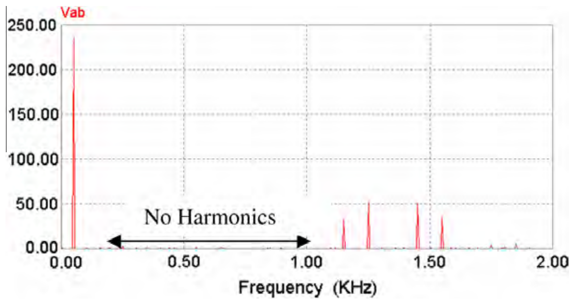

Fig. 5b. Harmonics spectrum for inverter output voltage for induction motor drive (after eliminating 5th, 7th, 11th, 13th, 17th and 19th harmonics using EP) at $M = 0.9$.

Source Rectifier is developed using six diodes as bridge. This rectifier is being connected to Voltage Source Inverter through the Inductor and Capacitor which is acting as a DC link between the rectifier and inverter. The load to the proposed converter is a three phase squirrel cage induction motor. In this method, dual transformer and 12 pulse rectifier are avoided to eliminate certain lower order harmonics. High capacity dual transformer connections are also avoided to eliminate the lower order harmonics using Genetic Algorithm and Evolutionary Programming approach. Simulations were carried out on a Pentium IV 2.4 GHz, 512-MB RAM processor. The coding was written using MATLAB 7.0.

The harmonics are to be observed in the output line-to-line voltage. With the five switching angles calculated, the whole switching pattern is constructed using quarter wave symmetry method. The output line-to-line voltage waveforms for the modulation index, $M = 0.9$ with induction motor drive are shown in Figs. 3a and 3b respectively.

A low power laboratory prototype Voltage Source Inverter, based on MOSFET Voltage Source Inverter was developed and tested to verify the feasibility and validity of theoretical and simulation findings. The pre-calculated PWM signals are implemented by a low cost, high speed ATMEL microcontroller. A digital real-time power quality analyzer (ALM 30) was used to display and capture the output waveforms. The experimental inverter output voltage waveform for induction motor drive using GA and EP are given in Figs. 4a and 4b respectively. The waveform of the output voltage shows that there is excellent correlation between the simulated results waveform and experimental results waveform.

Harmonic Spectrum is obtained for the inverter output voltage with induction motor drive for both Genetic Algorithm and Evolutionary Programming method. The Harmonics Spectrum of output voltage with induction motor drive is shown in Figs. 5a and 5b respectively. Simulation results of output voltage harmonic spectrum shows that harmonics up to 19th are eliminated using GA

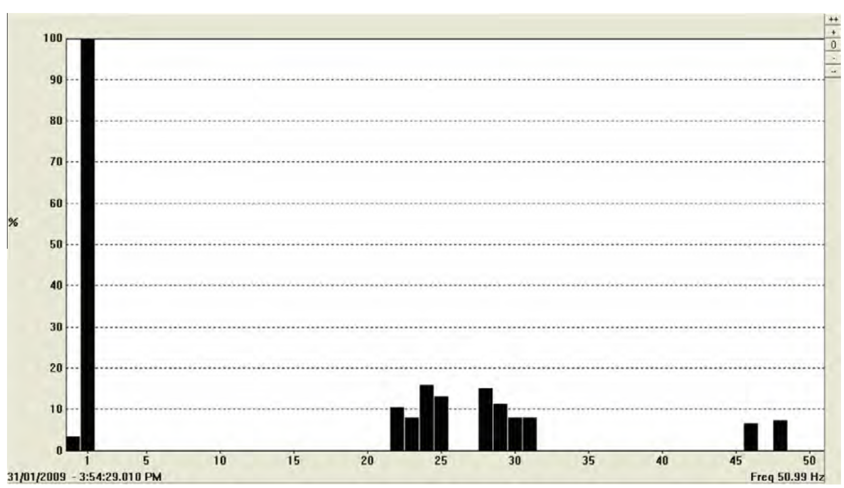

Fig. 6a. Experimental harmonics spectrum for inverter output voltage for induction motor drive (after eliminating 5th, 7th, 11th, 13th, 17th and 19th harmonics using GA) at $M = 0.9$.

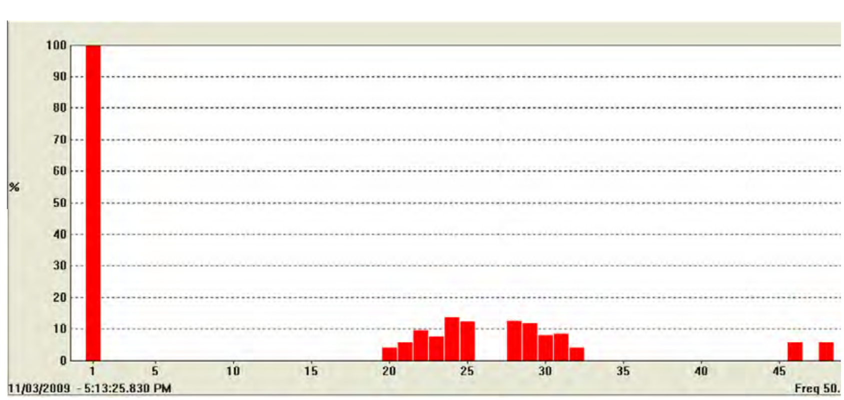

Fig. 6b. Experimental harmonics spectrum for inverter output voltage for induction motor drive (after eliminating 5th, 7th, 11th, 13th, 17th and 19th harmonics using EP) at $M = 0.9$.

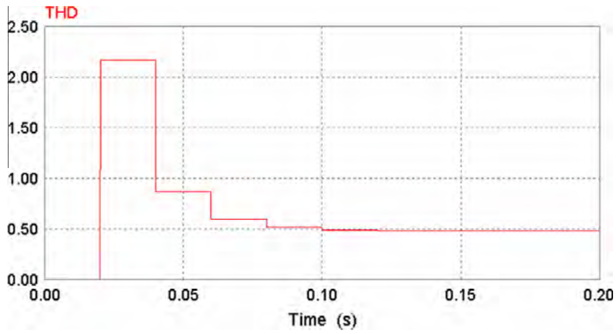

Fig. 7a. Total harmonic distortion of output voltage using Genetic Algorithm.

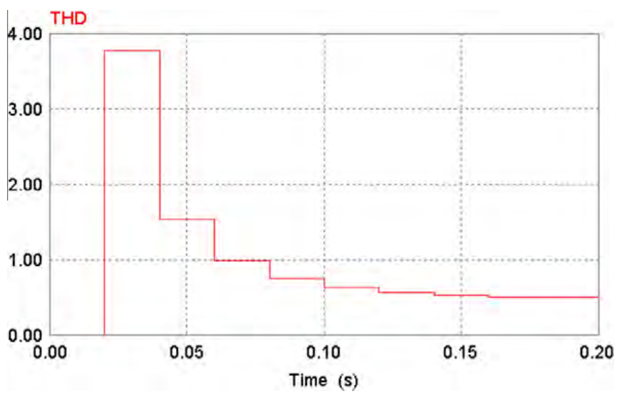

Fig. 7b. Total harmonic distortion of output voltage using Evolutionary Programming.

and EP approach. The experimental harmonic spectrum of inverter output voltage for induction motor drive using GA and EP are given in Figs. 6a and 6b respectively. The lowest harmonics available in the output voltage is 23rd, which is considered to be the higher order harmonics and that can be easily removed using LC filter circuits. The harmonics spectrum figures show that almost all 5th, 7th, 11th, 13th, 17th and 19th harmonics are eliminated for the modulation index value 0.9. These are the characteristic lower order harmonics to be eliminated for the six pulse converter.

7. Discussion

This paper points out that GA and EP shows great potential in solving not only the required switching angles, but also in the optimization of nonlinear converter switching characteristics in general. MATLAB 7.0 solutions coupled with PSIM 6.1 implementation results verify and yield good output voltage and current waveforms.

The novelty of the paper is elimination of lower order harmonics of low frequency inverter feeding induction motor drive without using dual transformer. Comparing Genetic Algorithm and Evolutionary Programming, the total Harmonic distortion is greatly reduced using Genetic Algorithm approach. The maximum value of Total Harmonic Distortion of output voltage using Genetic Algorithm is obtained from Fig. 7a is around 2.2 and the maximum value of Total Harmonic Distortion using Evolutionary Programming can be calculated from Fig. 7b is around 3.8. So we can say that the Total Harmonic Distortion of the output voltage is reduced more using the GA approach and that is more efficient than Evolutionary Programming. The spectrum of the output voltage obtained with a feature of the THD shows very good correlation between experimental and simulation results. The spectrum of the output voltage clearly shows the absence of the targeted harmonics while controlling the fundamental at a predefined value. The target is achieved and harmonics up to 19th in Voltage Source Inverter feeding induction motor drive were totally eliminated. This highlights the PWM–SHE method, which provides a clean power converter environment and meets most accepted standards.

8. Conclusion

An efficient technique of calculating switching angles through the Genetic Algorithm method is illustrated. A six pulse converter is proposed as the power circuit for the three phase drive system. PWM–SHE switching is proposed for three phase Inverter circuit. This method avoids using 12 pulse rectifier and the traditional complex calculations. Analysis of the harmonics spectrum shows that, 5th, 7th, 11th, 13th 17th and 19th harmonics are eliminated through Genetic Algorithm and Evolutionary Programming. In this approach, the dual transformers are not used to eliminate the 5th and 7th order harmonics. High capacity dual transformer connections are also avoided to eliminate the lower order harmonics using Genetic Algorithm and Evolutionary Programming approach. It remains to be a topic for further investigations to design similar real-time PWM systems.

References

Agelidis, V. G., Balouktsis, A. I., & Cossar, C. (2008). On attaining the multiple solutions of selective harmonic elimination PWM three level waveforms through function minimization. *IEEE Transactions on Industrial Electronics, 55*, 996–1004.

Barkati, S., Baghali, L., Berkouk, E. M., & Boucherit, M.-S. (2008). Harmonics elimination in diode clamped multilevel inverter using evolutionary algorithms. *Electronics Power System Research, 78*, 1736–1746.

Chiasson, J. N., Tolbert, L. M., McKenzie, K. J., & Du, Z. (2004). A complete solution to the harmonic elimination problem. *IEEE Transactions on Power Electronics, 19*, 491–499.

Dohidah, M. S. A., Agelidis, V. G., & Rao, M. V. (2006). An abolishing symmetry requirements in the formulation of a five level selective harmonic elimination PWM technique. *IEEE Transactions on Power Electronics, 21*, 1833–1837.

Eltamaly, A. M. (2008). A modified harmonics reduction technique for a three phase controlled converter. *IEEE Transactions on Industrial Electronics, 55*, 1190–1197.

Enjeti, P. N., Ziogas, P. D., & Lindsay, J. F. (1990). Programmed PWM techniques to eliminate harmonics: A critical evaluation. *IEEE Transactions on Industrial Applications, 26*, 302–316.

Holtz, J. (1992). Pulse width modulation – A survey. *IEEE Transactions on Industrial Electronics, 39*, 410–420.

IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std. 519-1992, 1992.

Maswood, A. I., Wei, S., & Rahman, M. A. (2001). A flexible way to generate PWM–SHE switching pattern using genetic algorithm. In: *Proceedings of the IEEE applied power electronics conference, Anheim, CA, USA* (pp. 1130–1134).

Maswood, A. I., Neo, T. G., & Rahman, M. A. (2001). An online optimal approach to PWM SHE gating signal generation. *IEEE Power Engineering Review*, 61–62.

Maswood, A. I., & Wei, S. (2005). Genetic algorithm based solution in PWM converter switching. *IEE Proceedings on Electric Power Applications, 152*, 473–478.

Ozpineci, B., Tolbert, L. M., & Chiasson, J. N. (2005). Harmonic optimization of multilevel converter using genetic algorithms. *IEEE Power Electronics Letters, 3*, 92–95.

Patel, H. S., & Hoft, R. G. (1973). Generalized techniques of harmonic elimination and voltage control in thyristor inverters – Part I – Harmonic elimination. *IEEE Transactions on Industrial Application, 1A-9*, 310–317.

Patel, H. S., & Hoft, R. G. (1974). Generalized techniques of harmonic elimination and voltage control in thyristor inverters – Part II – Voltage control techniques. *IEEE Transactions on Industrial Application, 1A-10*, 666–673.

Shen, W., & Maswood, A. I. (2000). A novel current source PWM drive topology with specific harmonic elimination switching. In: *Proceedings of the Canadian conference on electrical and computer engineering, Halifax, Canada* (pp. 53–55).

Shi, K. L., & Li, H. (2005). Optimized PWM strategy based on genetic algorithms. *IEEE Transactions on Industrial Electronics, 52*, 1458–1461.

Sinha, N., Chakrabarti, R., & Chattopadhyay, P. K. (2003). Evolutionary programming techniques for economic load dispatch. *IEEE Transactions on Evolutionary Computation, 7*, 301–306.

Sundareswaran, K., & Chandra, M. (2002). Evolutionary approach for line current harmonic reduction in AC/DC converters. *IEEE Transactions on Industrial Electronics, 49*, 716–719.

Sun, J., & Grotsotollen, H. (1992). Solving nonlinear equations for selective harmonic eliminated PWM using predicted initial values. In: *Proceedings of the IEEE IECON, San Diego, CA, USA* (pp. 259–264).

Sun, J., Beineke, S., & Grotsllen, H. (1994). DSP based real-time harmonic elimination of PWM Inverters. In: *Proceedings of the IEEE power electronics specialists conference, Taipei, Taiwan* (pp. 679–685).

Wagner, V. E. (1993). Effect of harmonics on equipment. *IEEE Transactions on Power Delivery, 8*, 672–680.

Wells, J. R., Nee, B. M., Chapman, P. L., & Krein, P. T. (2005). Selective harmonic control: A general problems formulations and selected solutions. *IEEE Transactions on Power Electronics, 20*, 1337–1345.

Zacharia, P., Menti, A., & Zacharias, T. (2008). Genetic algorithm based optimal design of shunt compensators in the presence of harmonics. *Electric Power System Research, 80*, 728–735.