She PWM in Single Phase Matrix Converter using Real Coded Genetic Algorithm and Particle Swarm Optimization Techniques

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Abstract: In this paper, selective harmonic elimination pulse width modulation (SHEPWM) using Real Coded Genetic Algorithm (RGA) and Particle Swarm Optimization technique (PSO) for single phase Matrix converter is developed and discussed. In these techniques, the objective function is optimized for optimum switching angles. The switching frequency is fixed and is equal to output frequency. The objective function is modified to improve the input power factor of the single phase matrix converter. To verify the efficiency of these algorithms, the power converter has been simulated in MATLAB/SIMULINK and the obtained results are reported. The FFT analysis of the simulated output voltage waveform confirms the effectiveness of the proposed method.

Keywords: Single Phase matrix converter, Selective harmonic Elimination, Pulse Width Modulation, Real Coded Genetic Algorithm, Particle Swarm optimization, Total Harmonic Distortion

1 Introduction

Many applications such as industrial heating, light control, soft start induction motors, speed control of ac motors require continuously varying AC voltage from fixed AC voltage source. AC voltage regulator with phase angle control and integral cycle control techniques are commonly employed for these requirements. The advantages of these techniques are simplicity, cost effective, reliable and ability to control large amount of power. On the other hand, the delayed firing angle in these schemes causes the discontinuity in load current, high value of lower order harmonics and lagging power factor at the source side especially at the low voltage outputs. To mitigate these problems PWM AC choppers are preferred. In the PWM AC choppers, high switching frequency based PWM is preferred for the system in which switching losses are endurable. Carrier based Sine PWM (SPWM), Space Vector PWM (SVPWM) are examples of high switching frequency PWM techniques.Carrier based PWM is implemented in various ways : sub oscillation method, Modified sub oscillation method[1]. Low switching frequency based PWM is preferred for the system in which switching losses are intolerable and can tolerate the harmonics to certain extend. The low switching frequency is typically around the fundamental frequency of the output voltage. Selective Harmonic Elimination PWM (SHEPWM), Optimal Minimization of the Total Harmonic Distortion (OMTHD) and Optimized Harmonic Stepped Waveform (OHSW) are examples of low switching frequency PWM techniques[1]. In these techniques, the AC chopper waveforms are analyzed using Fourier theory and sets of nonlinear transcendental equations were obtained using any iterative procedure such as Newton-Rapson, Random search, Rosenbrocks method. The convergence in thesetechniques depends on the choice of initial values. Stochastic optimization techniques overcome the drawback and are used to find the global optimum solution with short time searching. In this approach objective function is formed using the analytical equations and the objective function is minimized to get the optimal solution. Genetic Algorithm(GA), Particle swarm optimization(PSO), Bee colony algorithm(BCA), Fire fly algorithm, Differential Evolution(DE) are some of the optimization techniques [2-11]. These techniques are used for SHE in AC/AC converter also [9-11]. Hopfield neural network based approach also used to solve the SHEPWM problem [12].

In Selective harmonic mitigation PWM(SHMPWM), the selected harmonic contents are restricted within the values specified by grid codes EN50160 and CIGRE WG 36-05 [13]. In SHEPWM for N switching angles, N-1 number of harmonics can be eliminated but in SHMPWM N2 number of harmonics can be limited within the values specified by any grid code. In this paper GA and PSO arenot only used to eliminate the selected harmonics (SHEPWM)and output voltage regulation but also to improve the input power factor and the results are compared.

2 Circuit Analysis

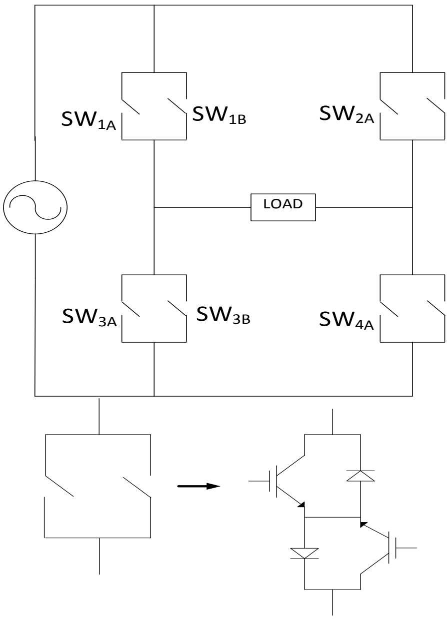


Fig. 1a. Circuit Diagram of Single phase matrix converter

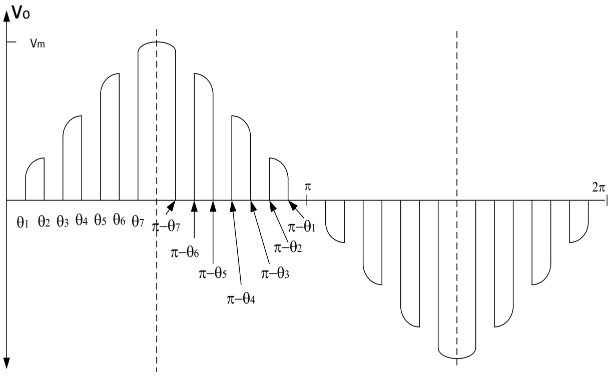


Fig. 1b. Synthesized output voltage (50Hz) of single phase matrix converter

The single phase matrix converter consists of four switches SW_1, SW_2, SW_3, SW_4 is illustrated in Fig. 1a. Bidirectional power flow in AC to AC converter demands the bidirectional switches that capable of blocking voltages in both polarity and conduction of current in both direction. A discrete semiconductor fulfilling these requirements is not available in practice and hence an antiparallel IGBT, diode pair is used here. Theoretically the switching is simultaneous and instantaneous. In real time the finite switching times and delays in the circuit are taken into account.

The input and the output voltages are given by

$$v_i(t) = \sqrt{2}V_i sin\omega_i t \quad (1)$$

$$v_o(t) = \sqrt{2}V_o sin\omega_o t \quad (2)$$

$$v_o(t) = Ri_o + L\frac{di_o(t)}{dt} \quad (3)$$

The switching sequence for the output frequency of 50 and 100Hz are summarized in Table1. At anytime‘t’ two switches are ON.

Fig. 1b shows the ideal synthesized output voltage waveform of single phase matrix converter with the output frequency of 50Hz. The waveform possesses N switching angles between 0 and$\frac{\pi}{2}$. Since the square wave symmetry is preserved in the output voltage waveform, all the even harmonics are eliminated and odd harmonics alone present in the output. Among the N switching angles, one angle is used for the control of fundamental voltage and N-1 switching angles for the elimination of N-1 selected lower order harmonics. In this paper seven switching angles are generated.

3 Formulation of Transcendental Equations

The Fourier series expansion of output voltage is

$$V_o = V_m \sum_{n=1}^{\infty}(A_n \sin(\mathrm{n\omega t}) + B_n \cos(\mathrm{n\omega t})) \quad (4)$$

where $A_n$and B_n are the Fourier coefficients

$n$is the order of the harmonic.

$V_m$is the peak value of the output voltage

The fundamental coefficients $A_1$and B_1 are expressed as

$$A_1 = \frac{1}{2\pi}\left[\sum_{i=1,2}^{N}\left((-1)^{\mathrm{i}}\left(\alpha_{\mathrm{i}} - \frac{\sin 2\alpha_{\mathrm{i}}}{2}\right)\right)\right] \quad (5)$$

$$B_1 = \frac{1}{2\pi}\left[\sum_{i=1,2}^{N}\left((-1)^{\mathrm{i}+1}\left(\frac{\cos 2\alpha_{\mathrm{i}}}{2}\right)\right)\right] \quad (6)$$

The coefficients $A_n$and B_n are expressed as

$$A_n = \frac{1}{2\pi}\left[\sum_{i=1,2}^{N}\left((-1)^{\mathrm{i}}\left(\frac{\sin((1-\mathrm{n})\alpha_{\mathrm{i}}}{1-\mathrm{n}} - \frac{\sin((1+\mathrm{n})\alpha_{\mathrm{i}}}{1+\mathrm{n}}\right)\right)\right] \quad (7)$$

$$B_n = \frac{1}{2\pi}\left[\sum_{i=1,2}^{N}\left((-1)^{\mathrm{i}+1}\left(\frac{\cos((1-\mathrm{n})\alpha_{\mathrm{i}}}{1-\mathrm{n}} - \frac{\cos((1+\mathrm{n})\alpha_{\mathrm{i}}}{1+\mathrm{n}}\right)\right)\right] \quad (8)$$

f_{out}	Interval	Mode	Switching State	Description
50	1	Duty Interval	SW_{1A} & SW_{4A}	SW_{1A} & SW_{4A} - ON state Others – OFF state
		F.W interval	SW_{3B} & SW_{4A}	SW_{3B} & SW_{4A} – ON state Others – OFF state
	2	Duty Interval	SW_{1B} & SW_{4B}	SW_{1B} & SW_{4B} – ON state Others – OFF state
		F.W interval	SW_{3A} & SW_{4B}	SW_{3A} & SW_{4B} – ON state Others – OFF state
100	1	Duty Interval	SW_{1A} & SW_{4A}	SW_{1A} & SW_{4A} – ON state Others – OFF state
		F.W interval	SW_{3B} & SW_{4A}	SW_{3B} & SW_{4A} – ON state Others – OFF state
	2	Duty Interval	SW_{2A} & SW_{3A}	SW_{2A} & SW_{3A} - ON state Others – OFF state
		F.W interval	SW_{2A} & SW_{1B}	SW_{2A} & SW_{1B} – ON state Others - OFF state
	3	Duty Interval	SW_{2B} & SW_{3B}	SW_{2B} & SW_{3B} – ON state Others – OFF state
		F.W interval	SW_{3B} & SW_{4A}	SW_{3B} & SW_{4A} – ON state Others – OFF state
	4	Duty Interval	SW_{1B} & SW_{4B}	SW_{1B} & SW_{4B} – ON state Others – OFF state
		F.W interval	SW_{3A} & SW_{4B}	SW_{3A} & SW_{4B} – ON state Others – OFF state

Table 1. Switching Sequences

The output voltage is articulated as

$$V_0 = V_m \sum_{n=1}^{\infty} \mathrm{C_n}\left[\sin\left(\mathrm{n}\theta + \phi_\mathrm{n}\right)\right] \qquad (9)$$

Where $C_n = \sqrt{(A_n)^2 + (B_n)^2}$

$$\phi_n = \tan^{-1}\left(\frac{B_n}{A_n}\right)$$

Let $F(\alpha)$ be the objective function to be minimized and is defined as

$$F(\alpha_1, \alpha_2, \alpha_3 \ldots.\alpha_N) = (C_i - MI)^2 + {C_3}^2 + {C_5}^2 + \ldots. + {C_{2N-1}}^2 \quad (10)$$

With the constrain $0 \le \alpha_1 \le \alpha_2 \cdots \le \alpha_N \le \frac{\pi}{2}$

Where modulation index $MI = \frac{V_{o1RMS}}{V_{iRMS}}$

The objective function $F(\alpha)$is minimized subject to the condition in equation (10). Hence the desired output voltage is regulated over the range 0 to V_m by changing the modulation index and selected harmonics up to 13th order are eliminated.

4 Power factor Improvement

The fixed input voltage V_i is transformed into variable output voltage V_o by the matrix converter. The load current I_o and input current I_i are expressed as

$$i_o = I_{om} \sin\left(\omega t - \phi_o\right)(11)$$

$$i_i = I_{im} \sin\left(\omega t - \phi_i\right)12)$$

Where ϕ_o and ϕ_i are the output and input current phase angles respectively. The phase angle ϕ_o depends on the load where ϕ_i depends on three factors such as power circuit, control technique and the load power factor. Since the power circuit – matrix converter and the load power factor are fixed, the power factor can be improved using any one control technique. Phase shifting method is used in this paper.

With the phase shifting the output voltage is expressed as

$$v_o(t) = \sqrt{2}V_o sin(\omega_o t + \phi_r) \quad (13)$$

where ϕ_r is the phase shifting angle

The load current

$$i_o(t) = \sqrt{2}I_{om} sin(\omega_o t - \phi_o + \phi_r) \quad (14)$$

The input current

$$i_i(t) = \sqrt{2}I_{im} sin(\omega_i t - \phi_i + \phi_r) \quad (15)$$

In equation (15),

if $\phi_r = \phi_i$, then $i_i(t) = \sqrt{2}I_i sin(\omega_i t)$ and the input power factor becomes unity. Hence equation (5) and (6) can be rewritten as

$$A_1 = \left(\frac{1}{2\pi}\left[\sum_{i=1,2}^{N}\left((-1)^{\mathrm{i}}\left(\alpha_{\mathrm{i}} - \frac{\sin 2\alpha_{\mathrm{i}}}{2}\right)\right)\right]\right) - MI \times cos\phi_1 \quad (16)$$

$$B_1 = \left(\frac{1}{2\pi}\left[\sum_{i=1,2}^{N}\left((-1)^{\mathrm{i}+1}\left(\frac{\cos 2\alpha_{\mathrm{i}}}{2}\right)\right)\right]\right) - MI \times sin\phi_1 \quad (17)$$

where ϕ_1 is the phase angle of the fundamental load current.

5 Real Coded Genetic Algorithm

Genetic algorithm is inherently parallel because of simultaneous evaluation of many points in search space. Hence GA has reduced chance of converging to local optima and more chance to converge in global optima [14]. Initially GAwas designed to operate with binary codes. Nowadays Real coded GA (RGA) is used due to their supreme behavior such as reduced computational effort, absolute precision etc. The steps involved in RGA based approach are illustrated.

5.1 Step 1: Random generation of initial population

Generating N switching angles is the solution to this problem. Each switching angle is a gene represented by real numbers. There are N genes in each chromosome. Each chromosome represents the solution to the problem. Population consists of sets of chromosomes. Population is initialized with random number between 0 and $\frac{\pi}{2}$.

5.2 Step 2: Evaluation of fitness function

The objective function in this study is to minimize the selected harmonics hence fitness function has to be minimized. Since GA is used only for maximization problem the fitness function is modified as below

$$FN = \frac{1}{1+f(\alpha)} \quad (18)$$

Fitness of each chromosome is computed.

5.3 Step 3: Generation of off spring

Offspring is a new (Child) chromosome. From the fitness value of the each chromosome best parents are selected for reproduction. Tournament selection is used as selection mechanism in this work to avoid premature convergence. The selected parents are subjected to Simulated Binary Crossover (SBX) and polynomial mutation. Self adaptive simulated binary crossover based RGA was successfully applied to various engineering optimization problems [15].

In Simulated Binary (SBX)crossover, two children solution $y_i^{(1)}$ and $y_i^{(2)}$ are wrought from the parent solution $x_i^{(1)}$ and $x_i^{(2)}$. The SBX operator simulates the working principle of single point crossover on binary strings.

$$y_i^{(1)} = 0.5\left[(1-\beta_i)x_i^{(1)} + (1+\beta_i)x_i^{(2)}\right] \quad (19)$$

$$y_i^{(2)} = 0.5\left[(1+\beta_i)x_i^{(1)} + (1-\beta_i)x_i^{(2)}\right] \quad (20)$$

The spread factor β is defined as the ratio of absolute difference in offspring values to that of parents' values.

$$\beta = \left|\frac{y_i^{(1)} - y_i^{(2)}}{x_i^{(1)} - x_i^{(2)}}\right| \quad (21)$$

Polynomial probability Distribution

$$P(\beta) = 0.5\,(n_c + 1)\beta^{n_c} if \beta < 1$$

$$= 0.5\,(n_c + 1)\frac{1}{\beta^{n_c+2}} otherwise \quad (22)$$

n_c is a nonnegative real number known as crossover distribution index represents the distance of the children from the parent.

$$\int_0^{\beta_i} P(\beta)\,d\beta = u_i \text{where} u_i \in [0,1] \quad (23)$$

Non-uniform polynomial mutation

Newly generated offspring undergo polynomial mutation operation to create mutated offspring. New offspring y_i is determined using equation

$$y_i = x_i + (x_i^U - x_i^L)\delta_i \quad (24)$$

where$x_i{}^U$ and $x_i{}^L$ are the upper and lower limit values. $\delta_i$is calculated from the polynomial probability distribution. The function is given by

$$P(\delta) = 0.5(n_m + 1)(1 + |\delta|)^{n_m} (25)$$

$$\delta = (2r_i)^{\frac{1}{n_m+1}} - 1 if\ r_i < 0.5$$

$$\delta = 1 - [2(1 - r_i)]^{\frac{1}{n_m+1}} if r_i \geq 0.5 (26)$$

$n_m$is the mutation distribution index/ mutation constant and random number $r_i \in [0,1]$. Newly generated offspring will become the population for the next generation. The procedure is repeated from step 2 till the stopping criterion is reached. The parameters used in the algorithm are given in Table 2.

5.4 Step 5: Stopping criteria

The algorithm stops when any one of the following conditions occurs:

1. The number of iterations performed by the algorithm reaches the value of the maximum iteration.
2. The total number of objective function evaluations performed by the algorithm reaches the valueof maximum evaluation.
3. The change in the objective function from one generation to the next successful poll is less than the objective function tolerance.

6 Particle Swarm Optimization (PSO)

PSO is a population based stochastic optimization technique developed by Ebernart and Kennedy inspired by social behavior of bird flocking and fool schooling. The steps involves in PSO algorithm are given below

6.1 Step 1: Random generation of initial population:

It begins with the initialization of particle position (switching angles) between 0 and $\frac{\pi}{2}$ and velocities in N dimensional space.

6.2 Step 2: Evaluation of fitness function:

In each iteration, the particle moves according to the velocity and change its position. The fitness function is evaluated for each particle.

6.3 Step 3: Setting $\boldsymbol{P_{best}}$and$\boldsymbol{G_{best}}$:

The best position reached among the particle during their search is the particle best($\boldsymbol{P_{best}}$) . The best fitness value reached by the particle in all the searches is the Global best($\boldsymbol{G_{best}}$).

6.4 Step 4: Update the velocity and position of each particle:

Let V_i and X_i represent the velocity and position of i^{th}particle. The velocity and position of each particle is update as given below

$$V_i{}^{k+1} = \omega^k V_i{}^k + C_1 r_1 \left(Pbest_i{}^k - X_i{}^k\right) + C_2 r_2 \left(Gbest_i{}^k - X_i{}^k\right) (27)$$

$$X_i{}^{k+1} = X_i{}^k + V_i{}^{k+1} (28)$$

$$\omega^k = \omega_{mak} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} K (29)$$

Whereω^k - Inertia weight at iteration ,
$V_i{}^k$ - Velocity of i^{th} particle at iteration $k C_1$and C_2 – Acceleration factors
$r_1$andr_2 – Uniform random numbers ∈ [0,1]
$Pbest_i{}^k$- Best position of i^{th} particle at iteration$k$
$X_i{}^k$ - Position of i^{th} particle at iteration$k$
$Gbest_i{}^k$ - Best position of the group till iteration$k \omega_{max}$ and ω_{min} are initial and final weights $iter_{max}$ - total number of iterations.

The procedure is repeated from step 2 till the stopping criterion is reached. The stopping criteria of GA are applicable to PSO also. The parameters used in PSO algorithm is shown in Table 2.

7 Simulation Results

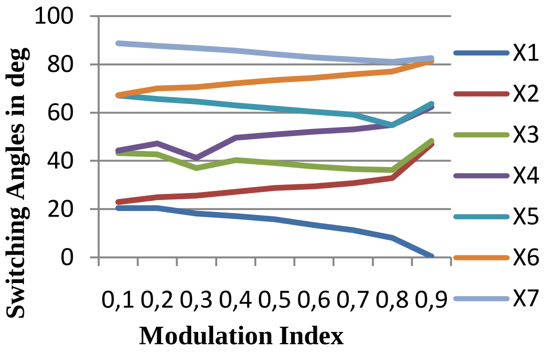
To verify and validate the algorithms, programs are developed in MATLAB mfile code. The programs are run in Pentium-V computer operating at 1.4GHz clock speed. The single phase matrix converter is realized in MATLAB/Simulink environment with the following parameters V_i = 100V, R=30Ω, L= 60mH, f_{in} = 50Hz, f_{out} = 50 & 100Hz.

Genetic Algorithm	PSO
No of Runs = 10	No of Runs = 10
Switching Angles = 7	Switching Angles =7
Population Size = 100	Population Size = 100
SBX crossover constant n_c = 2	Acceleration constants C_1 and C_2 = 1
Mutation constant n_m = 20	Maximum Generation = 100
Maximum Generation = 100	

Table 2. Parameters used in GA and PSO

Table 3 shows the harmonic contents of the order 3 to 13 for various modulation index in GA and PSO. The required fundamental voltage is obtained in both the techniques. Fig. 2 shows the switching angle trajectory of GA and PSO. The trajectory is almost linear. Fig. 3 shows the comparison of harmonic content for the modulation index of 0.8 and 0.4 and it is clear that the harmonic contents are less than the value specified by the EN50160. Fig. 4 shows the output voltage and current of single phase matrix converter and from the current waveform it is observed that the input side power factor is improved. For example, with the load of R=30Ω and L=30mH, the fundamental input current lags the voltage by 16.38° and with the phase shifting technique the fundamental phase angle reduced to 0.697.From Fig. 5, it is observed that the input power factor is close to unity for the variation of modulation index from 0.1 to 0.7. When the modulation index is greater than 0.7, the input power factor reduces with the increase in MI and also it is observed that the THD level is high for lower modulation index and the THD reduces as the modulation index increases because of increase in the fundamental harmonic component. Fig. 6 shows the harmonic spectrum obtained using GA and PSO. It shows that 3rd, 5th, 7th, 9th,11th and 13th harmonics are removed.

Fig. 7,8 and 9 shows the harmonic spectrum and output voltage with the modulation index of 0.3, 0.2 and 0.4 respectively with a output frequency of 100Hz. It shows that there is one full cycle within one half cycle of input voltage. From the output voltage it is observed that the waveform is non-symmetrical and due to this non-symmetry DC component and all even harmonics are injected. The fitness function of the SHE is modified to eliminate DC component and 2nd, 3rd,4th,5th,6th and 7th harmonics.



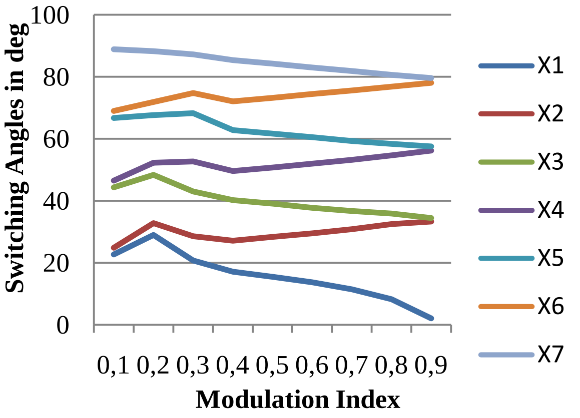


Fig. 2 Switching angle trajectory using GA and PSO

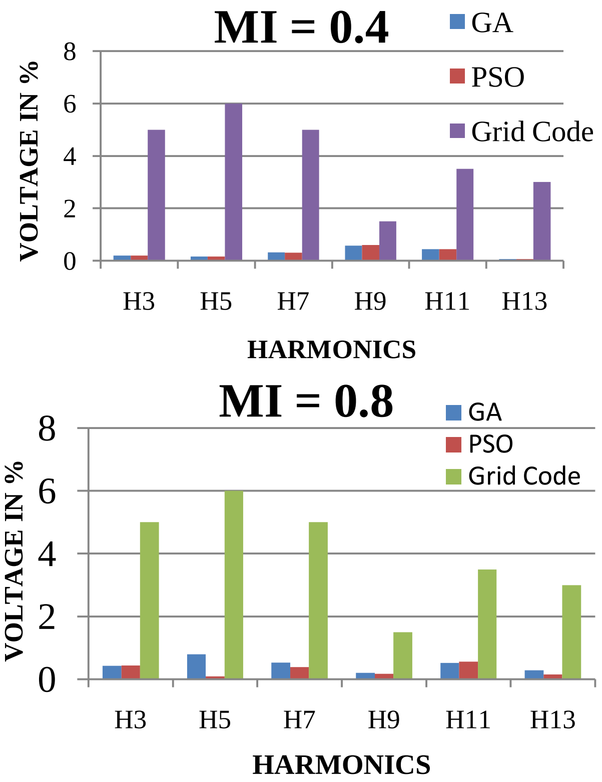
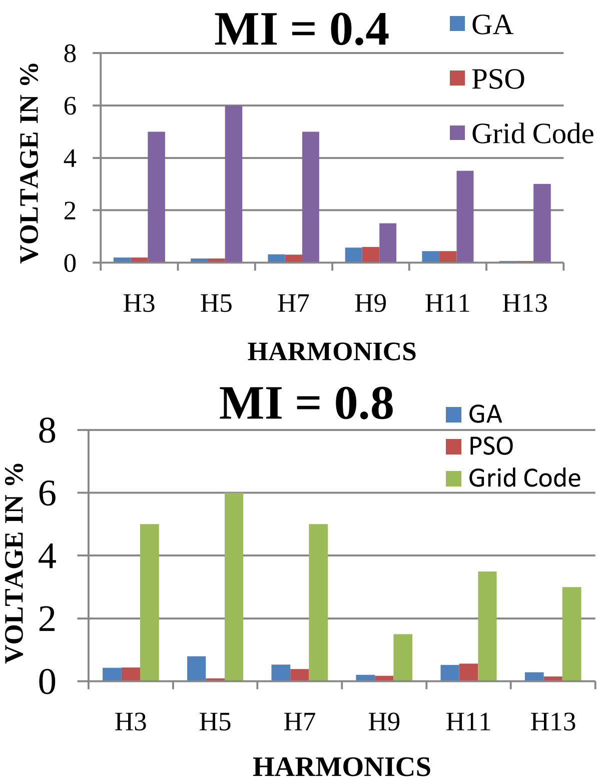


Fig. 3. Comparison of Harmonic contents using GA and PSO for MI = 0.8 & MI = 0.4



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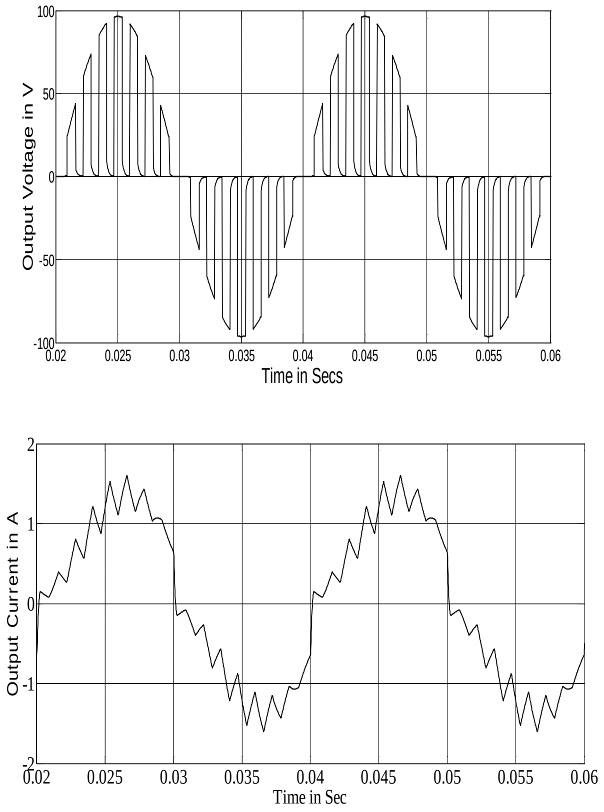

Fig. 4. Output Voltage and Output Current with MI =0.5

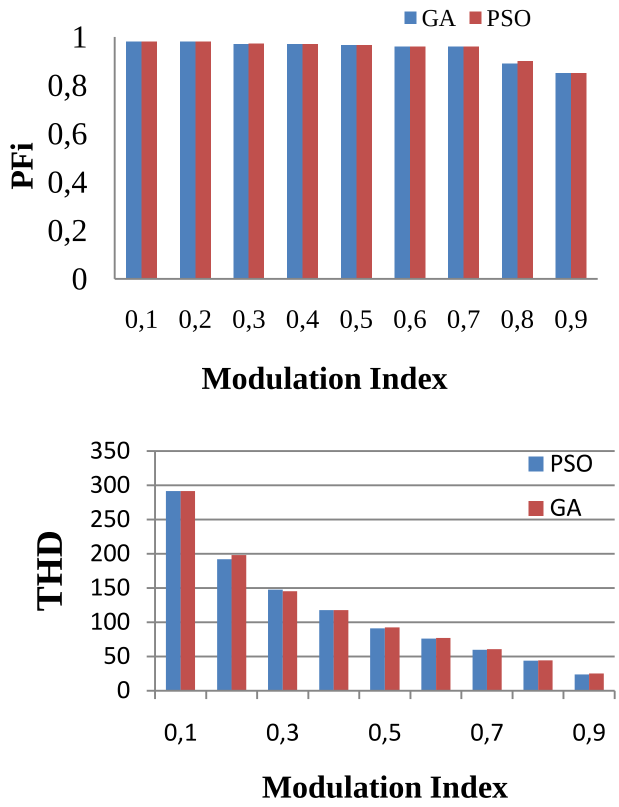

Fig. 5. Comparison of input power factor and THD with GA and PSO.

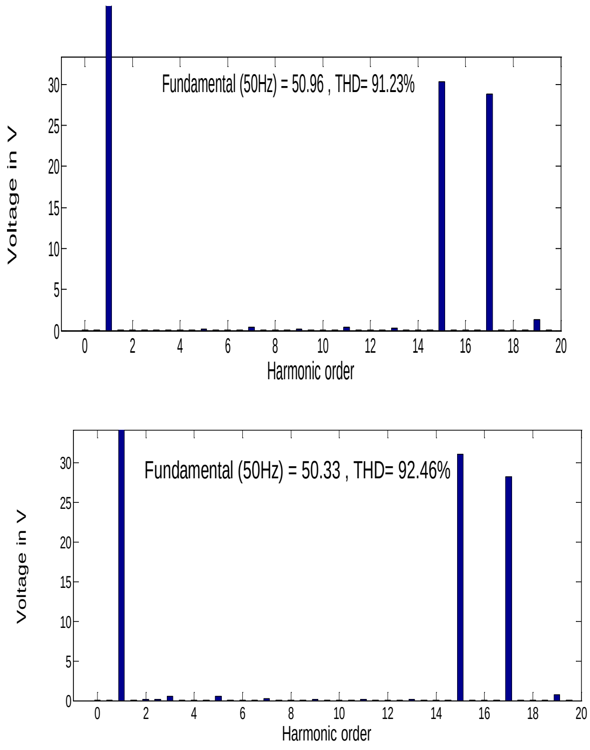

Fig. 6. Harmonic Spectrum of PSO & GA for MI =0.5

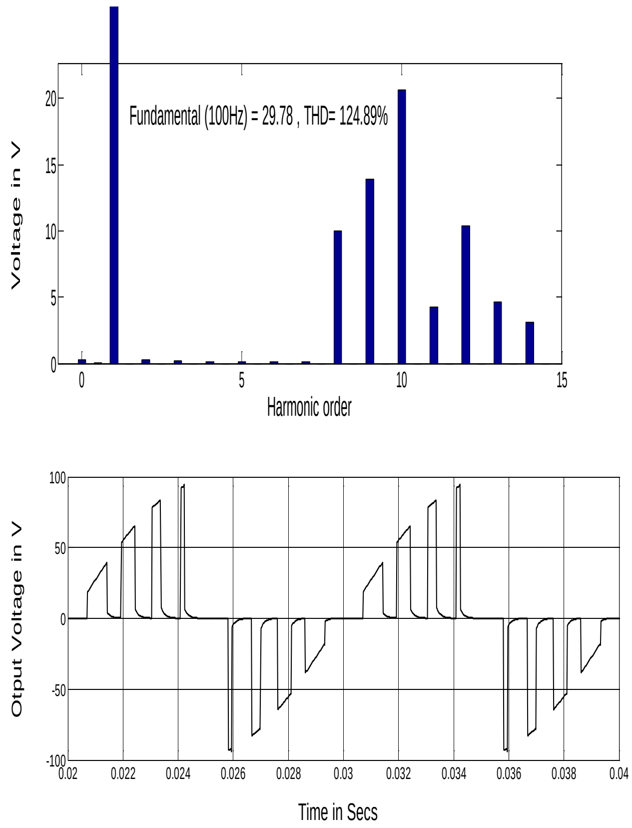

Fig. 7. Harmonic Spectrum and output Voltage for 100Hz with MI=0.3

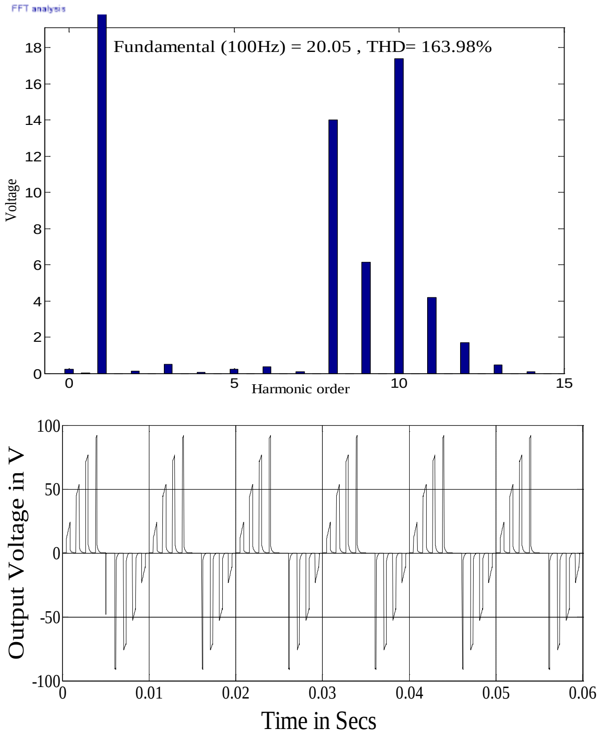

Fig. 8. Harmonic Spectrum and output Voltage for 100Hz with MI=0.2

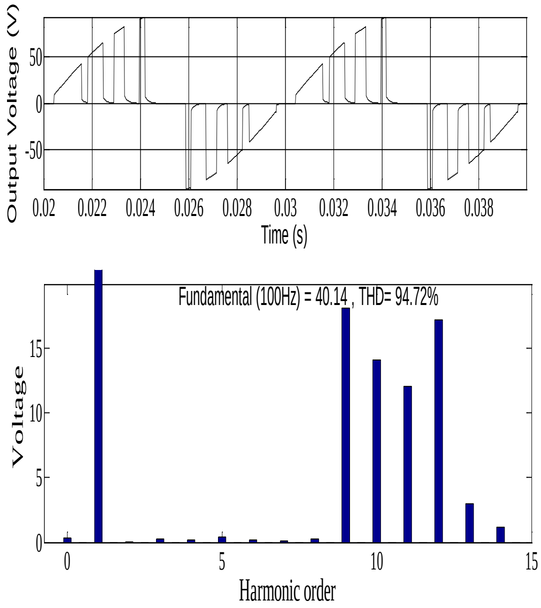

Fig. 7. Harmonic Spectrum and output Voltage for 100Hz with MI=0.4

8 Conclusion

A method to eliminate the selected harmonics, improvement of input power factor and voltage regulation in single phase matrix converter using Real Coded Genetic algorithm and PSO are presented in this paper. From the simulation results it is concluded that

1. From the calculated optimal switching angles the selected harmonics are eliminated and the voltage regulation is done.
2. The input power factor is close to unity for the variation of MI from 0.1 to 0.7. When the modulation index is greater than 0.7, the input power factor reduces with the increase in MI.
3. The THD of the output voltage reduces with the increase in modulation index.

   Although 50Hz and 100Hz output frequencies are discussed in this paper, different output frequencies like 25,150,200Hz etc can be obtained by properly modifying the transcendental equation and the control circuit of single phase matrix converter. Only selected results are presented to validate the theoretical analysis.

MI	Method	THD	Fundamental Voltage in V	Harmonic Voltage in %					
				H3	H5	H7	H9	H11	H13
Harmonic Limit as per EN 50160				**5**	**6**	**5**	**1.5**	**3.5**	**3**
0.1	GA	291.45	9.86	0.55	0.66	0.13	0.58	0.03	0.75
	PSO	291.63	9.85	0.51	0.31	0.51	0.19	0.44	0
0.2	GA	191.84	20.14	0.31	0.04	0.17	0.22	0.33	0.09
	PSO	198.22	19.09	0.18	0.21	0.25	0.11	0.22	0.15
0.3	GA	147.85	29.68	0.44	0.22	0.07	0.47	0.11	0.28
	PSO	145.27	30.39	0.23	0.21	0.2	0.23	0.2	0.31
0.4	GA	117.94	39.63	0.18	0.15	0.3	0.56	0.43	0.07
	PSO	117.95	39.62	0.19	0.16	0.32	0.57	0.44	0.06
0.5	GA	94.4	50.19	0.08	0.26	0.49	0.2	0.44	0.26
	PSO	95.66	49.55	0.64	0.59	0.32	0.11	0.09	0.2
0.6	GA	76.19	60.11	0.13	0.4	0.16	0.46	0.27	0.52
	PSO	77.26	59.98	0.09	0.1	0.62	0.36	0.25	0.14
0.7	GA	59.61	70.15	0.16	0.1	0.22	0.34	0.33	0.12
	PSO	60.76	69.43	0.42	0.22	0.12	0.19	0.39	0.81
0.8	GA	43.75	79.85	0.39	0.24	0.16	0.16	0.48	0.1
	PSO	44.54	79.83	0.25	0.28	0.23	0.27	0.36	0.16
0.9	GA	23.86	90.16	0.14	0.15	0.58	1.85	0.15	0.23
	PSO	25.41	89.47	0.1	0.24	0.03	0.26	0.76	0.83

Table 3. Comparison of THD and Selected Harmonic Contents for different MI using GA and PSO

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