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An Improved PSO for SHEPWM Applied to Three-Level Topology-based PMSM Driver System

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Abstract. For Permanent magnet synchronous motor (PMSM) drive systems, performance of inverter is greatly influenced by harmonics. This paper describes the Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) method based on Improved Particle Swarm Optimization (PSO) algorithm for harmonic minimization of Neutral Point Clamped (NPC) Three-level Inverter PMSM driver system. Under high speed condition, the SHEPWM is employed to reduce the switching frequency and to eliminate particular current harmonics. The problem of the SHEPWM method is presented by a constrained nonlinear objective function which has to be minimized. The proposed method does capable of solving the target equation precisely, eliminating the specific harmonics and achieving the output current results in a minimum Total Harmonic Distortion value. The results obtained with the Improved PSO application show the effectiveness of the proposed method. Experimental and simulation results indicated the effectiveness of the proposed method.

Keywords: improved particle swarm optimization, NPC Three-level Inverter, PMSM, SHEPWM

1 Introduction

PMSM is a multivariate close coupling, nonlinear, time-variable, symmetric parameter object, switching loss and cooling problems of a PMSM system tend to increase with raising in the power of the system and the DC-side voltage. Improving quality of output current is a pivotal technique that determines the performance of a PMSM. Various researches are carried out to improve the quality of output current indicated by a lower value of THD [1]. Multilevel inverters have been invented as the demands increases. This paper base on the particles swarm optimal algorithm SHEPWM for PMSM driver system with a Three-level topology inverter. Multi-level inverter produces a sine wave with a minimum value of THD [2]. The Three-level inverter is simple and easy to implement with respect to Five-level, Seven-level structure. Three-level inverter is suitable for medium and high voltage application i.e. Flexible AC Transmission Systems, compressors, and industrial drive [3].

In general, the Three-level inverter is categorized into three types: Diode-Clamped Three-level inverter, Flying Capacitor Three-level inverter, cascade H-bridge Three-Level inverter. Several methods like sine triangle PWM (SPWM) [4], and Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) [5] are implemented for harmonic elimination in the Three-level inverter. SHEPWM is a renowned technique for switching pulses generation. SPWM method is very effective for observing the inverter output current but this method can cause high switching loss due to high switching frequency. SHEPWM is the most effective method to eliminate low-order harmonics and subjected to low switching frequency. It improves output power quality and also reduces the cost of filter [6]. Switching angle equation is a set of nonlinear transcendental equations. Some methods like Newton-Raphson (N-R) method [7], Walsh functions [8] and Block-pulse functions [9] are involved in the harmonic minimization process in the

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Three-level inverter SHEPWM. All these methods have its own disadvantage to solve this harmonic problem. N-R method requires initial guess, and divergence problem gives no optimum solution. Walsh function and Block-pulse function only solve linear equations, in the case of non-linear transcendental equations, are difficult to find better-switching result [9]. The method requires proper initial values to converge to a proper solution. Recently, non-traditional methods based on evolutionary algorithms, such as Particle Swarm Optimization (PSO) [10], Bee Algorithms (BA) have been employed for inverter harmonic elimination [11].

In this research, an Improved Particle Swarm Optimization approach can be programmed in the SHEPWM method to solve the transcendental equation of switching angles. The proposed method can compute the optimal solution of switching angles to eliminate the low order harmonics and minimize the THD value efficiently, as compare with traditional Genetic Algorithm (GA). With the proposed method, the required switching angles are computed efficiently by Improved PSO and proposed algorithm gives the better harmonic profile of the overall inverter system.

2 SHEPWM for PMSM

In the medium-voltage high-power traction system, the limitation of the switching frequency of the inverter leads to worse performance that the waveform of PWM has large harmonics. SHEPWM, a method to eliminate the selected low order harmonics by optimizing switching time sequence, has been concerned greatly as its advantages of lower equivalent switching frequency, higher quality output voltage [12].

2.1 PMSM Mathematical Model

The hysteresis and eddy-current loss of the system were neglected to show that the D-axis was overlapping the excitation-axis. The PMSM mathematical model under D-Q coordinates can be defined as:

$$\begin{cases} U_d = R_s i_d - \omega \psi_q + \dfrac{d\psi_d}{dt} \\ U_q = R_s i_q + \omega \psi_d + \dfrac{d\psi_q}{dt} \end{cases} \tag{1}$$

$$J\frac{d\omega_m}{dt} = T_{em} - T_L - R_\Omega \omega_m \tag{2}$$

$$T_{em} = \frac{3}{2} n_p \left[\psi_f i_q + (L_d - L_q) i_d i_q \right] \tag{3}$$

Where R_s, ω_m and i_d/i_q are the stator resistor, the angular velocity of the PMSM, and the current of the direct/quadrature-axis, respectively. Ψ_d and Ψ_q are the flux linkages of the direct and quadrature axes, respectively; T_{em} is the electromagnetic torque; and T_L is the load torque. J and R_Ω are the rotational inertia and the drag coefficient of the PMSM.

In the PMSM control strategy, U_d and U_q were calculated using the difference between the field ($i^*_{d/q}$) current and the actual ($i_d/_q$) current by using a proportional integral derivative (PID) algorithm in the inner current-loop. The flux linkage of the stator can be defined as follows:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{4}$$

Where Ψ_f is the permanent magnet flux, a constant determined by the properties of the permanent magnets.

2.2 Structure of Three-level Inverter

Fig. 1 shows the topology of the diode-clamped NPC three-level inverter in the PMSM system [13]. In addition, the inverter comprises two capacitors (C1 and C2), three bridges, each with four insulated gate bipolar transistor switches, and two clamped diodes. Each phase involves three types of switching states P, O, and N; this three-level inverter has 27 output modes.

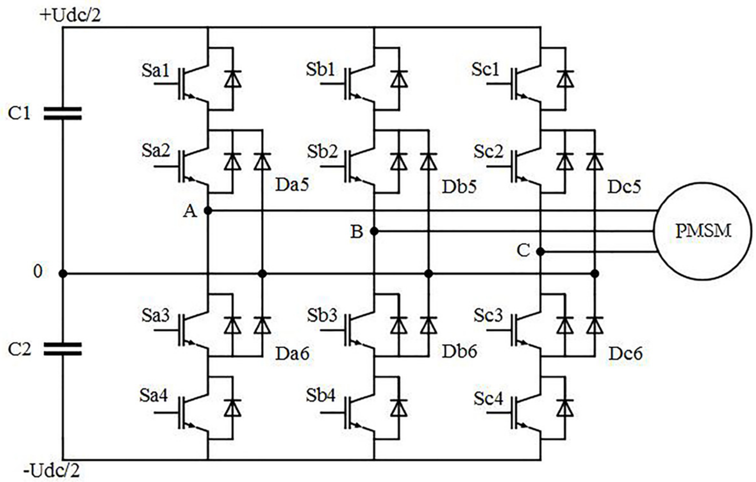


Fig. 1. Three-level inverter for the PMSM control system

For convenience, a switch state S_i is equal to

$$S_i = \begin{cases} \text{P, if } S_{i1,2} \text{ on and } S_{i3,4} \text{ off} \\ \text{O, if } S_{i2,3} \text{ on and } S_{i1,4} \text{ off}, \ (i = a,b,c) \\ \text{N, if } S_{i3,4} \text{ on and } S_{i1,2} \text{ off} \end{cases} \quad \textbf{(5)}$$

Therefore, the phase voltage Ui is defined as

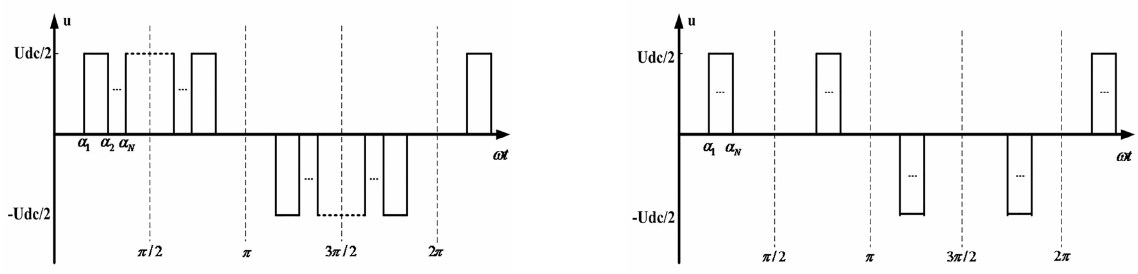
$$U_i = S_i \frac{U_{dc}}{2}, (i = a,b,c) \quad \textbf{(6)}$$

Where U_a, U_b, and U_c, represent the states of the three-phase output voltage of the inverter, and U_{dc} is the DC-link voltage.

2.3 Three-level Inverter SHEPWM Equations

SHEPWM is the most famous switching strategy that is widely used to specifically eliminate the selected order harmonics from the output waveform of the inverter. NPC produces output phase voltage with suitable switching angles. Initially, harmonics are in the output phase voltage. Furthermore, odd harmonics are difficult to calculate although the even harmonics is zero at the output phase voltage. Hence, SHEPWM method can use Fourier analysis function calculate the odd harmonics in the phase voltage.

The phase voltage of the three-level inverter was divided into unipolar and bipolar types. In this study, unipolarity was selected for SHEPWM because of the output mode of this topology [14]. Fig. 2(a) and Fig. 2(b) show a typical SHEPWM phase waveform of the NPC three-level inverter. The SHEPWM of the three-level converter has N angles ($0 < \alpha_1 < \alpha_2 < ... < \alpha_n < \pi/2$) in the first quarter period.



(a) SHEPWM wave with odd angles (b) SHEPWM wave with even angles

Fig. 2.

According to the Dirichlet conditions, the Fourier series of the phase voltage can be defined as follows:

$$u(\omega t) = \sum_{n=1}^{\infty} \left[A_n \cos(n\omega t) + B_n \sin(n\omega t) \right] \quad n = 0,1,2,3,\ldots \tag{7}$$

$$A_n = \frac{1}{\pi} \int_0^{2\pi} u(\omega t) \cos(n\omega t)\, d(\omega t) \tag{8}$$

$$B_n = \frac{1}{\pi} \int_0^{2\pi} u(\omega t) \sin(n\omega t)\, d(\omega t) \tag{9}$$

The phase voltage $u(\omega t)$ is both an even-symmetry function between π/2 and 3π/2, and an odd-symmetry function. Therefore, the phase voltage $u(\omega t)$ can be given as follows:

$$u(\omega t) = -u(\omega t + \pi) \tag{10}$$

$$u(\omega t) = u(\omega t - \pi) \tag{11}$$

Upon substituting equations (10), (11) into (8), (9) respectively, (8), (9) can be rewritten as follows:

$$A_n = 0, n = 0,1,2,3,\cdots \tag{12}$$

$$B_n = \begin{cases} 0, n = 2,4,6,8,\cdots \\ \dfrac{2U_{dc}}{n\pi} \left[\sum_{k=1}^{N} (-1)^k \operatorname{Cos}(n\alpha_k) \right], n = 1,3,5,7,\cdots \end{cases} \tag{13}$$

It is assumed that the entire harmonic wave has been eliminated, indicating that for n = 1, 2, 3..., B_n is zero except for B_1. Modulation index M is defined as:

$$M = \frac{B_1}{U_{dc}/2} \tag{14}$$

Upon substituting (14) into (13), (13) can be rewritten:

$$\begin{cases} B_1 = \dfrac{2U_{dc}}{\pi} \left[\sum_{k=1}^{N} (-1)^{k+1} \cos(\alpha_k) \right] = M \dfrac{U_{dc}}{2} \\ B_n = \dfrac{2U_{dc}}{n\pi} \left[\sum_{k=1}^{N} (-1)^{k+1} \cos(n\alpha_k) \right] = 0 \end{cases} \tag{15}$$

From (15), the SHEPWM equations are a set of nonlinear transcendental equations. Solving a set of exact solutions required by the equation is the key to eliminating specific harmonic. In order to more accurately solve the switching angles, this paper adopts an optimized particle swarm algorithm to solve the SHEPWM equations.

3 PSO Algorithm for SHEPWM

In 1995, Kennedy and Eberhart presented PSO which is an investigative method. PSO is a population based stochastic optimization technique inspired by social behavior of bird flocking and fish schooling. The PSO is an inherently continuous algorithm which has been successfully applied to solve a wide range of optimization problems such as continuous nonlinear and discrete optimization problems [15-17].

3.1 Standard PSO

In the basic particle swarm optimization algorithm, particle swarm consists of nth particles, and the position of each particle stands for the potential solution in D-dimensional space. In PSO, optimal solution depends upon *Gbest* and *Pbest*. *Gbest* known as global and *Pbest* known as personnel best. Every time particles can be updated to define the possible solution with respect to position and velocity vectors.

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

$$\begin{aligned} V_i^{k+1} &= \omega^k V_i^k + C_1 r_1 (Pbest_i^k - X_i^K) + C_2 r_2 (Gbest_i^k - X_i^K) \\ X_i^{k+1} &= X_i^k + V_i^{k+1} \\ \omega^k &= \omega_{\min} + \frac{\omega_{\max} - \omega_{\min}}{1 - iter / iter_{\max}} \end{aligned} \quad \textbf{(16)}$$

Where ω^k is inertia weight at iteration k, V_i is velocity of i^{th} particle at iteration k, C_1 and C_2 are acceleration factors, r_1 and r_2 are uniform random numbers $\in [0,1]$, $Pbest_i^k$ is best position of i^{th} particle at iteration k, X_i^k is position of i^{th} particle at iteration k, $Gbest_i^k$ is best position of the group till iteration k. $\omega_{\max}$, $\omega_{\min}$ are initial and final weights, $iter_{\max}$ is total number of iterations. The steps involved in PSO algorithm are given below.

Algorithm 1. Particle Swarm Optimization (PSO)

```
Initialize the particles' positions(Xi), velocity(Vi), previous best
positions (Pbesti), and the number of particles N.
while (t < maximum number of iterations (T)) do
  for all Particles (i) do
    Calculate the fitness function for the current position Xi of the i^th
    particle (F(Xi)).
    If (F(Xi) < F(Pbesti)) then
          Pbesti = Xi
    end if
    if (F(Xi) < F(Gbesti)) then
          Gbesti= Xi
    end if
    Adjust the velocity and positions of all particles according to Equations
    (16).
  end for
  Stop the algorithm if a sufficiently good fitness function is met.
end while
```

In the particle swarm optimization algorithm, the mutual cooperation between the particles makes the algorithm have a faster convergence speed than other optimization algorithms. However, when the group position is the local best, the PSO convergence too fast will make it difficult for the particles to jump out of this local optimal region.

3.2 PSO with Improved Inertia Weight

In the standard particle swarm optimization algorithm, the solution of particle swarm optimization algorithm is the process of gradual loss of diversity, particles continue to track the global optimum value and make the PSO showed a strong convergence in evolution. $w \times v$ determines the update of particle velocity when the particle reaches the local optimal value. Therefore, the inertia weighting factor plays an important role in the speed of particle swarm update, which in turn can affect the diversity of the particle group [18].

In this paper, nonlinear time-varying weights were selected, and at the same time, the random number affecting the global optimal solution was mutated to balance local search and global search, improving the interactive transmission of information between particles in the population and increasing the diversity of the population.

Sigmoid basic function is shown in Fig. 3. In the new inertia weight coefficient formed by the Sigmoid function, the inertia weight value was small at the beginning, so that the previous speed of the PSO can be maintained during the initial search process to explore the entire solution space, avoiding particles being attracted to local optimum and guarantee the correctness of the update direction. With the number of iterations increases, large inertia weights are used to obtain globally optimal particle swarms more efficiently, the function gradually becomes saturated when the weight reaches the maximum value.

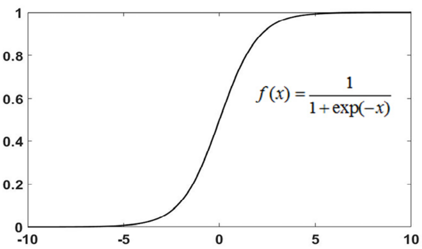


Fig. 3. Sigmoid basic function

The inertia weight expression of the time-varying Sigmoid function is as follows:

$$\omega(s) = 4\chi(1-\chi)\omega_{\min} + \frac{(\omega_{\max} - \omega_{\min})}{1 + \mu \exp(iter - a \times iter_{\max})} \quad \textbf{(17)}$$

χ is a uniformly distributed random variable, a is the contraction factor $\mu = 0.01 \times iter_{\max}$. The mutation operator that affects the global optimal solution random number is as follows

$$r_2^* = \frac{(1-\lambda_1)}{\sqrt{(Pbest_i^k - X_i^K)^2 + 1}} \quad \textbf{(18)}$$

The SHEPWM method is programmed by improved PSO algorithm using MATLAB/Simulink system. These SHEPWM together with Three-level NPC is used later on. In proposed SHEPWM method, PSO algorithm has been used to find the optimal solution for calculating the required switching angles. The no. of levels, maximum iteration, no. of switching angles and modulation index are initialized in PSO program. Meanwhile, using GA to solve the switching angles as comparative experiment. Table 1 presents the block parameter for the improved PSO algorithm, Table 2 presents the block parameter for the GA algorithm.

Table 1. Parameter used in improved PSO

Name	Value
No of runs	10
Switching angles	5
Population size	100
Acceleration constant C1 and C2	1.4
Inertia weight $\omega_{\max}$	0.9
Inertia weight $\omega_{\min}$	0.4
contraction factor a	0.75
Max Iteration	300

Table 2. Parameter used in GA

Name	Value
No of runs	10
Switching angles	5
Population size	100
SBX crossover constant n_c	2
Mutation constant n_m	20
Max Iteration	300

From Table 3, the improved particle swarm optimization algorithm can be used to reduce the harmonic distortion rate of the different modulation ratios compared with the genetic algorithm. When M=0.6, the THD of the improved PSO decreased by 1.64% compared with GA. When M=0.8, the THD of the improved PSO decreased by 1.26% compared with GA.

Table 3. Comparison of THD (%) for different M using GA and improving PSO

M	RMS output voltage (V_{oRMS})	GA	Improved PSO
0.5	86.602	7.37	5.79
0.6	103.923	6.57	4.93
0.7	121.243	5.69	4.07
0.8	138.564	4.79	3.53

4 Simulation and Experimental Results

Fig. 4 shows a vector control system schematic of a Three-level topology PMSM based on a maximum torque per ampere algorithm. The module calculated the modulation ratio (M) and angle of voltage vector (θ_v) for the PWM generation module.

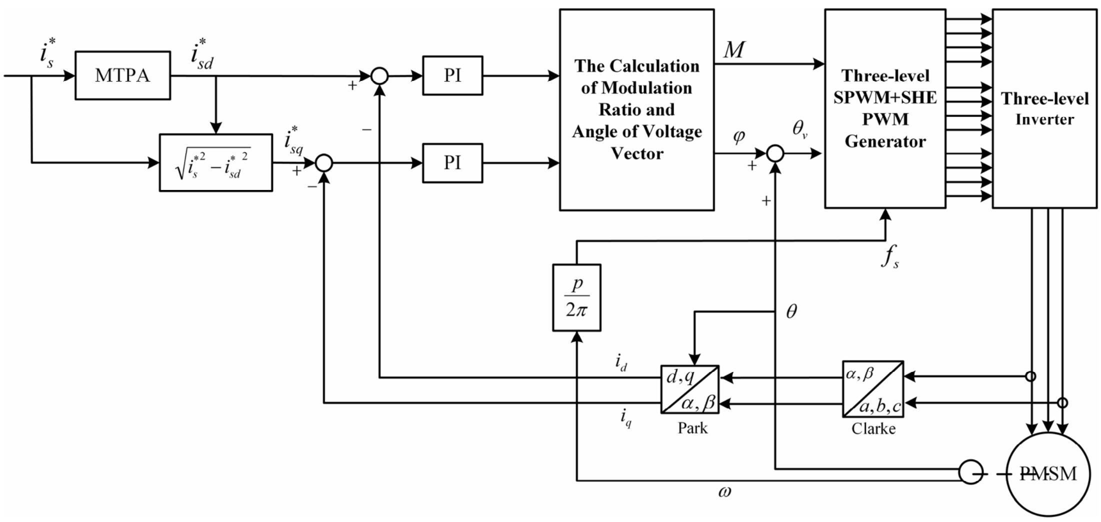


Fig. 4. PMSM control system schematic based on Three-level inverter

Fig. 5 summarizes the relation between the switching frequency and the motor speed (current frequency), which can be used to utilize modulations and to obtain the best performance of the PMSM.

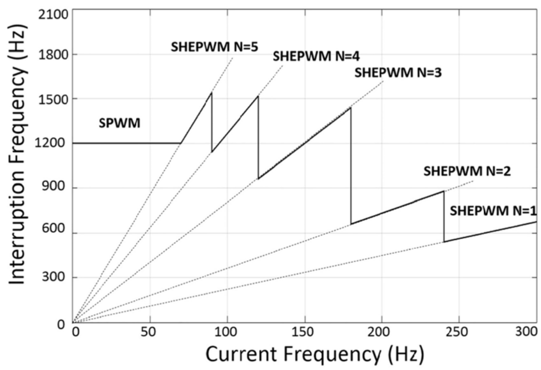


Fig. 5. Relation between the modulation and the switching frequency

In this study, the PMSM was surface-mounted, and three-phase symmetrical coils were employed in the stator. The simulation and experimental PMSM parameters are shown in Table 4.

Table 4. Simulation parameter of PMSM

Parameters	Value
Nominal voltage/V	200
Rated power/kW	22
Rated current/A	52
Rated torque/Nm	70
Rated speed/(r/min)	4000
Pole-pairs	4
Stator reluctance/Ω	0.22
D-axis inductance/mH	0.083
Switching frequency/kHz	2
Permanent Magnet Flux Linkage/Wb	0.05

When N=5, the Improved PSO and GA solve for the three-level SHEPWM line voltage as shown in Fig. 6, Fig. 7 respectively.

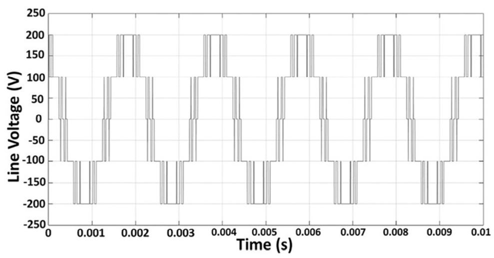


Fig. 6. Line voltage with Improved PSO (N=5)

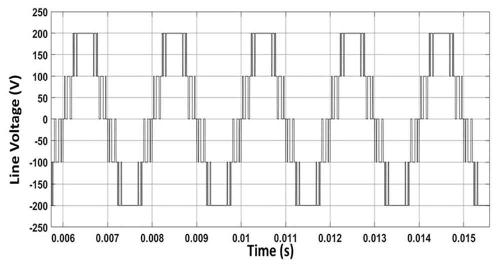


Fig. 7. Line voltage with GA (N=5)

When N=4, the Improved PSO and GA solve for the three-level SHEPWM line voltage as shown in Fig. 8, Fig. 9 respectively.

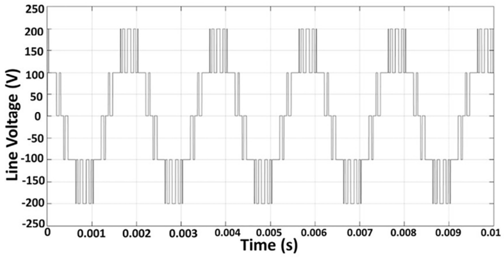


Fig. 8. Line voltage with Improved PSO (N=4)

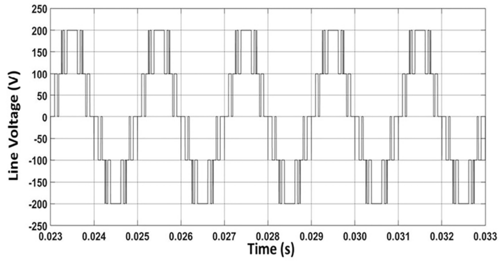


Fig. 9. Line voltage with GA (N=4)

The FFT analysis of stator current shows a significant improvement in reduction of total harmonic distortion (THD) in the Improved PSO approach compared to GA. The FFT analysis of stator currents verify that N switching angles per quarter cycle can eliminate N-1 harmonics. The Improved PSO and GA method THD result of N=5 and N=4 shown as Fig. 10 and Fig. 11 respectively.

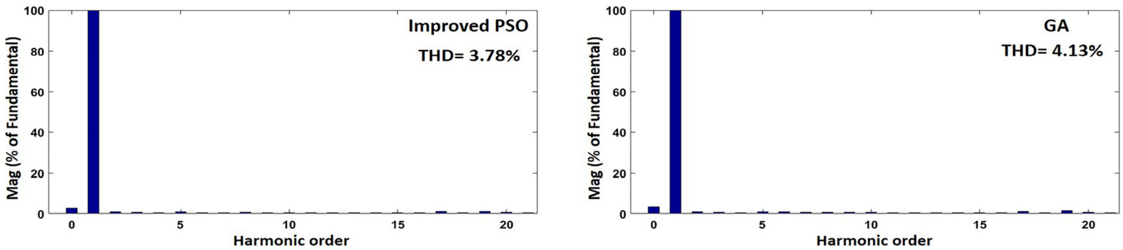


Fig. 10. FFT result with SHEPWM for N=5

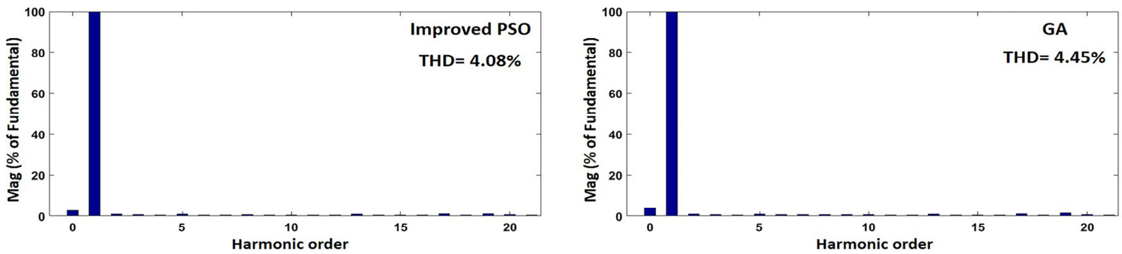


Fig. 11. FFT result with SHEPWM for N = 4

Fig. 12 and Fig. 13 show the PMSM and test device comprising a three-level inverter and the control system of the PMSM based on DSP TMS320F28335.

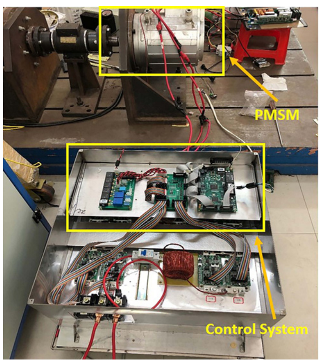


Fig. 12. PMSM drive system based on the three-level topology

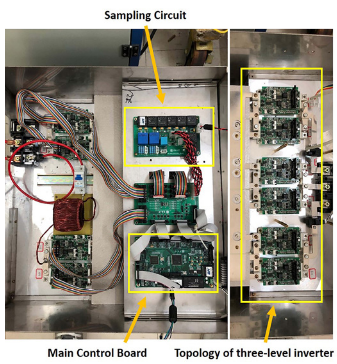


Fig. 13. Tree-level topology and PMSM controller

The experiment involved the study of current under different algorithm and switching angles. For the

SHEPWM with N = 4, the frequency of the stator current reached 120 Hz, indicating that the motor speed reached 1500 rotations per minute. The motor speed of this PMSM system was approaching its limits. Due to the limitation of the objective condition, the experimental results are partially complete SHEPWM with N = 5 and N = 4, respectively. The experimental results show that the SHEPWM with Improved PSO can provide a quality harmonic elimination.

Fig. 14 shows experimental result of the line voltage with Improved PSO method when the number of switching angles is 5. Fig. 15 shows experimental result of the line voltage with GA method when the number of switching angles is 5.

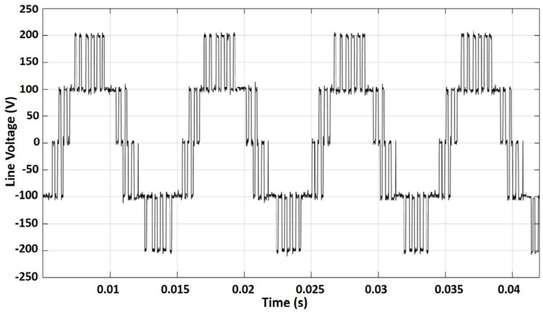


Fig. 14. SHEPWM line voltage with Improved PSO (N=5)

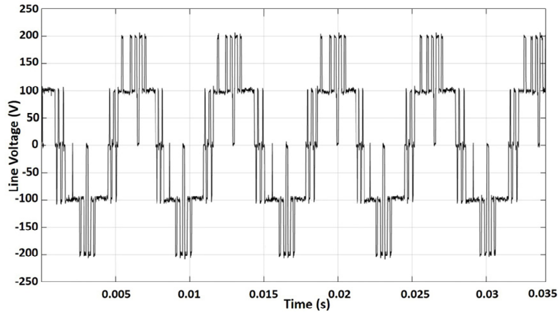


Fig. 15. SHEPWM line voltage with GA (N=5)

Fig. 16 and Fig. 17 show the PMSM stator current of phase A with improved PSO and GA method.

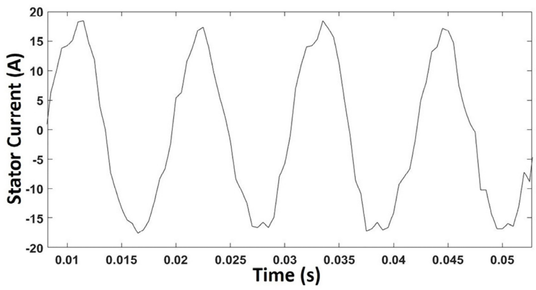


Fig. 16. Stator current of phase A with improved PSO (N = 5)

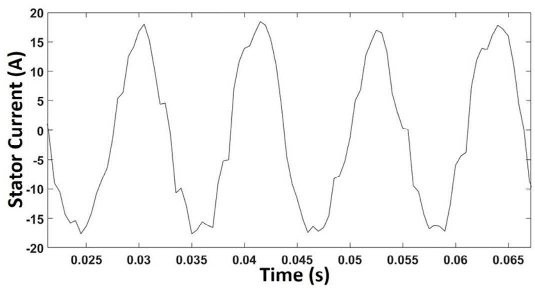


Fig. 17. Stator current of phase A with GA (N = 5)

Fig. 18 and Fig. 19 show experimental results of FFT analyses under different Algorithm for solving switch angle. The total harmonic distortions of the two method (Improved PSO for N = 5 and GA for N = 5) were 8.75% and 10.12%, respectively.

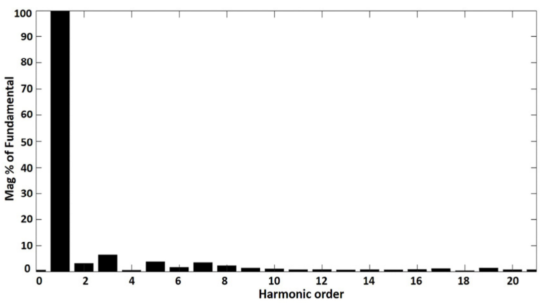


Fig. 18. FFT result with Improved PSO for N = 5 (experiment)

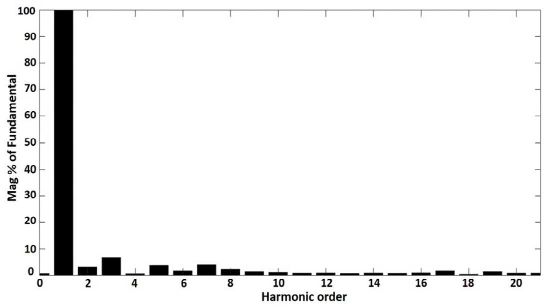


Fig. 19. FFT result with GA for N = 5 (experiment)

5 Conclusions

This paper proposed an Improved PSO method for SHEPWM applied on the three-level inverters in PMSM drive systems in order to satisfy the demands of low harmonic current in the high-speed condition. The method decreases the THD for the SHEPWM with different numbers of switch angles, which using the Improved PSO. Experimental and simulation results show Improved PSO can adaptively adjust the random number that affects the global optimal position in the later stage of the search while balancing the local optimal solution and the global optimal solution, and obtain the exact solution that meets the expectation, confirmed the effectiveness of the proposed method for selective harmonic elimination in the high-speed condition and a lower value of phase current THD.

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