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Neutral Point Clamped Single-phase Three-level Rectifier Operated with SHE-PWM Based on Improved Particle Swarm Optimization

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Abstract. The harmonic problems caused by converters influence the efficient and stable operation of electric railway systems. Rectifiers are the primary source of harmonic injection in converter system. In this paper, a selected harmonic elimination pulse width modulation (SHEPWM) scheme is presents for a Neutral Point Clamped single-phase three-level rectifier in electric railway traction systems. After the Fourier analysis of the harmonics, a calculation method based on improved Particle Swarm Optimization is proposed to solve the switching angles problems of SHEPWM. To verify the feasibility of the calculation results, a double-loop control scheme with a proportional resonant controller in a current inner loop was designed for coordination with the SHEPWM scheme. The viability and performance of the proposed method are shown through simulation and experimental results in a laboratory prototype.

Keywords: Neutral Point Clamped (NPC), Particle Swarm Optimization (PSO), Selective Harmonic Elimination Pulse Width Modulation (SHEPWM), single phase rectifier

1 Introduction

Due to grid pollution, there are a large number of low-order and high-order harmonics in the power grid. In the locomotive traction system, the traction motor is a significant part of the train, and the three-phase AC motor is driven by the AC-DC-AC converter system. A three-phase AC input motor with harmonics will have a certain negative effect, affecting the stability of the entire system. Therefore, the harmonic elimination of the converter system has certain research significance.

Currently, single-phase three-level converters are widely used as railway locomotive traction rectifiers due to their low current harmonics, unity power factor, stable and adjustable DC-link voltage [1]. The topology of a single-phase three-level neutral point clamped rectifier is shown in Fig. 1.

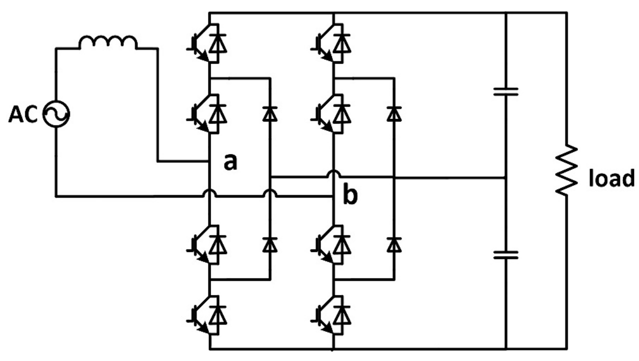

Fig. 1. Topology of NPC single-phase three-level rectifier

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The rectifier is the main source of harmonics throughout the converter system [2]. The harmonic current is amplified by resonance at a specific frequency. This causes various problems in railway systems such as interference in adjacent communication lines, overheating and vibration at the power capacitors [3]. In the pursuit of realising more safe and stable trains, increasingly more scholars are devoted to eliminating the problem of harmonic waves in rectifiers. The effects of harmonics and detailed models of harmonic current waves were analysed in a previous study, but no solutions were provided [4].

The traditional PWM modulation strategy generates a large number of low-order harmonics at low switching frequencies. The specific harmonic elimination pulse width modulation strategy (SHE-PWM) can effectively eliminate a certain number of harmonics completely, but needs to solve a set of nonlinear equations.

There are many solutions for the equation, such as the Homotopy method, Newton's method, Walsh transform, and intelligent algorithms such as the genetic algorithm, particle swarm optimization [5-8]. PSO is a optimization method for SHE-PWM problem that has been recently applied for various waveforms. PSO was used to find the solution of the switching angles that minimize the total harmonic distortion (THD) of the multilevel wave form rather than a complete elimination of low-order harmonics [9].

In this paper, a novel selected harmonic elimination pulse width modulation (SHEPWM) scheme for a single-phase three-level rectifier is proposed to eliminate specific harmonic waves. The rest of this paper is organised as follows: Derivation and Analysis of the Solution Equation of SHEPWM Switching Angles are analysed in Section 2. How to improve the PSO algorithm used by SHEPWM, how to use the switch angle to establish the objective function and judge the fitness are introduced in Section 3. The voltage outer-loop and current inner-loop control scheme, which is used to generate the modulation index 'M' and phase angle 'θ' for the proposed modulation, is analysed in Section 4. Simulation and experimental results are presented and analysed in Section 5. Finally, conclusions are summarized in Section 6.

2 The Solutions for Switching Angles of SHEPWM

Based on the analysis and method of calculation for switching angle in inverter, Perform Fourier decomposition on the AC terminal voltage 'U_{ab}' of single-phase rectifier (as showed in Fig. 2) The PWM waveform can be defined by a single equation as follows:

$$U_{in} = a_0 + \sum_{i=0}^{n} (A_n \sin n\omega_0 t + B_n \sin n\omega_0 t) \tag{1}$$

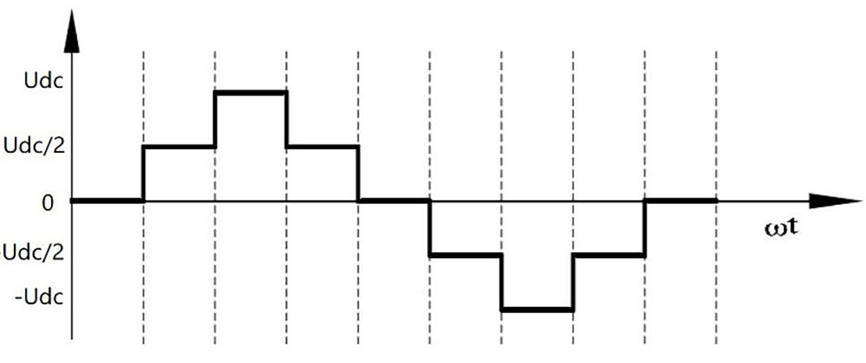


Fig. 2. Input reference multilevel waveforms of single phase rectifier

The multilevel waveforms match QW symmetrical, even harmonics and the sine coefficients of odd harmonics are all equal to zero, the equation can be simplified as:

$$A_n = \frac{2E}{n\pi} \sum_{k=1}^{\infty} -1^{k+1} cos\left(na_k\right) \tag{2}$$

The parameter a_k is the switching angles, and parameter k is the number of it. Define the value of "S_k" (If angle is the rising edge, "S_k" is 1; otherwise, "S_k" is −1), n is the number of harmonics then

$$A_n = \frac{2E}{n\pi}\sum_{k=1}^{m} S_k cos\left(na_k\right) \tag{3}$$

where parameter A_n is the amplitude of the nth harmonic, parameter m is the total number of switching angles, parameter E is the DC bus voltage.

M is the modulation index which is given by:

$$\mathrm{M} = \frac{A_1}{E} \tag{4}$$

This means that M can be interpreted as the ratio of the peak value of the rectifier's input reference voltage "A_1" and the value of the DC-link voltage "U_{dc}". Therefore, equation (**3**) can be modified as follows:

$$\sum_{i=1}^{m} S_k \cos(a_k) = \frac{\pi}{2}M \tag{5}$$

The main harmonic current wave is primarily concentrated in the 1000 Hz (20th) to 1500 Hz (30th) range. If the number of angles is set at 19, we can eliminate the 3rd, 5th, ... 37th harmonics, which cover the main harmonic frequency area. The switching frequency of the rectifier that is used in an electric train system is approximately in the 2 kHz to 10 kHz range. If the number of switching angles is 19, then the switching frequency is comparable to the normal level. According to the preceding analysis, the harmonic elimination formula is

$$\begin{cases} B_1 = \dfrac{2E}{\pi}\displaystyle\sum_{k=1}^{19} S_k \cos(na_k) = M \\ B_\mathrm{n} = \dfrac{2E}{\mathrm{n}\pi}\displaystyle\sum_{k=1}^{19} S_k \cos(na_k) = 0 \end{cases} \tag{6}$$
$$(n = 3,5,7...35,37)$$

There are multiple sets of solutions for the above nonlinear equations, and the solution is difficult. Can convert it into an optimization problem as follows:

$$\begin{aligned} &\min W((a1,a2....,a19) = (B_1 - M)^2 + \sum B_n^2 \\ &\text{s.t } 0 < a_1 < a_2 < ... < a_{19} < \frac{\pi}{2} \end{aligned} \tag{7}$$

The switching angles within the quarter period are constrained as

$$\begin{aligned} &\forall a_k \in \left(0, \frac{\pi}{2}\right) \\ &\forall a_k < a_{k+1} \\ &(k = 1,2...19) \end{aligned} \tag{8}$$

3 Proposed PSO Method

To solving nonlinear transcendental equations, the particle Swarm Optimization (PSO) is used. The population of the particle swarm algorithm consists of N real-coded particles [10], Define the decision variable as a set of 19 switch angles when solving the SHEPWM switch angle problem. The position vector of each particle is $\overline{X}_i = \{a1_i, a2_i, a3_i, \ldots a19_i\}$ .The velocity vector corresponding toeach particle is

$\vec{V}_i = \{V_{i1}, V_{i2}, V_{i3}, \ldots V_{i19}\}$ Let the set of solutions of all possible solutions for the nonlinear equation be a continuous search space. The best place for particles to pass their own history is $\overrightarrow{pbest}_i = \{pbest_{i1}, pbest_{i2}, pbest_{i3}, \ldots pbest_{i19}\}$. On the basis of it, the best position of the entire group is $\overrightarrow{gbest}_i = \{gbest_{i1}, gbest_{i2}, gbest_{i3}, \ldots gbest_{i19}\}$ the velocity vector of each particle is updated by considering the particle's current velocity and position which is given by

$$v_{i,j}^{G+1} = v_{i,j}^{G} + c_1 r_1 (pbest_{i,j}^{G} - x_{i,j}^{G}) + c_2 r_2 (gbest_{j}^{G} - x_{i,j}^{G}) \quad \textbf{(9)}$$

Parameter c_1, c_2 is the acceleration coefficient, r_1 and r_2 are randomly distributed random numbers between [0, 1]. $v_{i,j}^{c}$ is the inertial term of equation which reflects the memory of the particle's current speed. Inertia weights ω is added based on the classic PSO algorithm. Use inertia weight to control the effect of the previous speed on the current speed. Larger ω can enhance the global search capability of PSO. And smaller ω can enhance local search ability [11-13].

It is generally expected that particles have good search ability in the early stage of evolution, and have strong intensive mining ability in the later stage to improve convergence precision. The update of parameter ω is given by

$$\omega = 0.9 - \frac{(0.9 - 0.4) * G}{G_{\max}} \quad \textbf{(10)}$$

In this equation ω will linearly decrease from 0.9 to 0.4. This allows the PSO to search the set of solutions more comprehensively at the beginning, locate the approximate position of the optimal solution faster. As the ω decreases, the particle speed slows down and a fine local search begins. The improved velocity vector updated formula is given by

$$v_{i,j}^{G} = \omega v_{i,j}^{G} + c_1 r_1 (pbest_{i,j}^{G} - x_{i,j}^{G}) + c_2 r_2 (gbest_{j}^{G} - x_{i,j}^{G}) \quad \textbf{(11)}$$

The result of setting the minimum value equation is the objective function, and it is judged whether the fitness requirement is satisfied after each particle update is completed. Initialize the particle position and velocity at the beginning of the calculation, and obtain the converged switching angle after multiple iterations. Trend diagram of switching angle as a function of modulation is shown in Fig. 3.

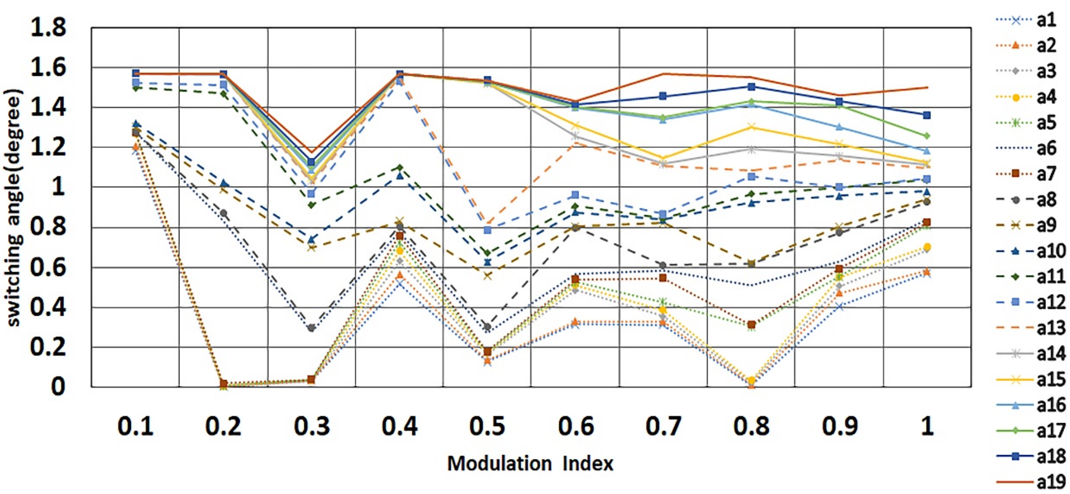


Fig. 3. Trend of switching angle with M

4 Double-Loop Control Scheme

To generate the modulation index 'M' and phase angle 'θ' for the SHEPWM scheme, the rectifier input reference voltage and the amplitude and phase of the rectifier input reference voltage is considered.

4.1 Generate the Rectifier Input Reference Voltage

Voltage outer-loop and current inner-loop double PI control is widely used to generate the rectifier input reference voltage for the modulation scheme in an electric railway traction system. A classical PI controller cannot eliminate the steady-state error in the current inner loop, and the steady state error causes a poor control effect. A proportional resonance controller can eliminate the steady-state error in the current inner loop. Simplified current inner loop is shown in Fig. 4.

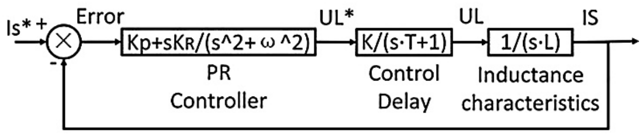


Fig. 4. Simplified current inner loop

When the input signal is a sine signal, parameter E(s) can be defined as

$$E(\mathrm{s}) = \frac{sLA\omega(Ts+1)}{sL(s^2+\omega^2)(Ts+1)+KK_p(s^2+\omega^2)+KK_R s} \tag{12}$$

The steady-state error can be eliminated by using the final value theorem:

$$\begin{aligned}
&\lim_{t->\infty} E(t) = \lim_{s->0} sE(\mathrm{s}) \\
&= s\cdot\frac{sLA\omega(Ts+1)}{sL(s^2+\omega^2)(Ts+1)+KK_p(s^2+\omega^2)+KK_R s} \\
&= \frac{s^2LA\omega(Ts+1)}{KK_p\omega^2+s[L(s^2+\omega^2)(Ts+1)+KK_p s+KK_R]} \\
&= 0
\end{aligned} \tag{13}$$

where the steady-state error is 0.

4.2 Amplitude Calculation and Phase-Locked Loop

After generate “U_{ab}” by using the voltage outer loop and current inner loop control, the amplitude and phase of “U_{ab}”. The angle ‘θ’ Angle can be calculated by the basis of the initial phase, the value of “M” can be calculated using equation (**14**).

$$M = \frac{U_{\mathrm{ab}}^*}{\sin(\theta)} \tag{14}$$

Fig. 5 shows the system of a single-phase three-level rectifier with SHEPWM.

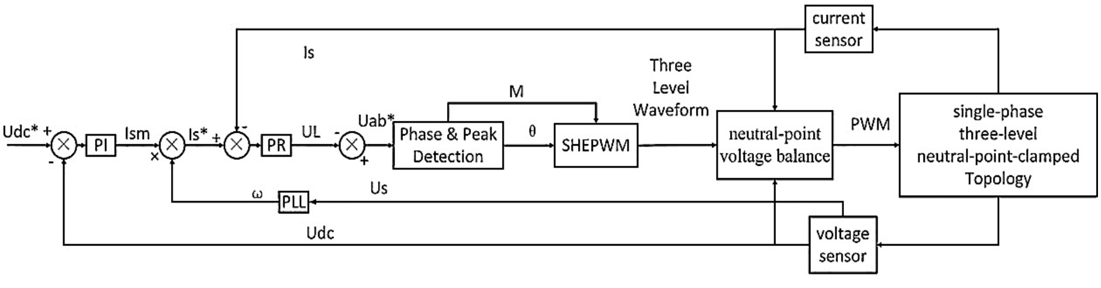


Fig. 5. Single-phase three-level rectifier system

5 Simulation and Experimental Results

5.1 Simulation Results

In order to analyze the switching angle of improved PSO to eliminate the harmonic performance, a single-phase three-level simulation model of SVPWM and SHEPWM was built, Compare SVPWM, single PR and improved PSO. The main simulation model parameters are listed in Table 1.

Table 1. Simulation model parameters

Parameters	Value
Grid Voltage (RMS) U_N /V	220
Grid Voltage Frequency F_{UN} /Hz	50
Boost Inductor L/H	4.7×10^{-3}
DC-link Capacitors C_1 & C_2 /F	4.7×10^{-3}
Load R/Ω	10
Output Reference Voltage U_{dc} /V	1100
Number of Switch Angle	19
Simulation Time Step L/s	10^{-7}

The simulation parameters, including the grid voltage, boost inductance, capacitance, output reference voltage, and switching frequency, are the same as the parameters of the multiple-unit trains of CRH (China Railway High-speed). Simulating AC input voltage and input DC voltage waveform through the rectifier of SHEPWM is shown as Fig. 6 (M is stable at around 0.8).

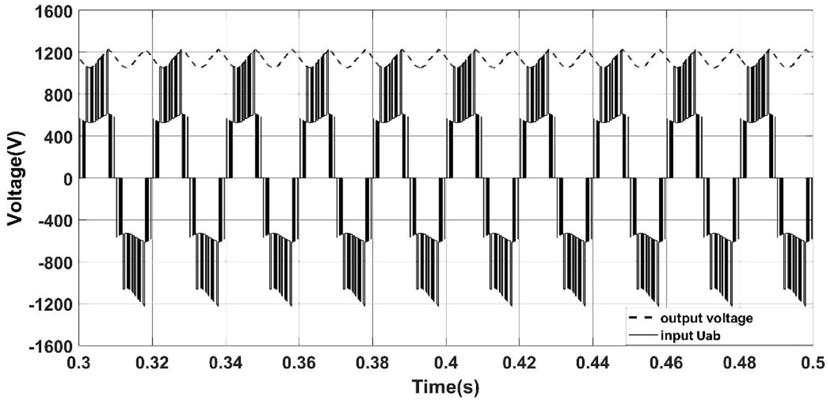


Fig. 6. Input and output voltage of rectifier

Compare the harmonic elimination and THD results of the three schemes as shown in Fig. 7.

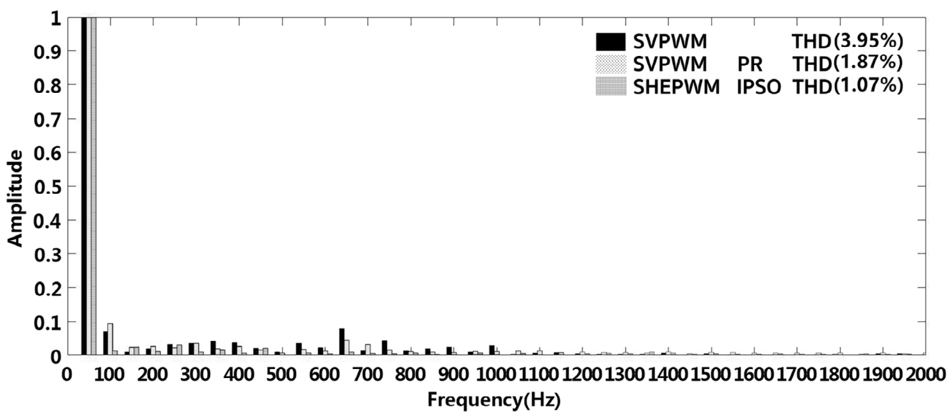


Fig. 7. FFT analysis and THD comparison

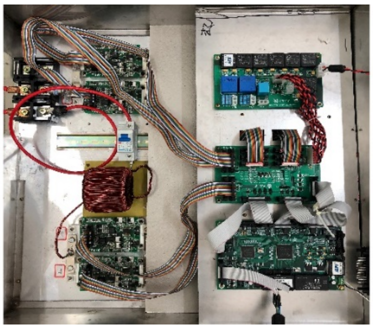
5.2 Experimental Results

Based on the simulation results, an experimental platform was built. Utilize an FPGA-based main control board, the performance of harmonic elimination based on improved PSO was verified. The primary scaled-down experimental prototype parameters are listed in Table 2.

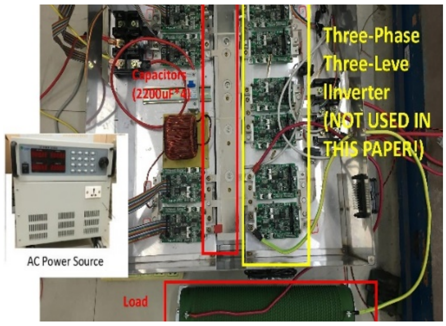
Table 2. Scaled-down experimental prototype parameters

Parameters	Value
Grid Voltage (RMS) U_s /V	20
Grid Voltage Frequency F_{UN} /Hz	50
Boost Inductor L/uH	1001.87
DC-link Capacitors C_1 & C_2 /uF	4400
Load R/Ω	10
Output Reference Voltage U_{dc} /V	120

Fig. 8 shows laboratory prototype. Fig. 9 shows the experimental Grid voltage and current and output voltage. The rectifier output voltage fluctuating near the reference voltage from 112V to 130V, the ripple voltage was less than 8.34%. Fig. 10 shows the three-level rectifier input voltage. As shown in Fig. 11 to Fig. 13, even harmonic currents and the selected odd harmonic currents were eliminated.

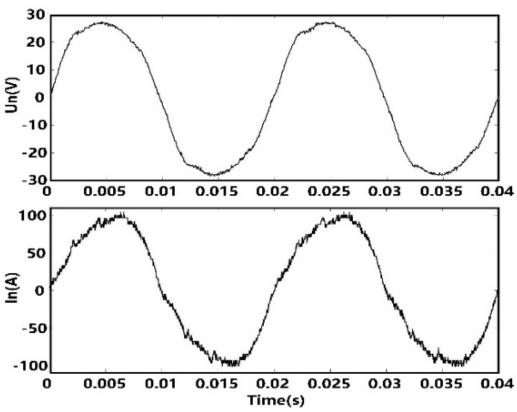


(a) First layer of laboratory prototype (control part)

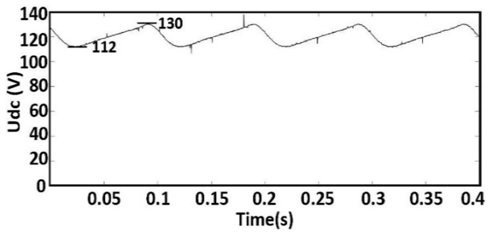


(b) Second layer of laboratory prototype

Fig. 8. laboratory prototype of rectifier



(a) Grid voltage and current



(b) output voltage

Fig. 9. Input voltage and current of grid and output voltage of rectifier

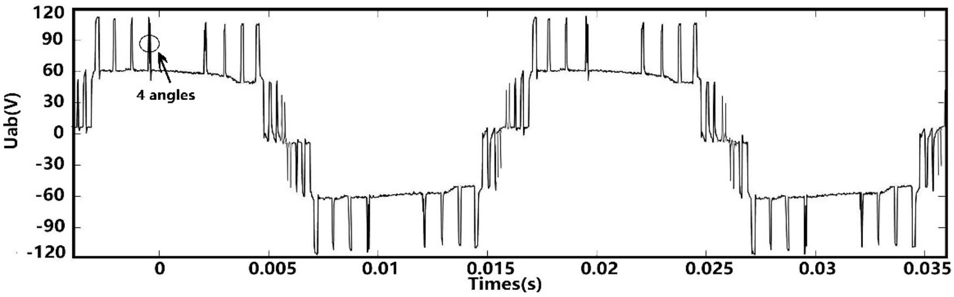


Fig. 10. Input voltage and current and output voltage of rectifier

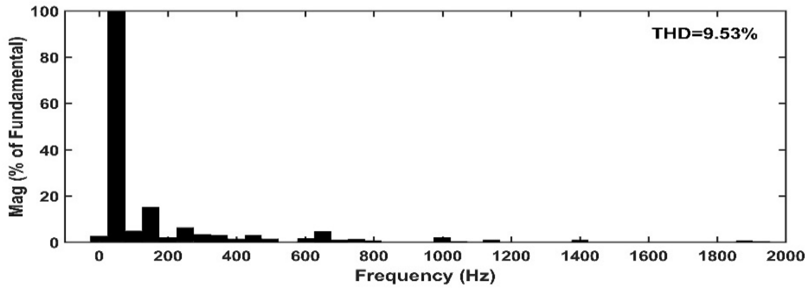


Fig. 11. FFT analysis of grid current (SVPWM)

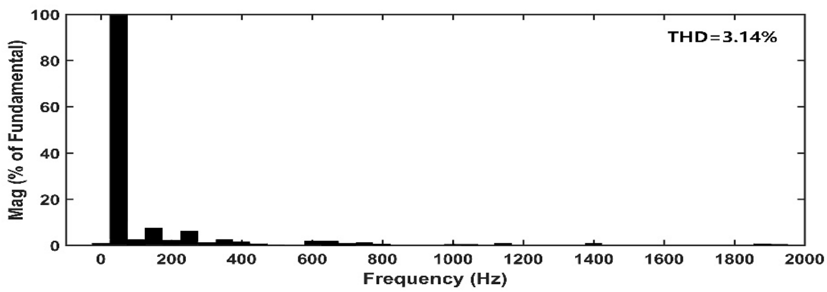


Fig. 12. FFT analysis of grid current (SVPWM+PR)

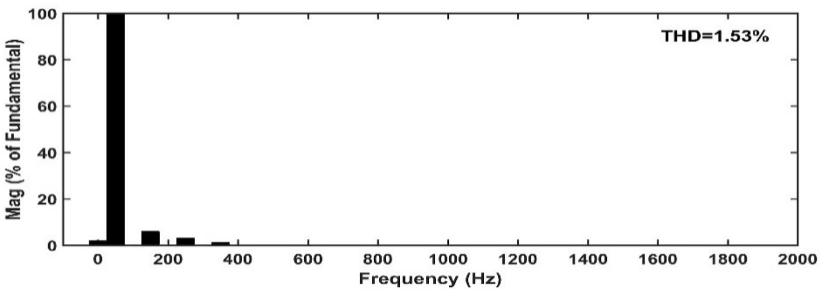


Fig. 13. FFT analysis of grid current (SHEPWM+PR)

6 Conclusions

A SHEPWM scheme was analysed and developed for single-phase three-level rectifiers. By using improved PSO to solve the rectifier SHEPWM switching angle, the dependence of the traditional solution on the initial value is eliminated. The proposed method eliminates the specific harmonics and reduces the rectifier AC measurement THD. Moreover, the simulation and experimental results confirmed the effectiveness of the proposed method in automatically achieving a precise pulse output, selected harmonic elimination, low THD, and constant output voltage.

Acknowledgements

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References

[1] S.L. Wang, W.S. Song, J.H. Zhao, X.Y. Feng, Hybrid single-carrier-based pulse width modulation scheme for single-phase three-level neutral-point-clamped grid-side converters in electric railway traction, Let Power Electron 9(13)(2016) 2500-2509.

[2] H.J. Kaleybar, H.M. Kojabadi, M. Brenna, F. Foiadelli, S.S. Fazel, An active railway power quality compensator for 2x25kV high-speed railway lines, in: Proc. IEEE 2017 1st International Conference on Environment and Electrical Engineering and IEEE 2017 17th Industrial and Commercial Power Systems Europe, 2017.

[3] H. Lee, C. Lee, G. Jang, S.-H. Kwon, Harmonic analysis of the Korean high-speed railway using the eight-port representation model, IEEE Transactions on Power Deliver 21(2)(2006) 979-986.

[4] M.-Y. Hsieh, Y.-M. Huang, H.-C. Chao, Adaptive security design with malicious node detection in cluster-based sensor networks, Computer Communications 30(11-12)(2007) 2385-2400.

[5] K.-H. Yang, D.-Y. Lu, X.-Q. Kuang, Z.-B. Yuan W.-S. Yu, Harmonic elimination for multilevel converters with unequal DC levels by using the polynomial homotopy continuation algorithm, in: Proc. IEEE Chinese Control Conference, 2016.

[6] T. Mistry, S.K. Bhatta, A.K. Senapati, A. Agarwal, Performance improvement of induction motor by Selective Harmonic Elimination (SHE) using Newton Raphson (N-R) method, in: Proc. IEEE International Conference on Energy Systems and Applications, 2015.

[7] J. Dai, G. Li, C. Hu, Study on a new method to eliminate the common-mode voltage based on improved SHEPWM, in: Proc. IEEE Industrial Electronics and Applications, 2015.

[8] E. Deniz, O. Aydogmus, Z. Aydogmus, GA-based optimization and ANN-based SHEPWM generation for two-level inverter, in: Proc. IEEE International Conference on Industrial Technology, 2015.

[9] M.S.A. Dahidah, G. Konstantinou, V.G. Agelidis, A Review of Multilevel Selective Harmonic Elimination PWM: Formulations, Solving Algorithms, Implementation and Applications, IEEE Transactions on Power Electronics 30(8)(2015) 4091-4106.

[10] L. Zhang, S.-T. Yang, J. Li, L.-L. Yu, A particle swarm optimization clustering-based attribute generalization privacy protection scheme, Journal of Circuits Systems & Computers 27(11)(2018) 1850179.

[11] H.-Y. Liu, S.-H. Xu, X.-Z. Liang, A modified quantum-behaved particle swarm optimization for constrained optimization, Journal of Computers 9(9)(2014) 703-706.

[12] G.-Y. Zhang, X. Xiao, J.-T. Xu, K.-M. Nie, Z.-Y. Gao, Particle swarm optimization design of low-power multistage amplifier using gm/ID methodology, Journal of Circuits Systems & Computers 25(9)(2016) 1650104.

[13] C. Zhu, E. Jiang, J. Zhang, J. Li, L. Zhao, A study on roughness coefficient using BP neural network, Journal of Computers 5(9)(2010) 20-23.