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An Optimal Random Carrier Pulse Width Modulation Technique Based on a Genetic Algorithm

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Abstract

Since the carrier sequence is not reproducible in a period of the random carrier pulse width modulation (RCPWM) and a higher harmonic spectrum amplitude is likely to affect the quality of the power supply. In addition, electromagnetic interference (EMI) and mechanical vibration will appear. To solve these problems, this paper has proposed an optimal RCPWM based on a genetic algorithm (GA). In the optimal modulation, the range of the random carrier frequency is taken as a constraint and the reciprocal of the maximum harmonic spectrum amplitude is used as a fitness function to decrease the EMI and mechanical vibration caused by the harmonics concentrated at the carrier frequency and its multiples. Since the problems of the hardware make it difficult to use in practical engineering, this paper has presented a hardware system. Simulations and experiments show that the RCPWM is effective. Studies show that the harmonic spectrum is distributed more uniformly in the frequency domain and that there is no obvious peak in the wave spectra. The proposed method is of great value to research on RCPWM and integrated power systems (IPS).

Key words: EMI, GA with a constraint, Mechanical vibration, Optimal carrier sequence, RCPWM

I. Introduction

Generally, pulse width modulation (PWM) has a wide range of applications in electronic and electric fields. This technology is used to modulate different waveforms by controlling the on-off switches to determine the duty ratio. However, a large number of harmonics accumulated at the carrier frequency and its multiples may cause a series of problems, such as electromagnetic interference, unexpected noise, mechanical vibration, and inoperability of some sensitive equipment. These problems are largely due to the poor quality of the power supply with plenty of harmonic.

According to the viewpoint that the duty ratio is independent of the switching frequency and the conduction position, both of which affect the spectrum distribution of the output voltage, A. M. Trzynadlowski proposed random pulse width modulation (RPWM). It seems to be a promising way to disperse the harmonic peaks around the carrier frequency and its multiples [1]-[3]. As a result, various researches are based on what is mentioned. According to the research of A. M. Trzynadlowski and Kirlin R's team, the RPWM can be classified into RCPWM, random switching PWM (RSPWM) and random pulse position PWM (RPPPWM). The other two random PWM technologies can be elucidated by the theory of RCPWM. However, the validity of RCPWM is more often judged by experiment than by theoretical analysis due to the non-existence of Fourier transformation in random harmonic so as not to deduce the expressions for the spectrum of RCPWM [4], [5]. For example, the research of F. M. Ma focused on the range of the random carrier frequencies and so the maximum harmonic spectrum amplitude declined 50% compared with the fixed carrier pulse width (FCPWM) when the fluctuating range of the random carrier frequencies is three times as large as that of the fundamental frequency [6]. Bin Wang presented a dual random PWM to obtain a more uniform distribution of the harmonic frequency spectra by adding random parameters [7]. Recently, some researchers have paid a lot of attention to the statistical parameters of the random carrier frequency to reduce EMI and mechanical vibration.

Although the above mentioned methods have some effect on

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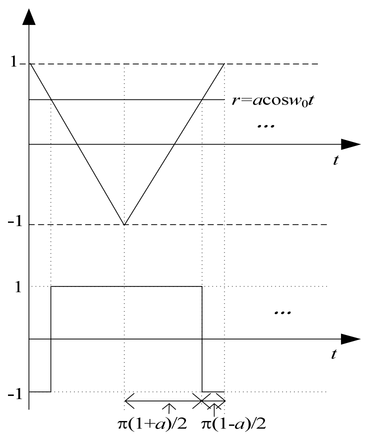


Fig. 1. Model of general pulse width modulation.

harmonic suppression, the random carrier sequence may not be an optimal one in each modulation cycle and the quality of the output power supplied varies with the random carrier sequence in different periods of time. Generally, there are still problems with the existing RCPWM methods as follows:

1) The value range of a random carrier frequency is uncontrollable. That is to say, the switching loss is increased when the carrier frequency is too high or mechanical vibration appears when the random carrier frequency is too low, especially, lower than 1000 Hz.

2) The quality of the output voltage is uncontrollable. Problems of electromagnetic compatibility will occasionally arise from an output voltage controlled by unpredictable pseudo random numbers, which may produce prominent peaks at some frequency points.

3) The real-time appearance of pseudo random numbers increases the amount of computation and introduces difficulties to the application of hardware.

A method to choose an appropriate random carrier frequency sequence which can be easily used is a problem which urgently needs to be solved. For this reason, this paper proposes a method involving a genetic algorithm combined with RCPWM. It also presents an experiment system based on the FPGA.

In order to obtain an optimum random carrier sequence, the value range of the carrier frequency is taken as a constraint and the reciprocal of the maximum amplitude of the harmonic spectra is taken as a fitness function to evaluate the quality of output voltage, thereby suppressing higher harmonic spectrum amplitudes.

A new hybrid optimal RCPWM hardware implementation scheme is proposed. Only a FPGA PCB is included, which means that an optimal off-line random carrier frequency sequence is stored in the FPGA to reduce the amount of computation and to guarantee the quality of the output voltage.

This paper includes several sections as follows. Section II is about the basic principle of RCPWM. Section III presents a model for combining a genetic algorithm with RCPWM. Section IV presents the results and analysis of RCPWM based on a genetic algorithm through a hardware platform with a 35 kW inverter to measure the output voltage and vibration acceleration. A comparison of FCPWM with the ordinary and optimized RCPWM shows that the voltages and vibration acceleration waveforms of the optimized RCPWM based on a genetic algorithm and the conventional RCPWM methods are distributed in a nearly flat state without any prominent harmonic peaks. What is more, the voltage and vibration acceleration waveform of the optimal RCPWM are similar to those of the conventional RCPWM. However, the voltage and vibration acceleration spectra of the optimal RCPWM are dispersed in a much flatter way. Section V provides some conclusions.

II. BASIC PRINCIPLE OF RCPWM

Fig. 1 shows a typical mathematic pulse width modulation model. The triangular carriers are taken as a series of sequences, which are used to modulate the signals.

In Fig. 1(a), U_c is the triangular carrier signal, U_s is the cosine modulation signal, a is the modulation depth, and w_0 is the fundamental angular frequency of the modulation signal. Partial amplification of pulse width modulation under the condition of average symmetric sampling is shown in Fig. 1(b).

A. FCPWM

If each T_i in Fig. 1(a) is equal, the general pulse width modulation model turns out to be a FCPWM. A Fourier expansion of the output voltage U_o leads to the following equation.

$$U_o = r + \sum_{n=1}^{\infty}(\frac{4}{n\pi})\sin[\frac{nr\pi}{2}\sin(\omega_0 t) + \frac{n\pi}{2}]\cos(n\omega_s t) \quad (1)$$

where $r{=}a\cos w_0 t$, w_s is the carrier angular frequency, and n is the harmonic order. The first item in Equation (1) can be determined when the fundamental angular frequency w_0 and modulation depth a are given. The second item is made up of the harmonic components and its spectrum is determined by the carrier angular frequency w_s. Each harmonic spectrum is accumulated at the same carrier angular frequency and its multiples. This is why unexpected harmonics cause a series of electromagnetic problems.

The second item in Equation (1) can be transformed by the first kind of Bessel function into：

$$\begin{aligned} H = &\sum_{n=1}^{\infty}(\frac{4}{n\pi})\{2\sum_{l=1}^{\infty}J_{2l-1}(\frac{an\pi}{2})[\sin[(2l-1)(\omega_0 t)]\cos\frac{n\pi}{2} \\ &+[J_0(\frac{rn\pi}{2})+2\sum_{l=1}^{\infty}J_{2l}(\frac{a\pi}{2})\cos(2l)(\omega_0 t)]\sin\frac{n\pi}{2}\}\cos(n\omega_s t) \end{aligned} \quad (2)$$

Hence, the harmonic spectra amplitudes A, and the total harmonic distortion (THD) can be expressed as:

$$A = (4U/n\pi)\times J_k(an\pi/2) \quad (3)$$

$$\mathrm{THD} = \sqrt{\sum_k(\frac{4J_k(an\pi/2)}{an\pi})^2} \times 100\% \quad (4)$$

where J_k is the first kind of Bessel function (k=1,3,⋯,n=2,4,⋯; k=0,2,⋯,n=1,3,⋯). As indicated by the above calculation, the harmonic spectrum amplitudes and THD are only related to the modulation depth.

B. RCPWM

Similarly, a RCPWM model, including its characteristics, can be deduced as follows.

If T_i in Fig. 1(a) changes randomly, the general pulse width modulation model turns out to be a RCPWM. By adding the angular frequency w_s randomly, equation (1), the RCPWM can be expressed as:

$$U_o = r - \sum_{n=1}^{\infty}\sum_{i}(\frac{4}{n\pi})\cos[\frac{nr\pi}{2}+\frac{(n-1)\pi}{2}]\cos(n\omega_i t) \qquad (5)$$

Similarly, the first item in Equation (5) is the fundamental frequency component and the second can be seen as a constant part, $(4/n\pi)\sin[(n\pi/2)\sin(\omega_0 t)+(n\pi/2)]$, multiplied by the random part, $\cos(nw_i t)$. In the frequency domain, the constant part is shifted by a random carrier angular frequency w_i since multiplication in the time domain is a convolution in the frequency domain. When the carrier angular frequency changes randomly in each modulation period, the harmonic spectrum cannot be accumulated at the same frequency or its multiples. The amplitude of the fundamental frequency spectrum and THD of the RCPWM are keep the same as those of the FCPWM, that is to say, the quality of the power supply is enhanced.

According to the above analysis, it is obvious that the fundamental frequency component and THD do not change while the harmonics are distributed randomly in the frequency domain. However, the carrier frequency changes in the RCPWM. Thus, the RCPWM cannot effectively eliminate the noise accumulated at the carrier frequency. Instead it shifts the harmonics' spectrum according to w_i in a wider frequency domain.

III. OPTIMAL RCPWM BASED ON A GENETIC ALGORITHM

A. Genetic Algorithm

The genetic algorithm provides a simpler method of searching and an optimized approach based on biological evolution theory. It has been widely used in many fields [8]. Its basic procedures are shown in Fig. 2.

The genetic algorithm is used to select an optimal solution from a population according to a fitness function after the encoding of the population. According to the result of the selection, a sub-population is generated by a crossover and mutation function. The sub-population stops searching after meeting the expected requirements. The process of its operation is so simple and easy to understand that the genetic algorithm has been used in more and more fields for optimum selection through an abstract model.

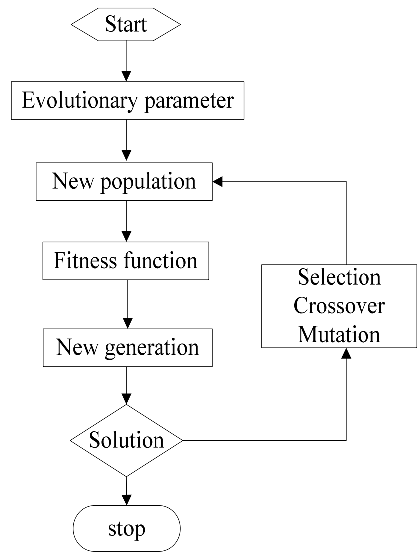


Fig. 2. Procedures of the genetic algorithm.

TABLE I
CORRESPONDING PARAMETERS RELATIONS BETWEEN GA AND RCPWM

Genetic algorithm	RCPWM
Gene	Carrier
Chromosome	Random carrier sequence
Population	A series of random carrier sequence
Fitness function	Reciprocal of the maximum harmonic
Individual	Solution
Reproduction	Choosing Chromosome based on fitness
Crossover	Producing carrier by exchanging code
Mutation	Producing carrier by changing code

B. Optimization for RCPWM based on a Genetic Algorithm

Based on the above analysis as well as the genetic algorithm, the RCPWM based on a genetic algorithm is described in this section.

Specifically, the corresponding relations of the principal parameters between a genetic algorithm and the RCPWM are shown in Table I. And a detailed flowchart is depicted in Fig. 3.

As shown in Fig. 3, a random carrier f_i is encoded as a gene in the genetic algorithm, the random carrier sequence corresponds to a chromosome in the genetic algorithm and the fitness function is the reciprocal of the maximum amplitude of the harmonic spectrum H_{max}, which is used for evaluating the quality of the output harmonic spectrum. Specially, Δf is a constraint which limits the value range of the random carrier frequency. Δf is expressed as:

$$f_c = f_{av} \pm \Delta f \qquad (6)$$

In order to control the switching loss, the switching time in the RCPWM should be the same as that used in the FCPWM. In addition, Δf limits the value range of the carrier frequency so as to ensure that the carrier frequency f_c is not too high or too low. A genetic algorithm with constraints set for the RCPWM is an innovative approach in the electronic domain.

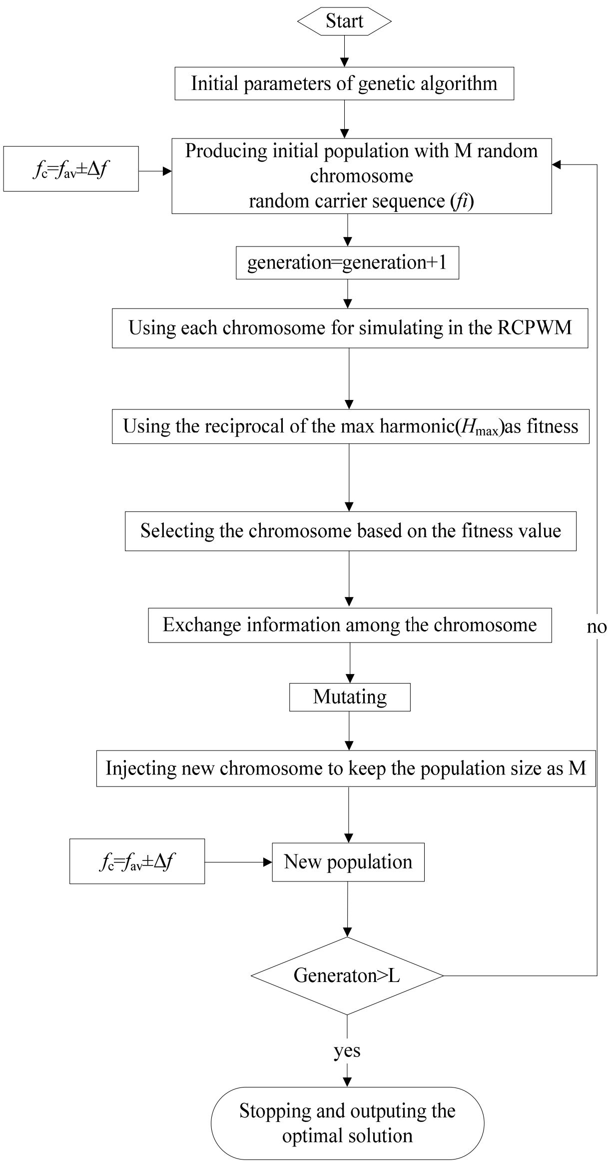


Fig. 3. Optimal RCPWM based on the genetic algorithm with constraint.

IV. Simulation and Experiment

A. Simulation and Analysis

To verify the optimal RCPWM proposed in this paper, the MATLAB simulation conditions have been set, which include the main circuit of a single phase two-arm bridge inverter, the DC input voltage 300 V, the fundamental frequency f_0=50Hz, modulation depth a=0.8, the value of the fixed carrier frequency f_c =5 kHz, the mean value of the random carrier frequency f_{av} =5 kHz, and 200 random carriers within 0.02 seconds during the RCPWM.

In addition, comparisons of the FCPWM, the conventional RCPWM, and the optimal RCPWM based on a genetic algorithm have been compared. The above mentioned parameters can maintain and fix the same number of switching times in the same period of the RCPWM. The main circuit of the inverter adopts the same topology, which is a single phase two-arm bridge, to ensure a fair comparison.

TABLE II
Parameters of the Main Circuit

Parameter	Value
DC input voltage	300V
Modulation depth	0.8
Resistance	10Ω
Inductance	2mH
Fundamental frequency	50Hz
Fixed carrier frequency	5kHz
Mean value of the random carrier frequency	5kHz
Repetition period of RCPWM	0.02s

The relevant parameters are shown in Table II.

Fig. 4 and Fig. 5 give an analysis of the MATLAB simulation results for the output voltages of the FCPWM and the conventional RCPWM, respectively.

As shown in Fig. 4, the spectra are obviously accumulated around the carrier frequency (f_c =5 kHz) and its multiples. The harmonic peak value at 5 kHz is close to 120% of the fundamental frequency amplitude. The peaks appearing around the carrier frequency and its multiples cause electromagnetic interference and malfunctions inside the power system as well as mechanical vibration and noise of the external load.

In Fig. 5, the maximum harmonic spectrum is near to 30% of the fundamental frequency amplitude, that is, almost 70% decreases. It is worth noting that the harmonic spectra lines concentrated at the carrier frequency and its multiples, such as 5 kHz, 10 kHz and 15 kHz in Fig.4, are scattered. As shown in Fig. 5, there are no longer peaks in the spectra of the RCPWM. This means that there is no energy concentrated at the carrier and its multiples when the signal is modulated by random carrier frequencies. Accordingly, the problems caused by the harmonics can be solved.

However, the maximum value of the harmonic spectrum varies with the random carrier sequence. Therefore, it is difficult to guarantee the quality of the output power supply. This is why a genetic algorithm is used to optimize the RCPWM.

Before the application of the optimization for the RCPWM based on a genetic algorithm, the value of Δf must be determined.

The wider the value of Δf is, the more varied the span of the random carrier sequence becomes and the more dispersed the spectra of the output voltages are. However, the spectra of the harmonics are prone to accumulating at a low frequency as the value of Δf becomes wider. On the other hand, the spectra of the output voltages cannot be fully dispersible in the frequency domain and obvious peaks cannot be decreased.

Fig. 6(a), (b) and (c) show the spectra of the output voltages

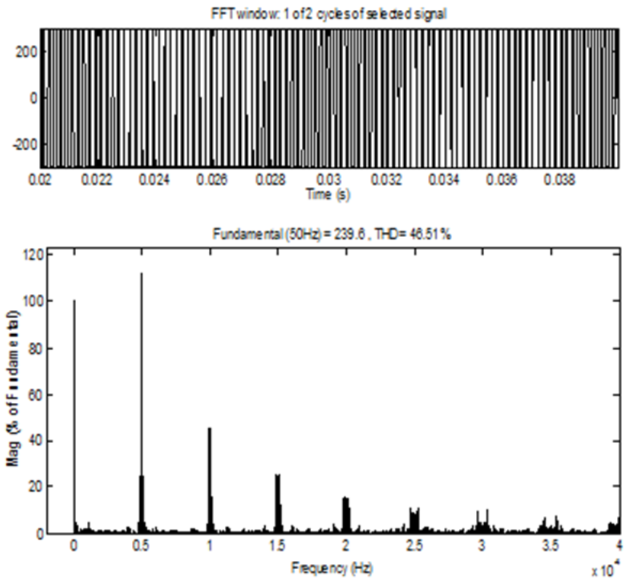


Fig. 4. The analysis of the output voltage spectrum of the FCPWM (f_c=5 kHz, f_0=50Hz).

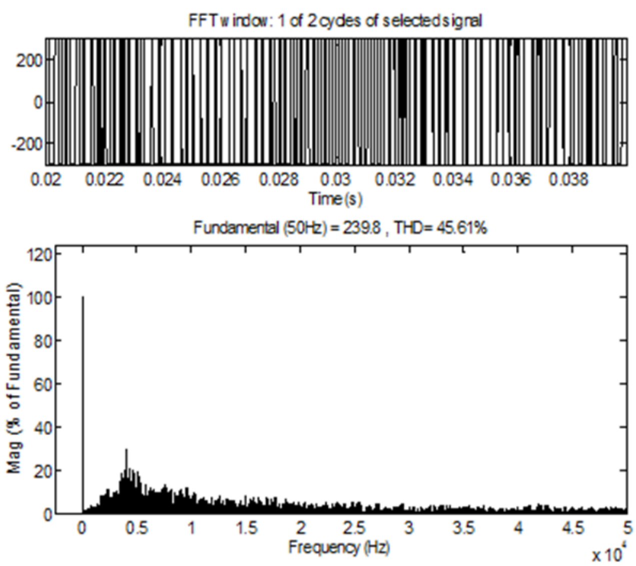
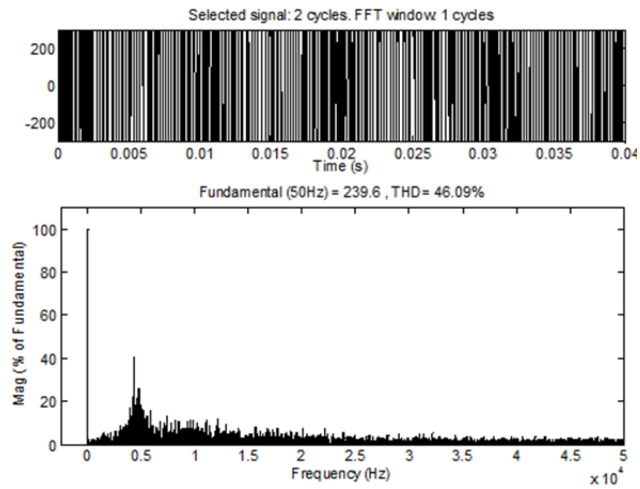


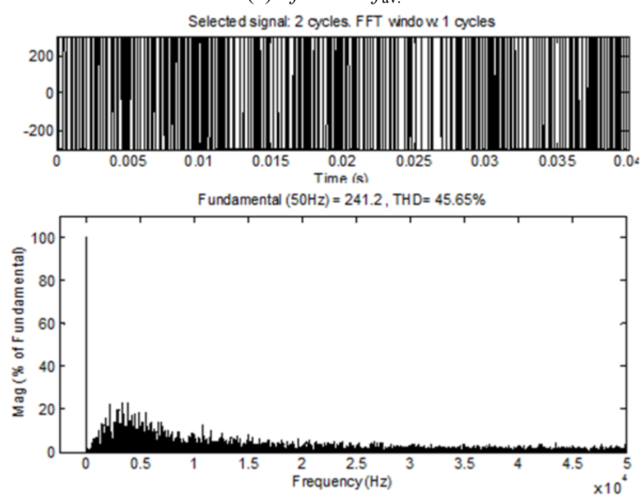
Fig. 5. The analysis of the output voltage spectrum of the conventional RCPWM (f_{av}=5 kHz, f_0=50Hz).

under the conditions shown in Table II and Δf is 30%, 60% and 80% of the average value of the random carrier sequence, respectively.

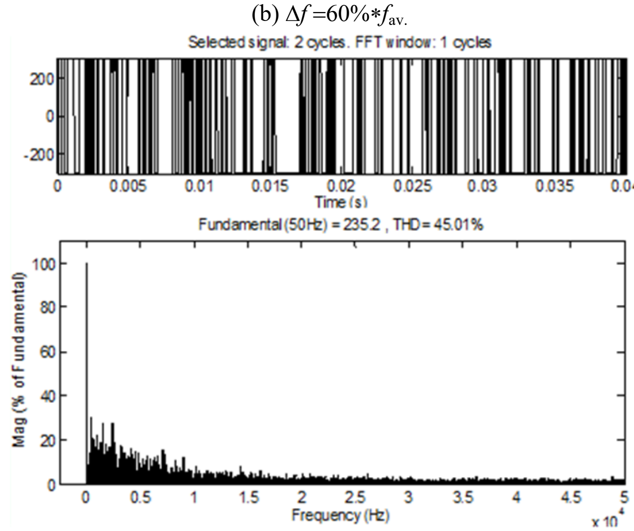
As shown in Fig. 6(a), there are distinct peaks distributed around the average value of the random carrier sequence, f_{av} and the spectra of the harmonics do not sufficiently scatter. Conversely, the spectra of the harmonics are more likely accumulated at frequencies lower than 5kHz, that is, the low frequency domain in Fig.6(c), which is under the value of Δf, is 80% of f_{av}. Hence, it is suggested that the value range of Δf should be from 40% to 70% of f_{av}. Therefore, there is a recommendation that the value of Δf in this paper be 60% of f_{av}.



(a) Δf=30%*f_{av}.



(b) Δf=60%*f_{av}.



(c) Δf=80%*f_{av}.

Fig. 6. The spectrum of the output voltage under different Δf (f_{av}=5 kHz, f_0=50Hz).

In the optimal RCPWM based on a genetic algorithm, the same circuit is used as in the FCPWM. The main parameters of the genetic algorithm are shown in Table III.

TABLE III
PARAMETERS OF GENETIC ALGORITHM

Genetic algorithm parameters	Value
Number of random carriers in 0.02 s	200
Population size	100
Reproduction	0.8
Crossover probability	0.8
Mutation probability	0.2
Δf	3kHz
The maximum number of genetic generations	90

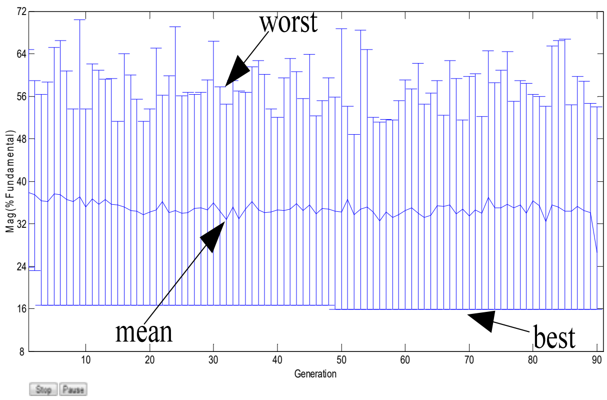


Fig. 7. The optimized process of RCPWM according to the genetic algorithm.

In the optimal RCPWM based on a genetic algorithm, the value range of the carrier frequency is $\Delta f = 3$ kHz, the size of the population is M=100, the reproduction probability is 0.8, the crossover probability is 0.8, the mutation probability is 0.2, and the maximum number of genetic generations is 90.

To make the optimal sequence searching process more visual, the reciprocal of the maximum harmonic spectrum is used in the optimized process. Thus, the maximum amplitude of the harmonic of the output voltage is directly shown in the figure.

The best, worst and mean values of the maximum amplitude of the harmonics in the genetic algorithm are shown in Fig. 7. The corresponding harmonic spectrum of the output voltage in the optimum RCPWM is shown in Fig. 8.

As shown in Fig. 7, according to the RCPWM optimized by a genetic algorithm, the maximum amplitude of the harmonic is up to about 70% of the fundamental frequency amplitude, while the minimum amplitude of the harmonic is close to 16%, which is much less than that of the harmonic in a common RCPWM. In addition, the minimum amplitude of the harmonic is about 16% from Generation 28 to Generation 90. It is implied that the minimum value is close to 16% under the conditions showed in Table Ⅲ. It is obvious that the quality of the output voltage cannot be controlled because the random carrier is unpredictable and uncontrollable.

When the optimal random carrier sequence is adopted, a fast Fourier transform (FFT) is used for the analysis of the output voltage, as shown in Fig. 8. It is obvious that the fundamental component is nearly 240 V and that the THD is close to 45%, which are similar to the results obtained with the other modulation methods. This is confirmed by the theory in Section II. At the same time, the harmonic distribution is more extensive and uniform than that by the FCPWM or the ordinary RCPWM which are shown in Fig. 4 and Fig. 5, respectively.

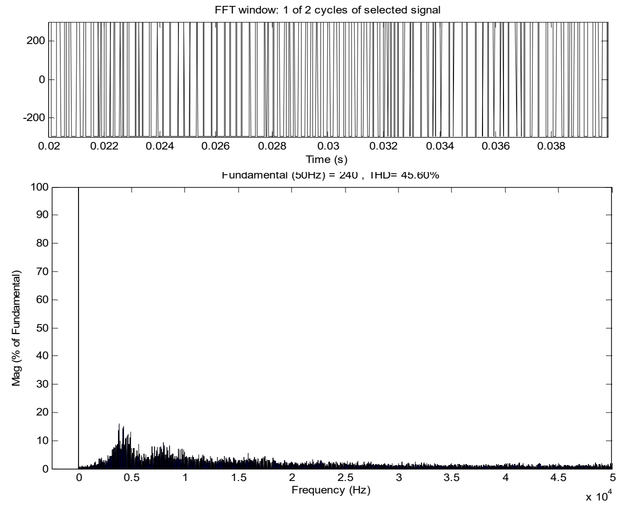


Fig. 8. The output voltage spectrum of RCPWM optimized by the genetic algorithm (f_{av}=5 kHz, f_0=50Hz).

B. Experiment and Analysis

In order to avoid a complicated real-time computation and to ensure the power quality, an experimental platform has been designed. As shown in Fig. 9, an optimal random carrier sequence is obtained from the simulation of the RCPWM by computer and then stored in the ROM of the FPGA. Since the 35kW inverter contains a FPGA, there is no need for extra hardware for the optimal RCPWM in the platform.

The off-line random carrier sequence repeats itself when the hardware system is working. In addition, the signal generator produces sinusoidal signals for the RCPWM.

The experimental parameters are the same as those in Table II. In order to measure the quality of the output voltage, a Tektronix 3308A is adopted to record and analyze the spectra of the output voltage. Moreover, an accelerometer (Buttkicker BK-GR2) is used to record the mechanical vibration produced by the motor. A schematic diagram and a photo of the experimental platform are shown in Fig. 9 and Fig. 10, respectively.

Due to the measurement range of the Tektronix 3308A, the frequency span is from 0 Hz to 250 kHz. Consequently, the waveforms recorded in the time domain are the same as being flitted by a low pass filter. Since the fundamental frequency is 50 Hz and the cut-off frequency is 250 kHz, it has little impact on the spectra of the output voltage.

The output voltage waveforms of the FCPWM, the conventional RCPWM, and the optimal RCPWM based on a genetic algorithm in the time domain are shown in Fig. 11. All

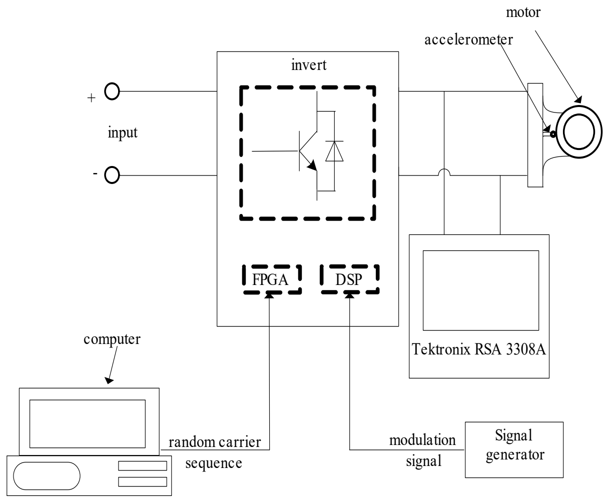


Fig. 9. The schematic diagram of the random carrier system.

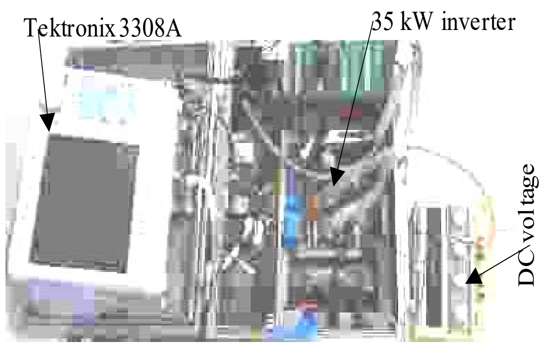


Fig. 10. The hardware platform.

of the experiments are done under the conditions shown in Table II and Table III. Accordingly, the spectra of the output voltage of the three PWM modulation methods are shown in Fig. 11, respectively.

In Fig. 11, the range of the measurement lasts 60 ms which is denoted on a scale of 20 ms per division in the horizontal axis. The vertical axis denotes the amplitude of the output voltage on a scale of 50 V per division. As shown in the figure, the voltage waveforms are nearly unchanged due to the added RCPWM.

In Fig. 12, the range of the measurement is from 0 to 250 kHz. Each grid of the horizontal axis represents 25 kHz. Each grid of the vertical axis represents 10dB, namely, the spectrum amplitude of the output voltage. According to the FCPWM spectrum shown in Fig. 12 (a), there are obvious peaks appearing at the carrier frequency and its multiples (f_c=5 kHz). However, in Fig. 12 (b) and (c), no carrier frequency (f_c=5 kHz) peak appears. In addition, the spectrum waveform in (c) is a lot more uniform than that in (b). That is to say, both the conventional RCPWM and the optimal RCPWM based on a genetic algorithm can disperse the harmonics accumulated around the carrier frequency and its multiples. However, the latter can spread the concentrated harmonic into a broader range.

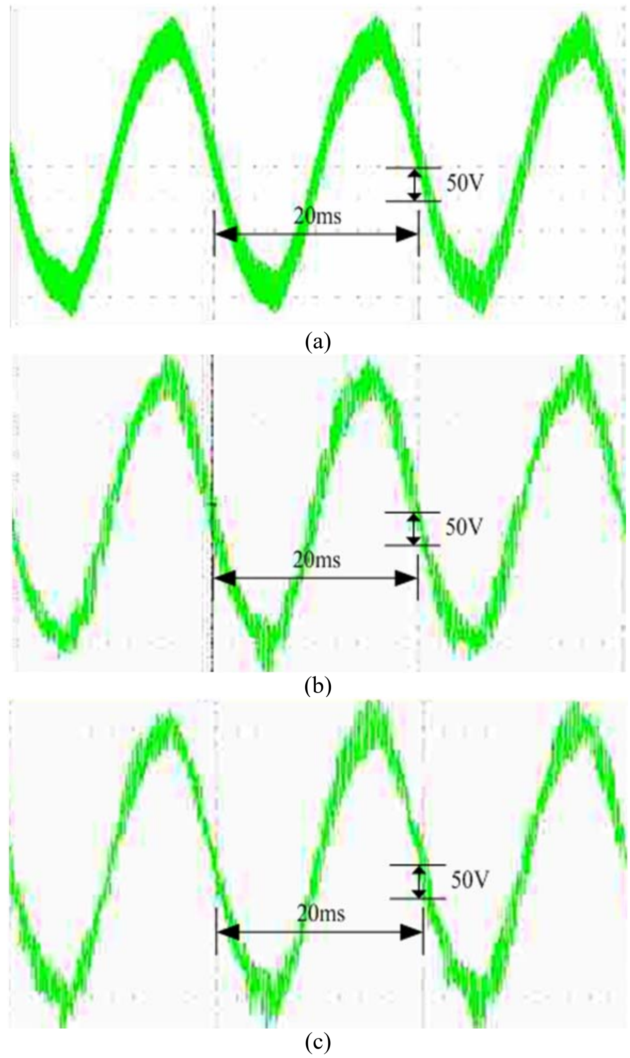
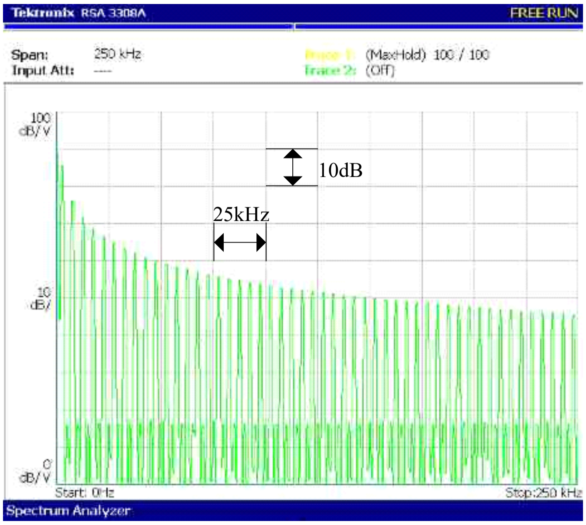


Fig. 11. The waveforms of the output voltage in the time domain accordance with the parameters in Table IIand III. (a) FCPWM (f_c=5 kHz, f_0=50Hz). (b) conventional RCPWM (f_{av}=5kHz, f_0=50Hz). (c) Optimal RCPWM based on the genetic algorithm (f_{av}=5 kHz, f_0=50Hz).

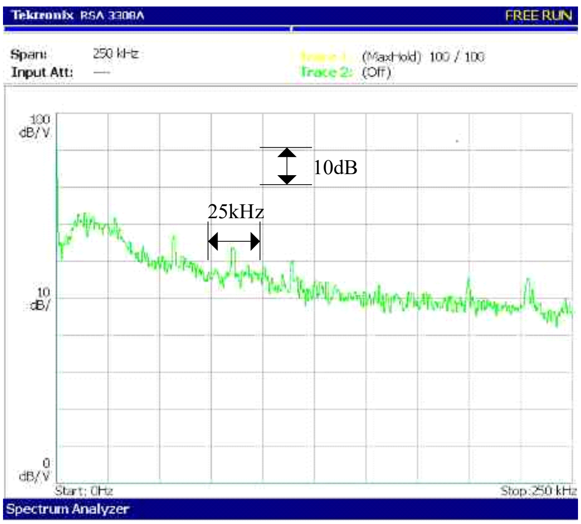
Accordingly, the spectra of the vibration acceleration data recorded by the accelerometer in the three kinds of modulation are shown in Fig. 13.

The range of the measurement is from 0 to 1.1 kHz. Each grid of the horizontal axis represents 1000 Hz. Each grid of the vertical axis represents 10dB, namely the spectrum amplitude of the vibration acceleration. It is clear that the distribution of the spectra of the vibration acceleration is similar to that of the harmonic spectra of the output voltage.

As shown in Fig. 13 (a), obvious peaks exist at the carrier frequency and its multiples (f_c=5 kHz). With the RCPWM shown in Fig. 13 (b) and (c), the vibration spectra have scattered. It is obvious that the dominant components have been considerably reduced, since the peaks at 5 kHz and 10 kHz have disappeared. The relatively large values of the vibration acceleration are all close to 60 dB, which is nearly 10 dB lower than the high values in Fig. 13 (a). In addition, the



(a)



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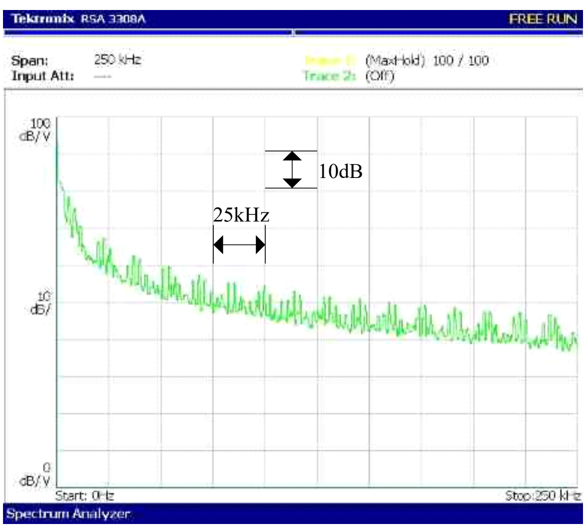
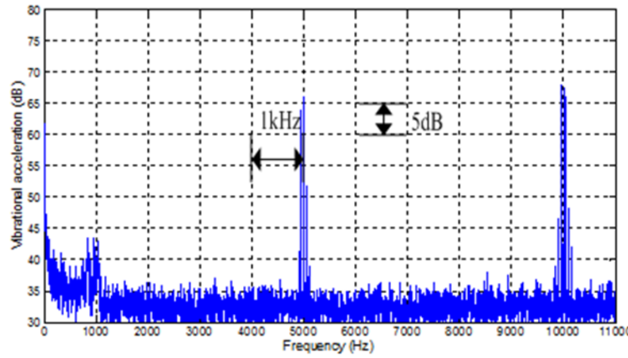
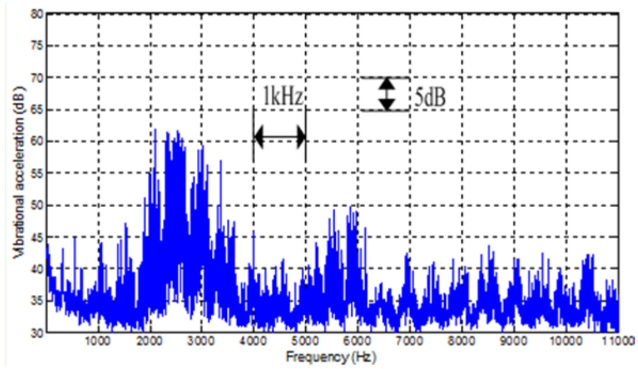


(c)

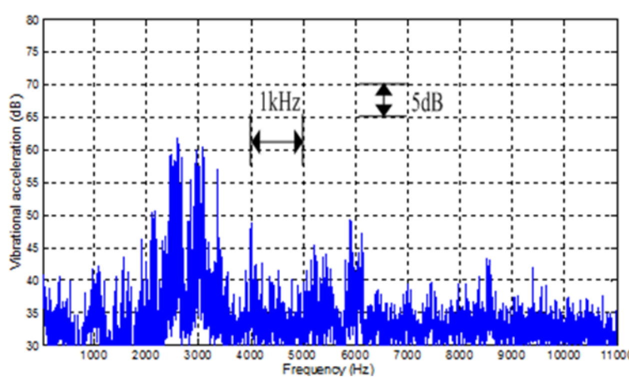
Fig. 12. The output voltage spectra under the condition of Table IIand III. (a) FCPWM (f_c=5 kHz, f_0=50Hz). (b) conventional RCPWM(f_{av}=5kHz, f_0=50Hz). (c) Optimal RCPWM based on the genetic algorithm (f_{av}=5 kHz, f_0=50Hz).



(a)



(b)



(c)

Fig. 13. The spectra of the vibration acceleration data (a) FCPWM (f_c=5 kHz, f_0=50Hz). (b) Ordinary RCPWM (f_{av}=5kHz, f_0=50Hz). (c) Optimal RCPWM based on the genetic algorithm (f_{av}=5 kHz, f_0=50Hz).

waveform in Fig. 13 (c) is more uniform than that in Fig. 13 (b).

It needs to be pointed out that mechanical vibration is very complicated in mechanisms. The specific relationship between it and the output voltage has gone beyond the scope of the research in this paper. However, the obvious peaks at the carrier frequency and its multiples are already very low, especially at low frequencies below 1 kHz, when the optimal RCPWM is conducted, as shown in Fig. 13 (c). That is to say, the optimal RCPWM based on a genetic algorithm can avoid resonance and depress the large amplitude of harmonics, which is of great value for preventing the severe damage caused by the harmonic in the low-frequency band.

V. CONCLUSIONS

This paper proposed an optimal RCPWM based on a genetic algorithm and designed an off-line hardware system suitable for the algorithm. The optimal carrier sequence chosen by the algorithm can be continuously repeated in a certain period of modulation which is a good way to solve the problems of electromagnetic interference and mechanical vibration.

The proposed modulation method and hardware system have been tested in a platform with a 35kW inverter. At the time of test, the fundamental frequency is f_0=50Hz, the modulation depth is a=0.8, the fixed carrier frequency is f_c=5 kHz and the average carrier frequency is f_{av} = 5 kHz. Experiments on the optimized RCPWM and the other two modulations have been carried out on this platform. A comparison and analysis of the harmonic spectra with the above mentioned three modulation methods show that the optimal RCPWM based on a genetic algorithm can spread harmonic energy under the precondition of ensuring the quality of the power supply. In addition, it has an advantage over the ordinary RCPWM in terms of its spectra dispersing capability when the carrier frequency is limited to a certain scope.

A RCPWM based on a genetic algorithm with multi-requirements or multi-constraints will be studied at a later date.

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