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Improvement of Electromagnetic Compatibility of Motor Drives Using Hybrid Chaotic Pulse Width Modulation

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This paper proposes and implements a new hybrid chaotic (HC) pulse width modulation (PWM) scheme for the reduction of electromagnetic interference (EMI) in alternating current (AC) motor drives. This scheme utilizes logistic mapping to simultaneously chaoticize both the carrier frequency and the pulse position. Compared with available chaotic PWM schemes such as the chaotic-pulse-position-modulated (CPPM) PWM and the chaotic-amplitude-frequency-modulated (CAFM) PWM, the proposed scheme is a synergy of CPPM-PWM and CAFM-PWM. Thus, it possesses a hybrid characteristic, namely the peaky EMI is suppressed while the occurrence of low-order noises is reduced. Both simulation and experimental results are provided to support the validity.

Index Terms—Chaos, electromagnetic compatibility, electromagnetic interference, motor drives, pulse width modulation.

I. INTRODUCTION

Since the switching frequency of pulse width modulation (PWM) schemes for alternating current (AC) motor drives is significantly raised for the reduction of their size and weight, the electromagnetic interference (EMI) is increased inevitably, which results in the degradation of electromagnetic compatibility (EMC) for electronic devices [1], [2]. In order to reduce the peaky EMI which usually occurs when using the fixed-frequency (FF) PWM [3], [4], various chaotic PWM schemes such as the chaotic-pulse-position-modulated (CPPM) PWM and the chaotic-amplitude-frequency-modulated (CAFM) PWM have been proposed [5], [6]. For the CPPM-PWM scheme, the pulse position is varied chaotically in every switching cycle. It can spread the discrete spectral power over a continuous spectrum so that the peaky EMI is significantly reduced. Nevertheless, some peaky EMI still exist at certain frequencies. For the CAFM-PWM scheme, the Logistic map is employed to chaoticize a frequency-modulated signal which in turn modulates the slope of the triangular carrier. It can effectively suppress all peaky EMI over the whole power spectrum. However, there are noticeable low-order harmonics.

In this paper, a new hybrid chaotic (HC) PWM scheme is proposed and implemented for AC motor drives, which can suppress the peaky EMI and reduce the occurrence of low-order noises. The key is to simultaneously chaoticize both the pulse position and the carrier frequency for the generation of PWM pulses. In order to illustrate the validity and merits of the proposed HC-PWM, both computer simulation and experimental verification will be given to compare the power spectra resulted from the FF-PWM, CPPM-PWM, CAFM-PWM and HC-PWM schemes. Finally, the proposed HC-PWM will be further compared with the well-known random-frequency (RF) PWM scheme [7], [8].

Fig. 1. HC-PWM inverter-fed AC motor drive.

II. HYBRID CHAOTIC PWM

For a typical inverter-fed AC motor drive as shown in Fig. 1, the common-mode (CM) currents are between the phases and the system ground, whereas the differential-mode (DM) currents are between different phases of the PWM inverter [9], [10]. Both the CM and DM currents are the main sources of EMI. In order to reduce or even suppress the EMI, it is imperative to improve the spectrum of inverter output voltages.

As shown in Fig. 2, the proposed HC-PWM scheme is a combination of the modulation of the carrier frequency by a chaotic sequence and the variation of pulse positions by chaotic bits in each switching cycle. This scheme is different from the available chaotic PWM schemes, such as the CPPM-PWM which is based on chaotic pulse positions under a fixed carrier frequency or the CAFM-PWM which is based on a chaotic carrier frequency under fixed pulse positions.

The proposed HC-PWM adopts the same chaotic sequence to chaoticize both the carrier frequency and the pulse position. This chaotic sequence \( \varepsilon_i \in (0,1) \) is generated by the Logistic map which can be expressed as \( \varepsilon_{i+1} = A \varepsilon_i (1 - \varepsilon_i) \) where \( A \in [0.1, 3.9] \). The Logistic is a one-dimensional discrete-time nonlinear system, which can exhibit plenty of dynamical behavior, including chaos. The corresponding bifurcation diagram is generated by plotting the extreme points of \( \varepsilon_i \) nearby the stable or unstable solutions with respect to different values of \( A \) as shown in Fig. 3(a), which illustrates that \( A \) can be used to tune the spectral power distribution from no frequency
modulation (FM), to periodic FM, to multi-periodic FM and finally to chaotic FM. As shown in Fig. 3(b), the maximum Lyapunov exponent, which denotes the rate of the attractor growth in the state space by the direction of maximum growth, is plotted with respect to different values of $A$. It indicates that chaotic behavior occurs for $A \in [3.57, 3.9]$, so $A = 3.9$ is selected for chaoization.

Firstly, the chaoization of the carrier frequency is carried out by adding a multiplication factor, namely the $\varepsilon_{C}$ generated by the Logistic map, to the conventional FF-PWM. Thus, the switching frequency can be expressed as:

$$f = f_{sw} + \varepsilon_{C}\Delta f \sin(2\pi f_{m}t)$$  \hspace{1cm} (1)$$

where $f$ is the real switching frequency, $f_{sw}$ is the fixed switching frequency, $\Delta f$ is the deviation frequency and $f_{m}$ is the modulation frequency. Secondly, the chaoization of pulse positions is carried out by a train of chaotic bits ($CB$) which is also generated by the Logistic map. This chaotic bit train functions to modulate the pulse position signal $q$ which is resulted from a comparison between the carrier signal $S_{car}$ and the reference signal $S_{ref}$ as given by:

$$q = \begin{cases} 
0, & S_{car} \geq S_{ref} \\
1, & S_{car} < S_{ref} 
\end{cases}$$  \hspace{1cm} (2)$$

Consequently, the desired HC-PWM signal is generated by applying the AND operator to $q$ and $CB$ as depicted in Fig. 4.

### III. Simulation Results

Computational simulation of those aforementioned PWM schemes is carried out by Matlab Simulink. The AC motor parameters are based on a practical induction motor as listed in Table I. By using the periodogram method, all power spectra of $V_{CM}$ and $V_{DM}$ based on using the FF-PWM, CPPM-PWM, CAFM-PWM and HC-PWM are computed from zero to 150 kHz under the same $f_{sw}$ and $\Delta f$. The corresponding power spectra from zero to 20 kHz are shown in Figs. 5–8. It can be observed that the FF-PWM spectra are crowded with peaky EMI while the CPPM-PWM spectra are imposed with occasional peaky EMI, whereas both the CAFM-PWM and the HC-PWM can suppress all peaky EMI.

Two performance indicators are employed for the assessment of the EMC of this motor drive. Since the conducted EMI with a frequency exceeding 9 kHz is stringently limited by many countries, the maximum power spectral density (PSD) in 9–150 kHz is used as the first performance indicator. In order to evaluate the content of low-order noises while the power spectrum is mainly from 2.99–3.01 kHz is used as another performance indicator.

Firstly, by comparing the maximum PSD of their $V_{CM}$ spectra in 9–150 kHz, namely 10.03 dBm/Hz for the FF-PWM, 6.04 dBm/Hz for the CPPM-PWM, 2.22 dBm/Hz for the CAFM-PWM and 0.05 dBm/Hz for the HC-PWM, it can be observed that the CAFM-PWM and HC-PWM suppress all peaky EMI more effectively than the other PWM schemes.
CAFM-PWM and 

11.88 dBm/Hz for the HC-PWM, it illustrates that the HC-PWM has a remarkable improvement over other PWM schemes. Similarly, from their $V_{DM}$ spectra, namely 14.78 dBm/Hz for the FF-PWM, 11.58 dBm/Hz for the CPPM-PWM, 

-0.61 dBm/Hz for the CAFM-PWM and 

-1.78 dBm/Hz for the HC-PWM, it indicates that both the CAFM-PWM and HC-PWM have significant improvement over the others while the HC-PWM is the better than the CAFM-PWM.

Secondly, by comparing the spectral power of their $V_{CM}$ spectra in 2.99–3.01 kHz, namely 10.03 dBm for the FF-PWM, 17.14 dBm for the CPPM-PWM, 2.22 dBm for the CAFM-PWM and 

-19.55 dBm for the HC-PWM, it illustrates that both the CPPM-PWM and the HC-PWM have a remarkable improvement over other PWM schemes. Then, from their $V_{DM}$ spectra, namely 14.78 dBm for the FF-PWM, 

-11.72 dBm for the CPPM-PWM, 

-1.42 dBm for the CAFM-PWM and 

-17.57 dBm for the HC-PWM, it confirms that both the CPPM-PWM and HC-PWM have significant improvement over the others while the HC-PWM is better than the CAFM-PWM.

Fig. 6. Simulated power spectra of CPPM-PWM. (a) $V_{CM}$. (b) $V_{DM}$.

Fig. 7. Simulated power spectra of CAFM-PWM. (a) $V_{CM}$. (b) $V_{DM}$.

Fig. 8. Simulated power spectra of HC-PWM. (a) $V_{CM}$. (b) $V_{DM}$.

IV. EXPERIMENTAL RESULTS

For experimentation, a practical 3-phase 4-pole 1.5-kW 220-V induction motor is adopted. The parameters of this induction motor for experimental tests are the same as that for computational simulations listed in Table I. All the aforementioned PWM schemes are implemented by a single-chip digital-signal-processing microcontroller (Texas TMS320F2812), including the chaoization of both pulse positions and carrier frequencies, the comparing and generating logics, and the error handling process. The output of this microcontroller is the chaoized PWM signals which are used to fed into a driver board. This driver board is designed to convert directly the control signal 0–3.3 V to the gate driving signal 0–15 V. The power stage is based on a six-in-one integrated power module (Mitsubishi PM75RLA120) which serves as the PWM inverter for the induction motor.

All power spectra of the FF-PWM, CPPM-PWM, CAFM-PWM and HC-PWM are directly measured by the power spectrum analyzer (LeCroy WR6100A). By comparing Fig. 9, Fig. 10, Fig. 11 and Fig. 12, it can be seen that the peaky EMI can be effectively suppressed by using the CAFM-PWM.
and HC-PWM schemes. Also, the maximum PSD measured in 9–150 kHz and the power spectra measured in 2.9–3.1 kHz are quantitatively compared in Table II which indicates that the HC-PWM can offer lower EMI than the CAFM-PWM in terms of the low-order noises around 3 kHz. Therefore, it is experimentally verified that the proposed HC-PWM can offer better performance than other chaotic PWM schemes.

**V. FURTHER COMPARISON**

In order to further identify the merit of the proposed HC-PWM, it is compared with the RF-PWM scheme which can effectively suppress the peaky EMI and low-order noises. The key of the proposed scheme is to simultaneously chaotic both the carrier frequency and the pulse position. It shows better performance than the available chaotic PWM schemes including the CPPM-PWM and the CAFM-PWM. Additionally, it is better than the RF-PWM in terms of the immunity of mechanical resonance.

**VI. CONCLUSION**

In this paper, a new hybrid chaotic PWM scheme has been proposed and implemented for AC motor drives, which can effectively suppress the peaky EMI and low-order noises. The key of the proposed scheme is to simultaneously chaotic both the carrier frequency and the pulse position. It shows better performance than the available chaotic PWM schemes including the CPPM-PWM and the CAFM-PWM. Additionally, it is better than the RF-PWM in terms of the immunity of mechanical resonance.

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