EMI Reduction in Switching Power Converter
by Using Chaotic Frequency Modulation Technique

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Abstract

In Conventional power converters electromagnetic interference (EMI) emissions comes from the switching of a DC voltage in pulse width modulation (PWM) process. The effective way to reduce EMI in power converter is to use frequency modulation technique which modulates the originally constant switching frequency by following a certain modulation profile (i.e. sinusoidal, sawtooth, triangular, exponential, random, chaotic). This paper is dedicated to chaotic switching frequency modulation technique which is the modified form of simple frequency modulation technique and also focusing on the effectiveness of simple frequency modulation in EMI reduction as a function of the different switching modulation profiles. The simulation results show that the EMI spectrum is decided completely by the peak amplitude of PWM spectrum. Chaotic frequency modulation technique is effectively reduce it by using a variable switching frequency (modulating a base value (carrier frequency, \( f_c \)) obtained by logistic map(bifurcation technique). And also compare chaotic frequency modulation with all other different modulating profile and finally conclude that chaotic frequency-spreading gives better spectral performances and results.

Keywords: Chaotic frequency modulation; EMI ; spread spectrum ; PWM converter
1 Introduction

As we know the widespread use of power converter makes substantial contribution to energy saving but simultaneously considerably increases noises and thus intensifies electromagnetic interference (EMI) and electromagnetic compatibility (EMC) problems[1]. Due to switch on and off large amount of current and voltages in power converters gives rise to EMI, also known as radio frequency interference (RFI)[6]. Within a few last decades the research is continued in this field, the many available techniques include appropriate design of converter (e.g., the use of input and output filters, correct design of printed circuit boards, grounding and shielding) having their limited size, weight, design complexity, efficiency, costs, etc. and proper organization of switching process i.e soft switching technique which significantly reduce the switching dv/dt and di/dt, but today it hasn’t acted on the noise source, the effect is limited[1].

Another effective techniques is to modulate the constant switching frequency $f_{sw}$, by the action of low frequency additional signal (periodic, random or chaotic) having a spectrum with lower peak amplitude than the constant frequency square signal, while keeping the desired duty. This can be achieved by using a variable switching frequency, obtained by modulating a base value (carrier frequency, $f_c$) in a way known as frequency modulation technique. Also known as spread-spectrum technique and still developed for radio communications, currently broadens its scope in the field of power converter[1].

Modified and effective way of simple frequency modulation is to use chaotic frequency-spreading technique has been a new effective technology for EMI suppressing recently. It modulate the original constant frequency by chaos system poses continuous spectrum with lower amplitude hence EMI will be suppressed effectively[2-3].

This paper, based on the analysis of the relationship between PWM switch scheme and EMI spectrum, a simulation study and analysis have been made on a commercial PWM scheme and compare them with latest technique. The chaotic converter work stable and EMI is suppressed effectively research for EMI problem now continuously growing and investigating with different modulation techniques.

2 Spread spectrum technique (switching frequency modulation technique)

The major cause of EMI in conventional PWM is periodic function of time, here we reduce EMI by using variable frequency obtain by different modulating profile

2.1 Simple frequency modulation techniques

In Simple frequency modulation technique, the initial energy is spread by different modulating technique thus giving a wider spectrum with lower amplitudes. Different modulation profile is

- sinusoidal
- triangular
- exponential
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The effect of frequency modulation on each individual harmonic can be derived from the study of a sinus wave modulated with the desired modulation profile[4].

A wider spectrum with lower amplitudes depends mainly on several factors as[5].

1. Modulation profiles
2. Modulating frequency \( f_m \)
3. Carrier frequency \( f_c \)
4. The modulation index \( m_f \)
5. Rate of percentage (\( \delta \) per unit ) or \( \delta\% \) (percent) (deviation)

\[
m_f = \frac{\Delta f_c}{f_c}
\]  \hspace{1cm} (1)

where \( m_f \) is modulating index
\( \Delta f_c \) is peak deviation of switching frequency

\[
f_m = \frac{\Delta f_c}{f_c}
\]  \hspace{1cm} (2)

\( \delta \) is the rate of modulation. (rate of modulation)

2.2 Chaotic frequency modulation technique

The working principal of chaotic frequency modulation technique is same as simple frequency modulation technique, here PWM frequency spread chaotically and energy can be distributed having lower amplitude. Then the EMI will reduce.

The Chaotic PWM frequency-spreading scheme of switch converter is defined by \( f(t) \) [2-3].

\[
f(t) = f_s + \Delta f
\]  \hspace{1cm} (3)

\( f_s \) is original constant PWM frequency
\( \Delta f \) denotes the modulating PWM frequency

Equation (3) shows that, When additional frequency (\( \Delta f \)) is zero, then PWM pulse varies like original constant frequency PWM; When additional frequency (\( \Delta f \)) varies periodically, then PWM pulse also varies periodically; When additional frequency (\( \Delta f \)) varies chaotically, then PWM pulse also varies chaotically[2-3].
In chaotic frequency modulation technique, $\Delta f$ varies according to Chaotic sequence and can be generated by following way

-- by chaotic map(logistic map)  
-- by simple chua’s circuit

Here we use logistic map(bifurcation technique) to modulate additional frequency. Modulating signal obtain from bifurcation technique[7-8].

$$\xi_{i+1} = A \xi_i (1 - \xi_i) \quad (4)$$

Where  
$A$ is control parameter  
$\xi(i)$ is the modulating signal, comes from logistic map (bifurcation technique) and according to which $\Delta f$ varies periodically or chaotically, and the state variable is updated at discrete time instants.

Matlab simulation of bifurcation diagram here can be generated by varying $A$ from 0 to 7.9. bifurcation simulation diagram shown in figure

![logistic map (bifurcation technique)](image)

Fig.2 logistic map (bifurcation technique)

When the control parameter $A$ is gradually increased from 0 to 8 the logistic map exhibits transition between regular and chaotic behaviour.

If $0 < A < 1$ the map generate fixed point(sequence) which is stable.

When $1 < A < 4$ this fixed point losses its stability and another fixed point appears inside the segment(0,1).

When $4 < A < 5$ the points $\xi_i$ is unstable.

When the value 5 is exceeded, the next bifurcation occurs and a new 4-cycle appears.

this cycle also become unstable after sometime, giving birth to subsequent stable 8 cycle, etc the subsequent period doubling bifurcation of an attractive cycle take place until the value $A$
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=7.9 is reached. At this value the period of the attractive cycle divergence and all finite cycle of period are repulsive.

When 0< A <8 the logistic map may have cycle of any periodic and aperiodic sequence which give rise to chaotic behaviour, the sequence is aperiodic and completely chaotic. As shown in figure.

When A=3.5

![Fig.3.(a) sequence variation when A=3.5](image)

When A=5.05

![Fig.3.(b) sequence variation when A=5.05](image)

When A =6.8
Matlab simulation and analysis

The theoretical principles for all are based on the modulation of a sinusoidal carrier modulated by a sinusoidal deviation function, which is presented below. Computer simulation of the whole system is carried out by using the Matlab M-file. The corresponding power spectra are plotted by a Matlab function, namely the periodogram method.

3.1 Basic fundamental principal of frequency spreading technique

Simple Carrier frequency signal, frequency spectrum and periodogram power spectra accordingly shown below.

Fig.4 Sinusoidal carrier signal and its spectra
(a) Simple Carrier frequency signal
(b) Frequency Spectrum and (c) Periodogram Power Spectra.
When sinusoidal carrier frequency is deviated by 6 different different frequency deviation

![fig.5 Deviated sinusoidal carrier signal and its spectra](image)

(a) deviated Carrier frequency signal, (b) Frequency Spectrum and c) periodogram power spectra

From the discussion and simulation results, it is clear that the measured emission is periodical with respect to switching frequency. The emission, therefore centre at the switching frequency and the harmonic frequencies. By modulating the switching frequency, side-bands are created, and the emission spectrum is broaden. The power is distributed into smaller pieces scattered around many side-band frequencies and amplitude of spectrum reduce. When amplitude reduce, EMI is effectively reduce.

**3.2.5 Several aspects must be remarked**

A true reduction is found at the nominal switching Frequency with increase deviation (rate of modulation $\delta$).

Larger values of frequency deviation (rate of modulation $\delta$) are to produce larger amplitude reduction at any modulation profile.

Modulation profiles determine the final shape of the side-band harmonics generated during the modulation process. The envelope of these sideband harmonics shows the concentration of the energy from sideband harmonics around the two frequencies defining the window bandwidth depend on modulating profile.

According to the analytical results, it is observed that the amplitude of side-band harmonics depends only on the modulation index $mf$ relative to each selected modulation profile.

Maximum reduction is found in spectrum of sawtooth modulating profile, then exponential modulating profile, and minimum in sinusoidal modulating profile.
3.3 chaotic frequency modulation technique
chaotic PWM scheme employs the chaotic map to vary the frequency-modulated signal which then modulates the carrier frequency, so-called the chaotically frequency modulated PWM. Here PWM frequency spread chaotically and having lower amplitude then the EMI will significantly reduce.

3.3.1 Matlab simulation of PWM drive
waveform under periodic PWM frequency spreading
Matlab simulation of PWM Drive Waveform such as Constant frequency spreading, Sine frequency spreading, Square frequency spreading and Sawtooth frequency spreading signal respectively, as shown in Fig.10 (a),(b),(c).

(a) Constant frequency spreading

(b) Sine frequency-spreading
3.3.2 Matlab simulation of power spectrum under periodic frequency spreading

The power spectrums of periodic are showed in Fig. Among the three periodic frequency-spreading schemes, spectrum of sawtooth frequency-spreading is smoothest; spectrum of square frequency-spreading signal is the most discrete. We can also observe that the spectrum of PWM drive consists of infinite discrete harmonics. Under periodic PWM frequency-spreading scheme the peak value of spectrum can be decreased compared with constant frequency, but it is still a discrete spectrum.
Fig. 11. Constant frequency Spreading Spectrum (a) Frequency Spectrum  (b) Periodogram Power Spectra

Fig. 12. Sinusoidal Frequency Spreading Spectrum (a) Frequency Spectrum  (b) Periodogram Power Spectra
First, by comparing the maximum PSD (periodogram) of their spectra, namely -3.1 dB/Hz for constant frequency spreading PWM, -6.5 dB/Hz for Sinusoidal frequency spreading PWM and
-5.67 dB/Hz for Sawtooth frequency spreading PWM, -5.35 dB/Hz for Square frequency spreading PWM.
It shows that the Sawtooth frequency spreading PWM and Square frequency spreading PWM have remarkable improvements over the Sinusoidal frequency spreading PWM. Second, by comparing the maximum Frequency Spectrum amplitude, namely 0.42 for constant frequency spreading PWM, 0.35 for Sinusoidal frequency spreading PWM and 0.33 for Sawtooth frequency spreading PWM, 0.34 for Square frequency spreading PWM. Its also again shows that the Sawtooth frequency spreading PWM and Square frequency spreading PWM have remarkable improvements over the Sinusoidal frequency spreading PWM.

3.3.3 Matlab simulation of PWM drive under random/chaotic frequency spreading

According to the PWM frequency spreading scheme formula. When $\Delta f$ varies randomly/chaotically, the frequency value of the PWM drive pulse varies randomly or chaotically respectively. The chaotic frequency-spreading signal source got either from a Chua’s circuit or logistic map. Drive waveform and its spectrum under random and chaotic frequency-spreading scheme are shown on Fig.15-16 and fig 17-18 respectively. Comparing with previous Fig 10 and Fig.11-14 respectively, and it will notice that harmonic power of the drive spreads over the frequencies; the peak level of the power spectra becomes less than that of the classical PWM scheme and the periodical. And also compare chaotic PWM and Random PWM, it shows that chaotic PWM having less and smooth spectrum and effective and better result than Random PWM.

In Random PWM frequency spreading technique, frequency spread randomly hence output values fluctuate every time and not gives similar result. While chaotic operation is deterministic but not predictable. This often misleads some to think that chaotic operation is a random process. Chaos is not a random process, but it usually looks like random. chaotic behaviour is undesirable, and can be controlled (or actually understood) easily. Overall we can say that chaotic frequency spreading is better and effective than all other spreading scheme.

Fig.15.Random Frequency Spreading
3.3.4 Matlab simulation of power spectrum under chaotic PWM frequency spreading.

The power spectrums of random and chaotic frequency-spreading are showed in Fig.

Fig.16. Chaotic Frequency Spreading

Fig.17. Random frequency spreading spectrum (a) Frequency Spectrum (b) Periodogram Power Spectra
Comparing the maximum PSD (periodogram) of their spectra, namely -23.8-24.4 dB/Hz for random frequency spreading PWM, -25 dB/Hz for chaotic frequency spreading PWM. It shows that the chaotic frequency spreading PWM and random frequency spreading PWM both have remarkable improvements over all above periodic and deviated frequency spreading PWM. But if we compare chaotic and random, then chaotic gives more better and smooth result. Also if provide flexibility and controllability. Similar result obtained when comparing the maximum Frequency Spectrum amplitude, namely 0.043-0.048 for random Frequency Spreading PWM, 0.040 for chaotic frequency spreading PWM. Chaotic frequency spreading gives smooth and better result than random frequency spreading.

4 Conclusion

Frequency modulation technique with different modulating profile i.e. sinusoidal, square, sawtooth, triangular and exponential, periodic, random and chaotic have been studied and compared with each other. Logistic map (bifurcation technique) can be used to modulate PWM pulses chaotically, a new chaotic frequency modulated PWM has been proposed and implemented to improve EMC of motor drives. MATLAB simulation results have confirmed that the proposed chaotic PWM can effectively suppress the peaky EMI which usually occurs in periodic PWM scheme (sinusoidal PWM, sawtooth PWM, square PWM etc.). Random frequency spreading scheme can generate random pulse by randomly selected value hence its value vary every time and hence not provide flexibility in the system while chaotic frequency spreading scheme can generate a well defined sequence which look like random and hence it gives flexibility, smooth spectrum and better control as compare to random frequency spreading scheme. Chaotic frequency spreading can be generate in many way by using many chaotic maps and Chua’s circuit. In future chaotic sequence would be analysis and generate by
unique chaotic sequence by different chaotic maps or by providing intelligent close loop
system. Overall we can say that the chaotic frequency modulation technique can offer better
spectral performances than the all other techniques.

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