Research on Common Mode Noise Evaluation Method*

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Abstract - **Common mode noise produced in single-phase full-bridge converter with bipolar SPWM is analysized. Common mode noise level evaluation method must be monodromy value and calculated simply in common mode EMI suppression system. The three evaluation indexes of maximal spectrum, average spectrum and common mode noise energy are proposed to express the common mode noise level. The computational complexity of three evaluation indexes and the relationship between three evaluation indexes and the delay time difference of two driving signals on three different conditions are studied. The computation of Common mode noise energy is very convenience without calculation of DFT or FFT. Simultaneously, the research results show that different operation conditions have no effect on the relationship between common mode noise energy and delay time difference of two driving signals. It is conclusion that common mode noise energy is a monodromy index ant can be considered as a good evaluation index of the common mode noise level.**

Index Terms – Single-phase full-bridge, Evaluation method, maximal spectrum, average spectrum, common mode noise energy.

I. INTRODUCTION

Severe electromagnetic interference (EMI) is due to high d*v*/d*t* and high d*i*/d*t* caused by high speed operating of switch devices in power electronic products [1-4]. In singe-phase full-bridge converter, common mode current of two legs provide perfect compensation and can be cancelled out each other in bipolar SPWM. In this case, the common mode EMI is zero in theory. However, different transmission delays of two driving signals in bipolar SPWM modulation technique always produce large common mode EMI current in real case. It is important for common mode EMI suppression to regulate of time delay of two driving signals [5].

In a close-loop common mode EMI suppression system, the evaluation of common mode noise level is very important to regulate the time delay of two driving signals. In EMC research, common mode noise level is characterized by the overall spectrum of common mode current which is not a monodromy index. However, a close-loop controller needs a monodromy feedback that can evaluate the common mode noise level efficiently to decide the regulation direction of driving signals. Furthermore, the evaluation index will also be calculated out simply except for a monodromy index.

In this paper, three evaluation indexes of maximal spectrum, average spectrum and common mode noise energy are discussed. The computational complexity of three evaluation indexes and the relationship between three evaluation indexes and the delay time difference of two driving signals are studied. Three different operation conditions: common mode current of two legs only have 1) phase drift, 2) distinct magnitude and 3) distinct oscillation frequency are taken into account. The research results show that the computation of Common mode noise energy is very convenience without calculation of DFT or FFT and three different operation conditions have no effect on the relationship between common mode noise energy and delay time difference of two driving signals. It can be conclusion that common mode noise energy will characterize the EMI noise level as a monodromy value and it is a good evaluation index of the common mode noise level.

II. COMMON MODE NOISE ANALYSIS FOR A BIPOLAR SPWM SINGLE-PHASE FULL-BRIDGE CONVERTER

A single-phase full-bridge converter consisted of IGBTs is shown in Fig.1. There is a thin insulation layer between the device junction and the base plate, which is usually fixed on a heat sink that is grounded for safety reason. This forms a parasitic capacitance (C_{p1} and C_{p2}) between the midpoints of legs and ground. As the IGBTs switching on and off in high speed, high *dv/dt* at the midpoints of legs results in charging and discharging currents through the parasitic capacitors [6-9]. Specifically, these currents flow through the parasitic capacitors and converge into the ground, which is named as common mode current that gets its way into the DC bus through some common mode capacitors (C_1).

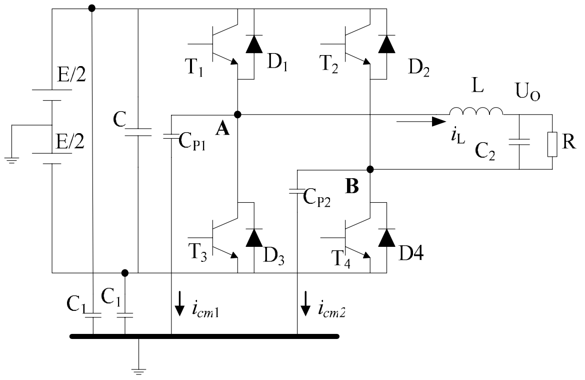

Fig.1 single-phase full-bridge converter

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In bipolar SPWM converter, switch pairs T_1-T_4 and T_2-T_3 turn on and off simultaneously, and the two switch pairs operates in a complementary manner. No matter what the actual direction of load current, the two midpoint voltages (V_A and V_B) always change in an opposite way. Usually, the parasitic capacitance between each inverter leg's midpoint and the ground can be considered to be equal. As a result, common mode current of two legs i_{cm1} and i_{cm2} is complementary perfectly and can be cancelled out each other.

Unfortunately, in a real converter system the driving signals always have to go through some processing circuits before arriving at the power devices. Such circuits usually include logic gates, voltage comparators, optical couplers, and some application-specific driving circuits. Due to inevitable deviations in signal transmission characteristics of these devices, transmission delay of each driving signal is different. Therefore, the exact synchronicity of switching actions never exists in real case.

An example of this situation is shown in Fig.2. Suppose the current of load i_L>0, T_1 and T_4 are all off, and i_L flows through D_2 and D_3. Then T_1 turns on ahead of T_4 due to faster transmission of its driving signal, i_L starts to flow through T_1 and D_2, and V_A changes from -E/2 to E/2. When T_4 turns on, i_L flows through T_1 and T_4, and V_B changes from E/2 to -E/2. When T_1 turns off, T_4 is still on, i_L goes through D_3 and T_4, and V_A goes back to its initial negative polarity. Finally when T_4 turns off, i_L flows through D_2 and D_3, and V_B goes back to positive polarity. Clearly, in this case (i_L>0) V_{G1} determines V_A and V_{G4} determines V_B. The two midpoint voltages no longer change in an exactly opposite way due to different transmission delays of gating signal V_{G1} and V_{G4}. Because the oscillation frequency of common mode current can be as high as of MHz, these differences (usually several hundred ns) can not be ignored when considering of the EMI in converter.

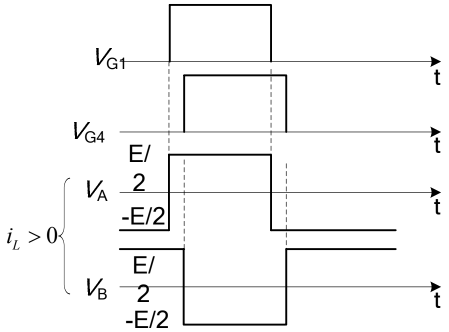

Fig.2 Midpoint voltages when consideration of different transmission delays of driving signals

III. COMMON MODE NOISE EVALUATION METHOD

In a close-loop common mode EMI suppression system, in order to regulate the delay time of two driving signals, evaluation of common mode noise level efficient is very important. A close-loop controller needs a monodromy feedback that can evaluate the common mode noise level efficiently to decide the regulation direction of driving signals. Furthermore, the evaluation index will be calculated out simply also.

A. Three evaluation indexes

In EMC research, only common mode noise overall spectrum can characterize common mode noise level roundly. If a monodromy index needs to be characterized the common mode noise level presumptively in noise spectrum, the three variables of spectrum can be mentioned easily. They are maximal spectrum, average spectrum and common mode noise energy, whose comparisons of them are as following.

B. Computation of three evaluation index

Maximal spectrum is the maximal value in whole spectrum. It can only illuminate the amplitude value of some one frequency, and it cannot characterize noise level when there is one more local maximum value. Spectrum average is the average value in whole spectrum. It shows the average level of common mode noise, but it cannot show the affect of an outstanding resonance peak in spectrum. Moreover, the maximal and average spectrum is calculation out by Fast Fourier Transform (FFT), and its computational complexity is large.

The basic theories of Digital Signal Process shows: For a signal which has limited energy, its energy is equal to a sum of squared value of each value in whole FFT spectrum. So the energy of spectrum can illuminate not only the average level of common mode noise but also the affect of some outstanding peak value in spectrum.

Common mode noise energy is given by

$$e_{cm} = \sum_{n=0}^{N-1} \left| i_{cm}[n] \right|^2 \qquad (1)$$

Where, N is the hits of common mode current in one switch cycle. And i_{cm} is the total common mode current of converter. According to Parseval's theorem, the energy in time domain is equal to the energy in frequency domain [10]. It is illustrated by

$$\sum_{n=0}^{N-1} \left| i_{cm}[n] \right|^2 = \frac{1}{N} \sum_{k=0}^{N-1} \left| i_{cm}[k] \right|^2 \qquad (2)$$

Where, i_{cm} is the Discrete Fourier Transform (DFT) of the common mode current i_{cm}. The rightmost part of (2) is also called the frequency-domain energy.

Equation (2) shows that common mode noise energy e_{cm} is equal to a sum of squared values of sampled value of common mode current in time domain. The computation of e_{cm} is very convenience without calculation of DFT or FFT. Simultaneously, e_{cm} has a direction proportion to the individual spectrum in the DFT of common mode current. It conclusion that common mode noise energy is a monodromy index ant can be considered as a good evaluation index of the common mode noise level.

C. Relationship between three evaluation indexes and delay time difference of two driving signals

According to facts mentioned above, the total common mode current of a full-bridge inverter become different along with the delay time of the driving signals on the cross of two legs. To select an ideally common mode noise evaluation index, the relationship between three evaluation indexes and delay time difference of two driving signals (lag or lead) is studied on three different conditions when common mode current of two legs only have phase drift, have distinct magnitude and have distinct oscillation frequency.

A MATLAB simulation model is constructed, as shown in Fig.3. A square-wave signal prompts a second order RLC damped circuit, which using the current response delegate the actual common-mode current of converter. i_{cm1}, i_{cm2}, and i_{cm} represent common mode current of the cross of two legs and total common mode current of converter. Delay blocket represents phase of common mode voltage. The time difference of delay blocket is the phase drift of common mode voltage of two legs. A second order RLC damped circuit is the equivalent path of common mode current loop [11].

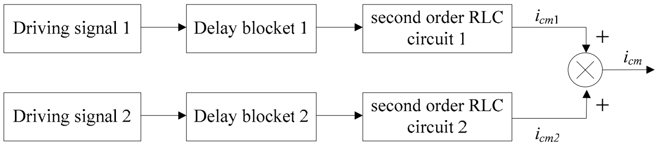

Fig.3 study model

The frequency of square wave driving signals is 8 kHz, and the duty cycle is 50%. The parameters of the series RLC circuit is R=150Ω, L=1mH, and C=1nF. The resonance frequency of RLC circuit is 160 kHz.

1) Common mode current of two legs only have phase drift:

At this condition, the parameters of driving signal 1 are the same as driving signal 2 and the parameters of second order RLC circuit 1 are the same as RLC circuit 2. But delay blocket 1 and 2 have different parameters, the delay time difference of two driving signals result in the phase drift of common mode current i_{cm1} and i_{cm2} of two legs.

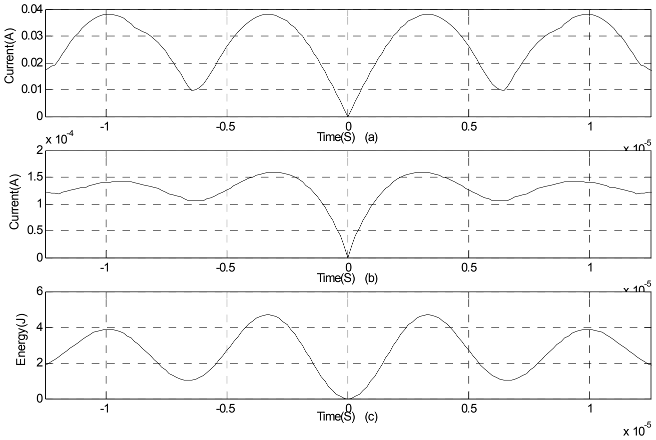

Fig.4 Three evaluation indexes along with the delay time difference of two driving signals: (a) maximal spectrum; (b) average spectrum; (c) common mode noise energy when i_{cm1} and i_{cm2} only have phase drift

Continuously adjusting delay time, make delay time difference of two driving signals uniformly change 80 steps in two oscillation cycle of common mode current. Taking into account the uncertainty of driving signal transmission circuit, i_{cm2} may lead or lag i_{cm1} also. The results of three evaluation indexes along with the delay time difference of two driving signals when i_{cm1} and i_{cm2} only have phase drift are shown in Fig.4, where the x-axis represents the time difference (Positive is lagging and negative is leading).

As shown in Fig.4, when time difference is ±kT (k=0, 1, 2, 3… and T is the oscillation period of RLC circuit), maximal spectrum, average spectrum and common mode noise energy all reach the minimum value. When time difference is ±kT/2, the three evaluation indexes all reach maximum value. Furthermore, when time difference varies between ±kT and ±(k+1)T/2, the three evaluation indexes vary monotonously and are symmetrical around the point of time difference is zero.

2) Common mode current of two legs have distinct magnitude:

Further consideration of IGBT parameters of two cross of two legs are different, at that time, the common mode current waveform of two legs i_{cm1} and i_{cm2} perhaps have distinct magnitude and frequency. There must be considered the impact on common-mode current i_{cm} under the two cases. In this paper, in order to make the study convenient, usually take into account two cases respectively: distinct magnitude and distinct oscillation frequency.

First, study the three evaluation indexes on the condition that i_{cm1} and i_{cm2} have distinct magnitude. Supposing the resistance of R is increased to 200Ω in RLC circuit 2 and the parameters of RLC circuit 1 are changeless, the common mode current i_{cm1} and i_{cm2} will have distinct magnitude obviously and i_{cm2} is less than i_{cm1}.

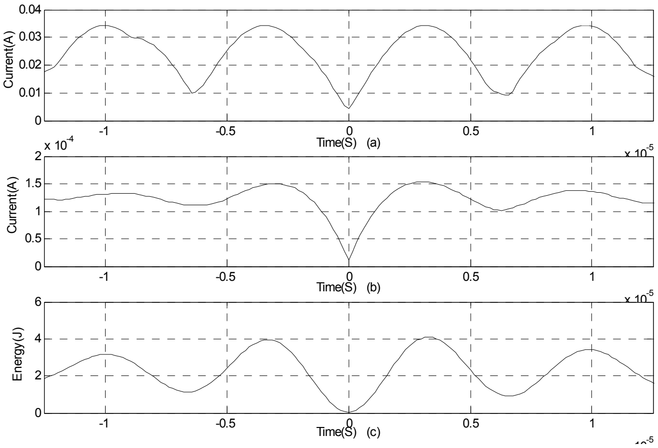

Fig.5 Three evaluation indexes along with the delay time difference of two driving signals: (a) maximal spectrum; (b) average spectrum; (c) common mode noise energy when i_{cm1} and i_{cm2} have distinct magnitude

According to mentioned above, continuously adjusting the lag and lead time, study the three evaluation indexes how to vary along with delay time difference of two driving signals. The results of three evaluation index along with the delay time difference of two driving signals when i_{cm1} and i_{cm2} have distinct magnitude are shown in Fig.5. It can be seen the relationship curve on this condition is similar to the condition of common mode current of two legs only have phase drift. The difference is that exact values of three evaluation indexes have disparity at the same time points on different operation situation. It show the condition when two common mode current have various magnitude only affect the value of three evaluation indexes, not have impact on the relationship between the three evaluation and delay time difference. The relationship curve is still symmetrical damped oscillation.

3) Common mode current of two legs have distinct oscillation frequency:

Then, investigate the relationship between three evaluation indexes and the delay time difference of two driving signals on the condition when i_{cm1} and i_{cm2} have distinct oscillation frequency. The parameters of RLC circuit 2 are shown as follows: R=150Ω, L=1mH, C=0.818nF. At this condition, the oscillation frequency of common mode current i_{cm2} is increased to 176 kHz and the oscillation frequency of i_{cm1} is still 160 kHz.

Continuously adjusting the lag and lead time, the results of three evaluation indexes varied along with the delay time difference of two driving signals when i_{cm1} and i_{cm2} have distinct oscillation frequency are shown in Fig.6. The relation curves of three evaluation indexes have no more symmetrical with the origin point where the delay time difference is zero. From Fig.6 (b), the minimum value of average spectrum appears at the point when the delay time difference is zero. However, the relationship curve of average spectrum loses its symmetry.

From Fig.6 (a) and (c), it can be seen the minimum value of maximal spectrum and common mode noise energy are not presented at that point, and the other maximum or minimum value of maximal spectrum and common mode noise energy are presented at different point. However, when time difference is ±kT, common mode noise energy reaches minimum value but maximal spectrum is not the minimum value. When time difference is ±kT/2, common mode noise energy reaches maximum value but maximal spectrum is not the maximum value. So its oscillation frequency is the same as resonance frequency of RLC circuit.

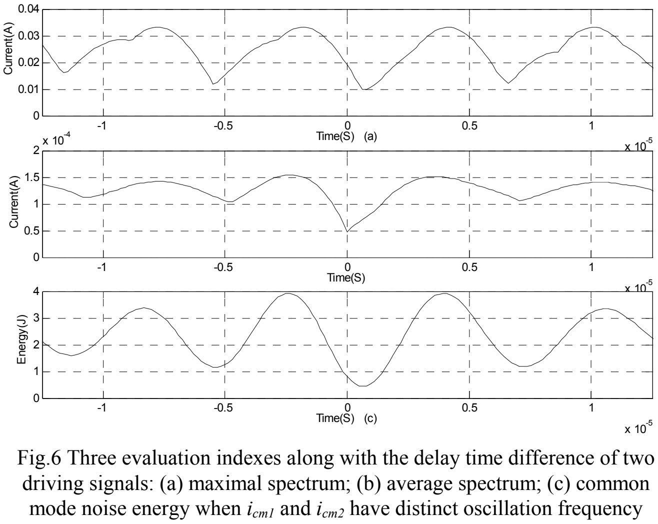

Fig.6 Three evaluation indexes along with the delay time difference of two driving signals: (a) maximal spectrum; (b) average spectrum; (c) common mode noise energy when i_{cm1} and i_{cm2} have distinct oscillation frequency

In conclusion, the relationship curve between common mode noise energy and delay time difference of two driving signals is symmetrical damped surge basically on three different conditions and the oscillation frequency is the same as that of RLC circuit. However, the relationship curves of maximal spectrum and average spectrum have not this character at three different conditions. Although the symmetric point of common mode noise energy is not the point where time difference is zero on the condition when i_{cm1} and i_{cm2} have distinct oscillation frequency, there is not impact on the evaluation of common mode noise level. Therefore, different operation conditions have no effect on the relationship between common mode noise energy and the delay time difference of common mode current of two legs. So it may be an ideally common mode noise evaluation index.

IV. COMMON MODE NOISE ENERGY

Certainly, common mode curret energy in a switch cycle is only explain spectrum energy of two individual common mode current pulse. In a PWM cinverter, there are many different switch cycle in one fundamental cycle. The relationship between common mode curret spectrum in a single switch cycle and in one fundamental cycle is studied as folllowed.

When the magnitude and phase angle of the nth harmonic of common mode current is served by A_n and θ_n. The common mode current in one single cycle can be expressed in frequency domain by the following equation:

$$i_{cm}=\sum_{n=0}^{N-1}A_n e^{jn\omega t+\theta_n} \tag{3}$$

Suppose the carrier ratio of a converter is C. the common mode current in one fundamental cycle is sum of common mode current in C switch cycle with different phase angle. The phase angle of different switch cycle is a_0~$a_{C\text{-}1}$, and a_0=0. So the common mode current in one fundamental cycle is

$$\begin{aligned} i_{cm\Sigma} &= \sum_{n=0}^{N-1}A_n e^{jn\omega t+\theta_n}(1+e^{jn\alpha_1}+e^{jn\alpha_2}+\ldots+e^{jn\alpha_{C-1}}) \\ &= \sum_{n=0}^{N-1}A_n e^{jn\omega t+\theta_n}\sum_{l=0}^{C-1}e^{jn\alpha_l} \end{aligned} \tag{4}$$

Consideration of most bad condition, $a_0= a_1=\ldots=a_{C\text{-}1}=1$. Equation (4) becomes to be

$$i_{cm\Sigma}=\sum_{n=0}^{N-1}CA_n e^{jn\omega t+\theta_n}=C\cdot i_{cm} \tag{5}$$

The common mode current energy of time or frequency domain in one fundamental cycle can be expressed by

$$e_{cm\Sigma}=\sum_{n=0}^{N-1}\left|CA_n\right|^2=C^2\sum_{n=0}^{N-1}\left|A_n\right|^2=C^2 e_{cm} \tag{6}$$

Thus it can be seen the common mode current energy in one fundamental cycle ($e_{cm\Sigma}$) is proportion to the energy in one switch cycle (e_{cm}). The common mode noise energy calculated by (1) can reflect the relative size of whole spectrum of common mode noise. Consideration of the large calculation of FFT and feedback only needs its relative size, the common mode noise energy in one switch cycle is a good measure of the overall noise spectrum comparing from other two evaluation method mentioned above.

V. CONCLUSION

In a bipolar SPWM singe-phase full-bridge converter, the common mode EMI is zero in theory. However, in a real case, delay time difference of driving signals for the cross of two legs always produce large common mode EMI current. In order to regulate the time delay of two driving signals to suppress the common mode EMI, the efficient evaluation of common mode noise level is very important.

A close-loop controller needs a monodromy feedback that can evaluate the common mode noise level efficiently to decide the regulation direction of delay time. In spectrum, three evaluation indexes of maximal spectrum, average spectrum and common mode noise energy are studied.

The computation of Common mode noise energy is very convenience without calculation of DFT or FFT compared with maximal spectrum and average spectrum. The relationship between three evaluation indexes and the delay time difference of two driving signals on three different operation conditions: common mode current of two legs only have 1) phase drift, 2) distinct magnitude and 3) distinct oscillation frequency are studied. The results show different operation conditions have no effect on the relationship between common mode noise energy and the delay time difference of common mode current of two legs. In conclusion, common mode noise energy is a much better evaluation index of common mode noise level compared with maximal spectrum and average spectrum.

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