Predicting the Conducted Emission of a CRM PFC Below 1MHz by Transient Modeling

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***Abstract*—Power Factor Corrections (PFC) are widely used in ac to dc power supplies. Modeling the PFC circuits and predicting the conducted emission (CE) are important in power supply designs. This paper introduces a transient model of a critical conduction mode (CRM) power factor correction. The control circuit of the PFC is built to achieve a CRM working condition with a constant on-time switching. The simulated time domain noise waveform is converted to the conducted EMI in frequency domain via short-time fast Fourier transform (STFFT). The simulated conducted EMI is compared to measured results below 1MHz.**

Keywords—electromagnetic interference (EMI), conducted emissions (CE), power factor correction (PFC)

I. INTRODUCTION

Power factor corrections (PFC) are widely used in ac to dc power supplies to achieve a high power factor (PF). PFC shapes the input current of power supplies to makes it in phase with the input voltage and minimize its line-frequency harmonics [1], [2]. In this case the power loss is minimized and the interference with other devices being powered from the same source is also minimized. Active PFCs are usually implemented by placing a controller boost converter after the input rectifier as shown in Fig. 1. PFC boost converters can work in three conditions: continuous conduction mode (CCM), critical conduction mode (CRM) and discontinuous conduction mode (DCM). In lower power applications like power adaptors and televisions (TV), CRM PFC boost converters are very popular because they are inexpensive, efficient and relative simple to use.

Conducted electromagnetic interference (EMI) of power supplies is strictly regulated by various EMC standards and needs to be taken into consideration during the design stage. Being able to model and predict the conducted emissions (CE) from a power supply is very important and can help determine the required filter attenuation and corner frequency in EMI filter design. The characteristics of the conducted EMI from a CRM PFC boost converter has been discussed in previous studies [3]-[6]. The switching noise of the boost converter is usually considered as the main noise source. The CE of a PFC can be predicted by multiplying the spectrum of the measured noise source with the transfer function [7]. However, the spectrum of the noise source needs to be measured in this method. One solution is to calculate the spectrum of the noise source using analytical formulas. But as frequency gets higher or the structure of the power supply gets more complicated, the analytical formulas may not work well as the approximation is compromised.

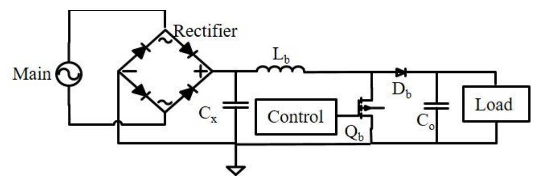

Fig. 1. A PFC boost converter

This paper will introduce a CRM PFC model used in transient simulation. A control circuit is built to make the boost converter work in critical conduction mode with a constant on-time. The noise voltage at the line impedance stabilization network (LISN) is obtained from the transient simulation and converted to conducted emissions (CE) in frequency domain via short-term fast Fourier transform (STFFT). With a transient model, the conducted EMI can be predicted at the design stage, without the measured noise source. This modeling approach is applied to a power supply consisting of a CRM PFC boost converter and an LLC converter in an LED TV. Both differential mode and common mode CE are predicted from the transient simulation model and compared to measured results up to 1 MHz.

This paper is organized as follows: Section II describes the control circuit and the transient model of a CRM PFC. CE comparison between proposed transient model and measurement on a real power supply in TV is shown in Section III. Section IV concludes the paper.

II. TRANSIENT MODEL OF A CRM PFC

In PFC boost converter, the switching is controlled so that the average inductor current follows the input voltage of the PFC, which is usually the voltage after the rectifier. The inductor current increases when the switch is turned on and decrease when the switch is turned off. For a CRM PFC, the switch is turned from off to on when the inductor current reaches zero. Since the output voltage of the PFC boost converter is almost a constant while the input voltage after the rectifier is changing in half line period, the duty cycle is varying in half line period. For a CRM PFC with a constant on-time, the off-time of the switch is varying, thus making the switching frequency vary in half line period. The PFC is switching at the maximum frequency when the input voltage reaches the minimum value and switching at the minimum frequency when the input voltage is at its maximum level. An accurate switching frequency is very important in a CRM PFC model as the switching noise is the main noise source of the conducted EMI.

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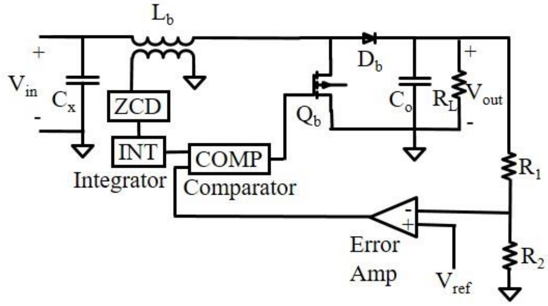


Fig. 2. Control circuit of a CRM PFC

To accurately model the time domain switching waveform, the control circuit of a CRM PFC is built as shown in Fig. 2. When the power switch turns on, the inductor current ramps up until the comparator signal reaches the threshold. At this point the comparator output state changes and the power switch is turned off. Then the inductor current starts to ramp down until it reaches zero. The zero current detection (ZCD) circuit measures the voltage across the inductor. When the inductor current reaches zero, the voltage will also be zero and be detected by ZCD circuit. The switch is turned on again at this point.

The LISN needs to be included in the transient simulation to predict the conducted EMI. The LISN model can be placed between the input AC source and the rectifier for transient simulation. Assume the simulated noise voltage waveforms on two LISN resistors are V_1 and V_2, respectively. The differential mode (DM) and common mode (CM) noise voltages are calculated as:

$$V_{dm} = \frac{V_1 - V_2}{2} \tag{1}$$

$$V_{cm} = \frac{V_1 + V_2}{2} \tag{2}$$

With the noise voltages obtained from the transient simulation, the conducted EMI in frequency domain can be calculated via STFFT.

III. PFC MODEL ON A POWER SUPPLY IN TV

The transient simulation model is implemented to a power supply in a TV for validation. The power supply consists of a rectifier, a CRM PFC boost converter and an LLC resonant converter. For this PFC boost converter, L_b = 248 μH, C_x = 0.82 μF, C_o = 82 μF. In the PFC control circuit, R_1 = 6 MΩ, R_2 = 39.3 kΩ, V_{ref} = 2.5 V, the comparator and the integrator are set to make the on-time of the switch be constant 2.2 μs. In the LISN model, L_{LN} = 50 μH, C_{LN1} = 1 μF, C_{LN2} = 0.1 μF and R_{LN} = 50 Ω.

The complete transient model of the PFC is described in Fig. 3. Three parasitic capacitors C_{p1}, C_{p2} and C_{p3} are included to model the common mode current path. C_{p1} represents the parasitic capacitor between the drain node of the switch MOSFET and the metal chassis. C_{p2} represents the parasitic capacitance between the power ground and metal chassis. C_{p3} represents the parasitic capacitance between the metal chassis and the earth ground. The power supply board is installed on the TV chassis and is 6 mm above the TV chassis. In the measurement setup, the TV chassis is 40 cm next to a vertical metal wall and 80 cm above the horizontal ground as shown

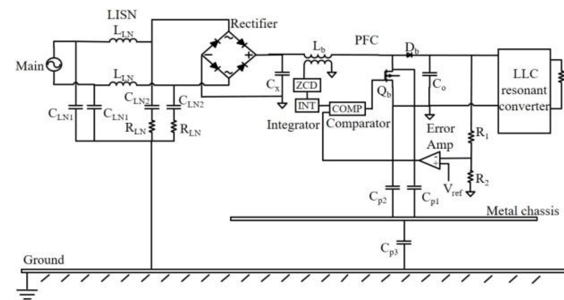


Fig. 3. Complete PFC model for a TV power supply

in Fig. 4. In this scenario, C_{p1} = 4.0 pF, C_{p2} = 10.0 pF and C_{p3} = 58.4 pF based on ANSYS Q3D Extractor simulation results [8].

A transient simulation is performed using ANSYS Twin Builder [9]. To validate the PFC is working as expected, the simulated inductor current, PFC input voltage and control signal waveforms are shown in Fig. 5. It can be seen that the inductor current is in phase with PFC input voltage and the envelope of the inductor current has the same shape as the input voltage, thus achieving a high power factor. The duty cycle and switching frequency of the PFC are changing during

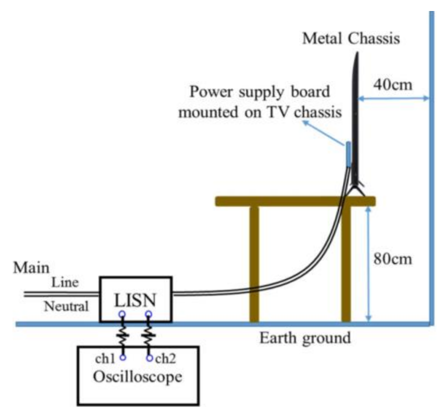
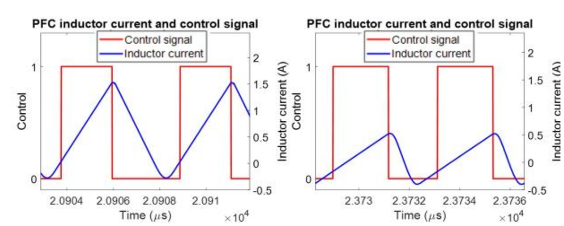
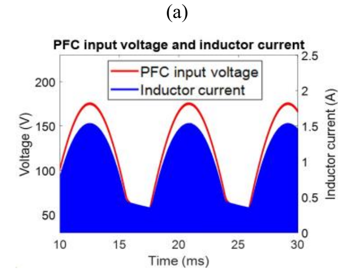


Fig. 4. Setup of the conducted EMI noise measurement.



(a)



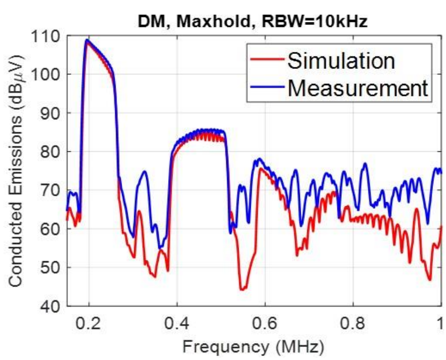
(b)

Fig. 5. (a) The inductor current waveform and control signal at different switching frequency, (b) The PFC input voltage and inductor current.

half line period. The on-time is controlled to be 2.2 μs. So the PFC is working in CRM with a constant on-time. The voltage waveforms on two LISN resistors are converted to the conducted EMI via STFFT. In STFFT, the sampling frequency is 100 MHz and the resolution bandwidth is set to 10 kHz. In measurement, the time-domain waveforms of the two LISN ports are recorded and converted to the conducted EMI with the same STFFT settings. The simulated and measured conducted EMI results are compared in frequency domain by taking maxhold in time. Fig. 6 shows that the simulated CE agrees with measured results below 1MHz. The switching frequency of the PFC is varying from 190 kHz to 250 kHz and is captured by the transient model accurately. At a few frequency points such as 390 kHz and 546 kHz, there are some discrepancies between simulation and measurement because the conducted EMI from the LLC resonant converter is not included in this model.

In TV power supplies, a ground filter is usually placed between the power ground and metal chassis to reduce the common mode CE. In this case, a filter consisting of a 100 pF capacitance and a 1 μH inductance is applied. The results with the ground filter included are shown in Fig. 7. It can be seen that the simulated results match well with measured results below 1 MHz. The common mode CE is reduced due to the effect of the ground filter. Similarly, the noise from LLC is not considered in this model so the discrepancy at some frequency points can be observed.

The main advantage of the proposed transient model is that it can predict the CE at the design phase. This model can be easily adapted when the range of PFC switching frequency changes or filters are added in the design. The design of EMI filters can benefit from this transient model.



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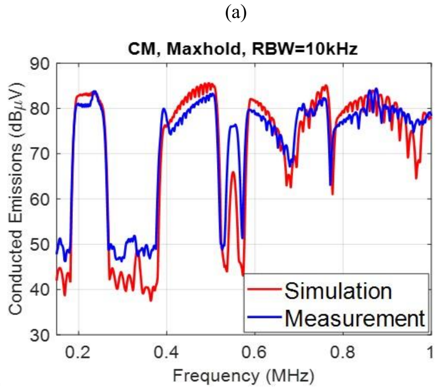

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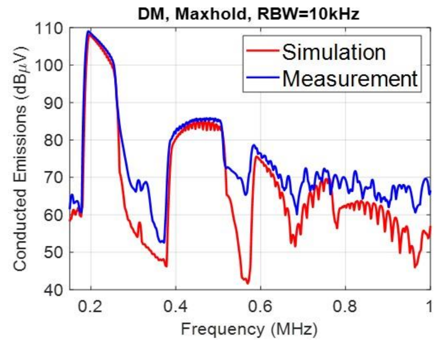
Fig. 6. (a) DM CE, (b) CM CE.



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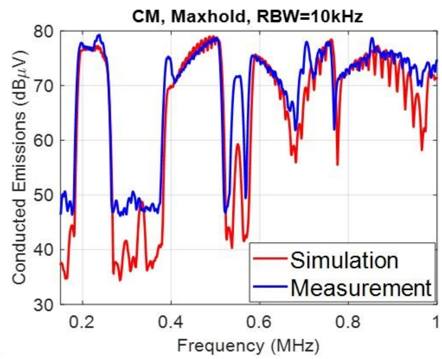

(b)

Fig. 7. (a) DM CE, (b) CM CE with the ground filter.

IV. Conclusion

A CRM PFC model is built to predict the conducted EMI using transient simulations. The PFC control circuit is built to control the switching frequency. LISN circuit and common mode current paths are included for EMI prediction. The model is validated with a real power supply board in a TV. Both DM and CM conducted EMI from the simulation model match well with measurements below 1 MHz. The future work include taking the load converter after the PFC stage into account and improving the model to work for higher frequency ranges.

Acknowledgment

This paper is based upon work supported partially by the National Science Foundation under Grant No. IIP-1440110.

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