Coupled Inductor as a Differential Mode Noise Filter in SMPS

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Abstract—**EMI is an issue in Switched Mode Power Supplies (SMPS) especially in boost converter topology. High frequency switching in SMPS causes EMI. To reduce this, EMI filters are used which are bulky. Here we use coupled inductor to reduce differential mode noise. Here inductor of boost converter is replaced by coupled inductor. Effect of variation of coupling factor on attenuation of differential mode noise is considered in this paper. Non-ideal cases of smoothing transformer are also considered**

Keywords—Differential Mode Noise, Smoothing transformer, Coupling factor, Attenuation Gain

I. Introduction

Switched Mode Power Supply (SMPS) is the strongest noise generator in the system. EMI occurring in it will be transferred to the other parts of the system. This paper deals with attenuation of Differential Mode (DM) noise. DM noise occurs in the frequency range 150 kHz to 2 MHz. To reduce this noise EMI filters are used. But inductors and transformers in it would make system bulkier. So coupled inductor is used here instead of an EMI filter hence reducing the size and weight. Its filtering performance is analyzed considering non-ideal cases of coupled inductor. Coupling factor mismatches and tolerances are also considered. Analysis regarding optimized distribution of capacitance between two capacitors is also done in this paper.

II. Literature Survey

Coupled inductor and integrated magnetics technique existed for many years. Balog, David C. Hamill and P. T. Krein [5] describes coupled inductor circuit topology starting with ideal case and then substituting real circuit elements. Again R. Balog and P. T. Krein have analyzed smoothing transformer as a linear two port network [2] which serve as a filter building block [1]. Juergen Stahl, Rene Junghaenel, Martin Schmidt, Manfred Albach have analyzed filtering function of smoothing transformer [6] in the interesting frequency range of differential mode noise. Juergen Stahl and Manfred Albach considers the effect of parasitic elements and component tolerances [1].

III. Ripple Current Steered Boost Converter

Inductor of boost converter is replaced with a pair of coupled inductors (smoothing transformer) and a capacitor in series with it. It is shown in Fig. 1. Then noise produced due to switching of MOSFET T and diode D is attenuated using coupled inductor [6]. Coupled inductor here stores energy as well as steers ripple current. Hence this boost converter can be called as Ripple Current Steered Boost (RCS boost) Converter [1].

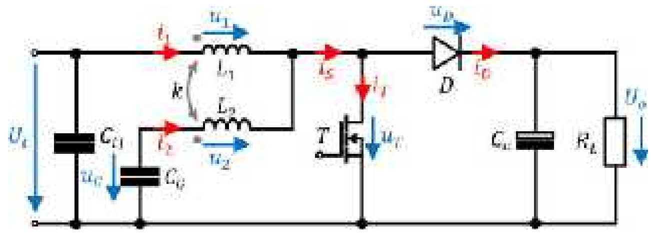

Fig. 1. RCS Boost Converter.

An additional capacitor is also there at the input. This is to get fourth order filtering action. For analysis filtering part is first separated from the noise producing elements. To study attenuation, a comparison is made between boost converter and RCS boost converter. For comparison overall capacitance of boost (C_{i2}) and RCS boost (C_{i1}) converters are assumed to be equal

$$C_{i2} = C_{i1}+C_G \quad (1)$$

In real case parasitic components will be associated with inductor and capacitor. So inductor in filter is augmented with series resistor (Effective Series Resistor, ESR) and parasitic capacitor (Winding Capacitor). Capacitor is augmented with series resistor and series inductor (Effective Series Inductor, ESL).

IV. Coupled Inductor Theory

Coupled inductor technique involves simultaneous parallel energy-transfer pathways: electrical and magnetic [5]. Smoothing transformer (a pair of coupled inductor) and a dc blocking capacitor is shown in Fig. 2. Windings L_1 and L_2

carries dc and ac currents respectively. When capacitor C_G is large, ac voltage (V_c) across it becomes zero [5].

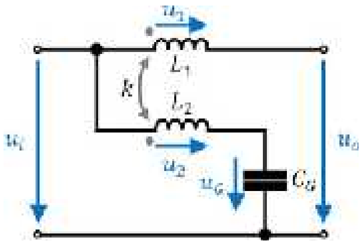

Fig. 2. Coupled Inductor with capacitor in series with one winding.

Then ac voltage across secondary winding L_2 will be transferred to L_1 winding. Now output voltage will have only dc component. This is how ideal smoothing transformer steers ripple. But zero ripple is not possible in real cases [2]. Because capacitor will have a finite value and some ripple would appear at the output port. For analyzing coupled inductor it can be represented in its equivalent "T" model as in Fig. 3. M is the mutual inductance and can be expressed as

$$M = k\sqrt{L_1 L_2} \tag{2}$$

where k is the coupling factor

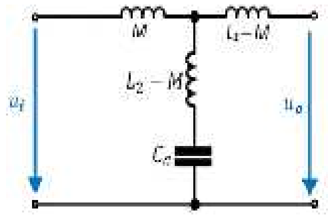

Fig. 3. Coupled inductor filter model represented by its equivalent "T" model.

Coupling factor ranging from $0 < k < 1$ is permissible. In practice, values of $k > 0.9$ are easily achievable. The operating regime of coupled inductor is sensitive to coupling factor k [6] which depends on many factors including magnetic flux path geometry.

In ideal case perfect compensation [5] in L_1 winding is possible for the matching coupling factor k_{01}.

$$k_{01} = \sqrt{\frac{L_2}{L_1}} \tag{3}$$

V. SIMULATION AND ANALYSIS

Frequency responses of coupled inductor are plotted for ideal and non-ideal cases and analysis is done. With coupling factor equal to k_{01} the filter will degenerate into a second order filter with characteristic 40 dB/decade roll off. When coupling factor is less than this value, it results in undercompensation. This can also be called as notch mode. When $k > k_{01}$, it results in overcompensation. This mode of operation is not useful since it gives worse attenuation [2].

Effective inductance (L_{seff}) provided by the smoothing transformer to the boost converter is analyzed to see the impact of coupling factor. Effective inductance is given by

$$L_{Seff} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} \tag{4}$$

L_{Seff} will be same as L_2 in case of ideal compensation from equation (3). But in real cases, it varies with k for different matching coupling factors k_{01}. Sensitivity of L_{Seff} for relative deviation of coupling factor is depicted in Fig. 4. Relative deviation of coupling factor is defined as

$$K = \frac{k - K_{01}}{K_{01}} \tag{5}$$

It can be inferred from Fig. 4 that L_{Seff} is less sensitive to k_{01} in the undercompensation region ($K < 0$). Effective boost inductance is strongly dependent on coupling factor in overcompensation region ($K > 0$). We should get perfect compensation. But manufacturing tolerance may cause inductance value to vary. So we always aim for a slight undercompensation region. Inductance values are set accordingly.

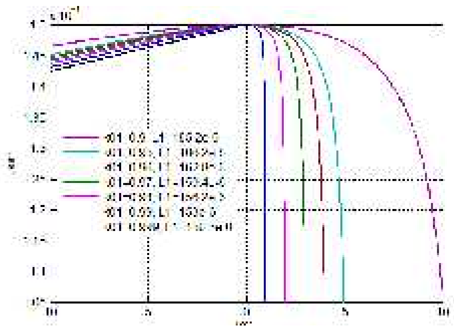

Fig. 4. L_{Seff} versus relative deviation of coupling factor.

A. *Effect of parasitic components*

First parasitic inductance (ESL) alone is considered. Frequency response of filter for different coupling factor mismatches (K) are shown in Fig. 5. Dashed line represents filter for boost converter. All others represents filter for RCS boost converter. For comparison, amplitude response of ideal filter is shown in Fig. 6 for various coupling factor mismatches.

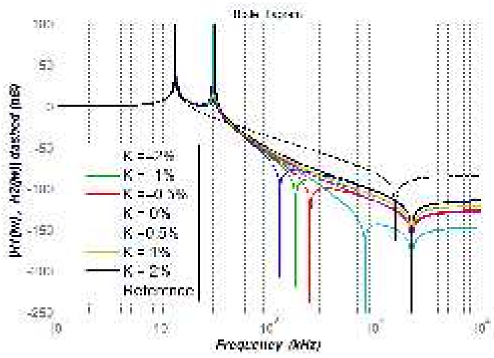

Fig. 5. Amplitude response taking ESL into account.

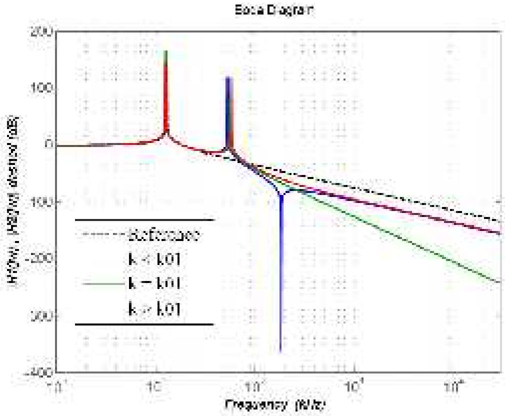

Fig. 6. Amplitude response of filter without parasitic components.

Comparing Fig. 5 and Fig. 6 we can observe that additional resonance appears in Fig. 5. The new additional resonant frequency f_{res} is due to natural resonance of the capacitors and is given by

$$f_{res} = \frac{1}{2\pi\sqrt{(ESL\,C)}} \tag{6}$$

In Fig. 5 we can see that better filtering obtained in the interesting frequency range for differential mode noise, 150 kHz to 2 MHz. Also we can see that undercompensation performs better in this range compared to ideal and overcompensation.

Considering winding capacitances and parasitic inductance another resonance f_{res4} occurs in the frequency range for DM noise as in Fig. 7. Comparing Fig. 5 and Fig. 7 we can see that this frequency is less than resonant frequency due to parasitic inductance. This resonant frequency f_{res4} can be calculated as

$$f_{res4} = \frac{1}{\sqrt{C_1}} \tag{7}$$

Though three winding capacitors are there viz C_1, C_2, C_{12}, major influence is due to C_1. Other two capacitors play minor role.

Influence of C_1 at the beginning of the frequency range is minor. Better attenuation is obtained in the range 100 kHz to 1 MHz.

Taking parasitic resistors also into account, resonances are damped as seen in Fig. 8. Damping of resonance step-up of first two pole pairs occurs at around 12 kHz and 50 kHz. Only R_1, R_2 and ESR_G have effect on the resonance. Wider frequency band is now obtained where coupled inductor performs better attenuation.

B. Attenuation Gain

Comparison of the two filters (filter for boost converter and filter for RCS boost converter) can be done with attenuation gain. Attenuation gain, A(s), can be determined using equation (8).

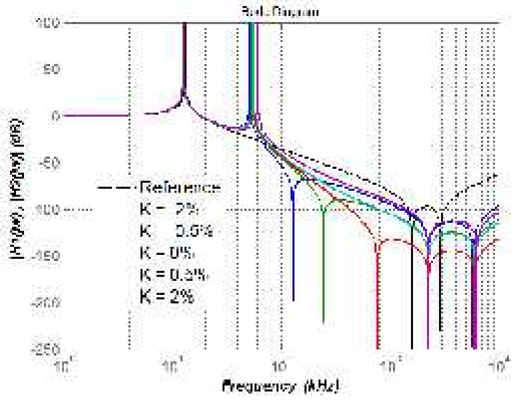

Fig. 7. Amplitude response taking ESLs and winding capacitances into account. Dashed line represents boost filter and others represent RCS Boost filter.

Positive value of attenuation gain gives good attenuation.

$$A(s) = \frac{H_2(s)}{H_1(s)} \tag{8}$$

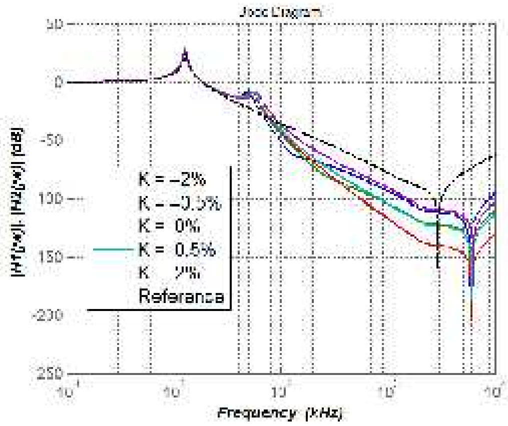

Fig. 8. Amplitude response taking ESL, winding capacitances and parasitic resistors.

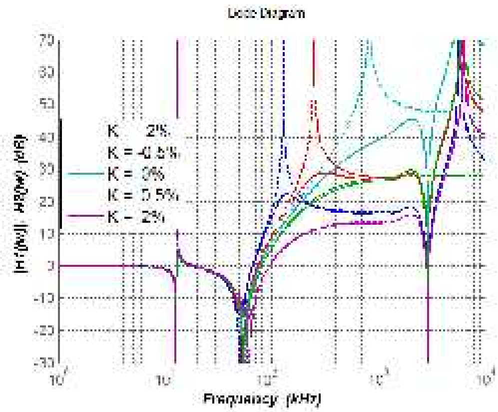

Fig. 9. Amplitude response of attenuation with and without(dashed) parasitic elements.

We can see from Fig. 9 that positive attenuation gain is obtained from frequency of 150 kHz where the EMI regulations start. Attenuation gain for ideal and non-ideal cases are shown in Fig. 9. Dashed line shows ideal cases. Different coupling factor mismatches are considered. It can be inferred from Fig. 9 that even with the presence of parasitic components perfect attenuation is obtained in the interesting frequency range of 150 kHz to 1 MHz. A slight undercompensation performs better in the starting of the frequency range than ideal compensation and overcompensation

We have taken same value of capacitance for C_{i1} and C_G in the analysis. Distribution factor ($0 \leq \gamma \leq 1$) is defined for further improvement in attenuation gain.

$$C_G = \gamma C_{i2} \text{ and } C_{i1} = (1-\gamma)C_{i2} \qquad (9)$$

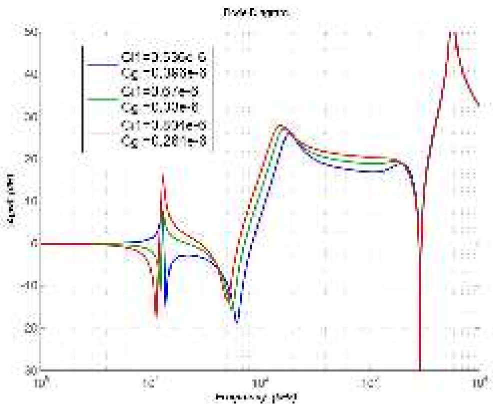

Fig. 10. Amplitude response with capacitance tolerance as a parameter.

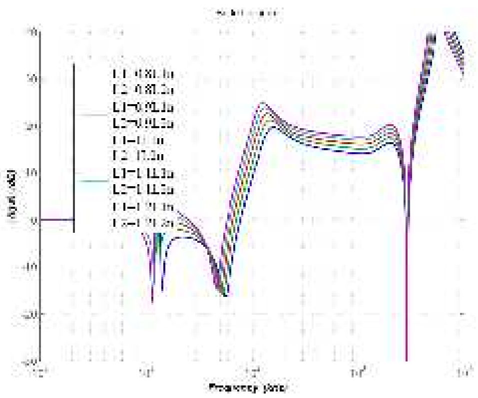

Fig. 11. Amplitude response with magnetic tolerance as a parameter.

C. Attenuation Gain

Manufacturing tolerances might cause capacitor and inductor values to vary. These two are considered then. Regular values are taken as $C_{i1} = 0.67\mu F, C_G = 0.33\mu F$ and their variation by 20% is assumed and corresponding amplitude response is plotted as in Fig. 10. For comparison, the sum of C_{i1} and C_G is still equal to C_{i2}. Tolerance causes attenuation gain to vary by a few dB, but the overall result is not much affected.

Fig. 11 shows the effect of tolerance in the magnetic component. Variation by 10% and 20% are considered. L_1, L_2 and coupling factor k varies due to tolerance in magnetic component. Attenuation should not vary largely. For this, inductance value should be allowed to vary within ±5% due to tolerance.

The variation of the coupling factor due to tolerances is equal to a variation of the factor κ. It has severe impact, but good attenuation gain is still possible.

VI. CONCLUSION

A filtering technique with integrated magnetics, taking non-ideal effects into account is presented. Coupled inductor gives attenuation of differential mode noise, even after parasitic components are considered. Analysis of a DM filter with smoothing transformer is shown. Parasitic elements as well as tolerances are considered and a comparison to a standard *LC*-Filter is done here. Even with parasitic components and tolerances, significant positive attenuation gain is left in the frequency range between 150 kHz and a few megahertz. It shows filtering behavior of the coupled inductor in the DM noise range.

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