Some Electromagnetic Aspects of Coreless PCB Transformers

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Abstract—In this paper, some EMI aspects of using coreless PCB transformers are addressed. Based on the antenna theory, the radiated power of a coreless PCB transformer is estimated and found to be negligible. The electromagnetic field plot of a power electronic circuit using a gate drive circuit isolated by a coreless PCB transformer has been recorded. The major radiated EMI source in the frequency range of 30 MHz to 300 MHz is found to be the copper tracks of the power circuit, where switching transients occur. The coreless PCB transformer can provide a reasonably high voltage gain. The impedance of the transformer circuit can be higher than 100 Ω in the frequency range of 8 MHz in this case by near-field magnetic coupling. Experimental results have confirmed that the application of coreless PCB transformer in gate drive circuit will not impose any serious EMI problem on the power electronic circuit.

Index Terms—Inductive components, magnetic coupling, PCB transformers.

I. INTRODUCTION

T RANSFORMERS are basic components in many electrical and electronic systems. Traditionally, magnetic cores are used in transformers for providing good magnetic paths for the energy to transfer from the primary to the secondary, or vice versa. Using transformers without closed magnetic cores can be found in some applications such as inductive chargers for batteries [1] in electric vehicles and commercial electric tooth brushes. These types of applications require that the secondary charger circuits to be easily removed from the primary charger circuit. Usually, the number of turns in transformers for inductive charger applications are fairly large so that the inductance of the windings provides a sufficiently large impedance to avoid short-circuit or near-short-circuit situation.

Research into the development of transformers on printed circuit board (PCB) has been reported. An interesting idea of printing the transformer windings on a double-sided PCB has been suggested [2]. A hole was made in the PCB so that two U-shape magnetic cores were glued together to form a closed magnetic path. The advantage of such arrangement is that the manual winding process can be eliminated. Many studies of developing planar windings and inductors on PCB or thin-film materials have been documented [3]–[7]. However, the use of coreless PCB transformers with only a few turns have only been reported recently in [8]. The reason for not being able to realize coreless PCB transformers earlier is probably because of some misunderstandings that:

1) printed windings with a few turns (short copper tracks) behave almost like “short-circuit,”
2) the magnetic coupling between the printed windings without using magnetic core is very poor;
3) the coreless transformer may have EMI problem.

In previous reports, the authors have clarified the first two misunderstandings and demonstrated that it is feasible to use coreless PCB transformers for power electronic gate drive circuits. By connecting an external capacitor across the secondary windings of the coreless transformer, the partial resonant effect of the external capacitor and the inductive components of the transformer can provide a reasonably high voltage gain. The impedance of the transformer circuit can be higher than 100 Ω in the example reported in [9]. Based on the coreless transformer concept, a direct gate drive suitable for the switching range from a few hundreds of kilohertz to a few megahertz [8] and a modulated gate drive with a switching frequency range from dc to at least 300 kHz [9], [10] have been successfully implemented. In addition, a coreless PCB transformer with two secondary outputs has been analyzed, tested [11] and employed in a converter circuit successfully [12]. While these successful implementations have confirmed the feasibility of using coreless PCB transformers for energy and signal transfer, the electromagnetic interference (EMI) aspects of the coreless PCB transformers has not been explored. In this paper, the EMI issues of coreless PCB transformers is theoretically assessed using the antenna theory. The field plot of a printed circuit board, on which the coreless PCB transformer isolated gate drive circuit and the power converter are built, has been recorded by a precision EMC scanner. A 3-D EM field simulation has also been performed. The EMI of the transformer and other factors in a power circuit has been examined. The major EMI source in the entire power circuit has been identified.

II. FAR-FIELD RADIATION

The dimension of the coreless PCB transformer (named as TR6) under consideration is shown in Fig. 1. The primary and secondary windings are identical. They are spiral in shape so as to minimize the interwinding capacitance [8]. They are printed directly opposite to each other on the two sides of a double-sided PCB with a thickness of about 1.54 mm. Each printed winding has 10 turns. The outermost turn has a radius of 5 mm. The transformer is used in a demodulated gate drive circuit [9], [10] shown in Fig. 5. The carrier frequency of the transformer is set at about 8 MHz, which is the “maximum-impedance frequency”
of the transformer. This frequency ensures that the transformer gate drive circuit consumes the minimum power in its operation [9].

Each turn in the spiral windings of the transformer can be regarded as a loop antenna [13], [14]. In order to simplify the analysis, we first consider the radiation from the outermost turn that has a radius of 6 mm. Radiation from the outermost turn is the worst case situation because the radiation efficiency and average radiated power increase with the radius of a loop antenna. If the radiation from the outermost turn/loop is small under such assumption, then the radiation from other inner turns/loops is even smaller since they have smaller radii than the outermost turn.

Consider a single loop in a $x$-$y$ plane. When a current flows in the loop at an angular frequency $\omega$, it is expected that some energy will be radiated in air. The radiation intensity $U$ can be shown [13] to be

$$U(\theta) = \frac{(Io \pi a^2)^2}{32\pi^2} \eta k^4 \sin^2 \theta$$  \hspace{1cm} (1)

where

- $I_o$ current in the loop,
- $\eta$ intrinsic impedance of the medium ($\eta = \sqrt{\mu/\varepsilon} = (k/\omega\varepsilon)$),
- $k_c = (\omega/\varepsilon) = (2\pi/\lambda)$
- $a$ radius of the loop;
- $c$ speed of light ($3 \times 10^8$ m/s) and
- $\theta$ radiation angle.

The time-averaged radiated power ($P$) of a loop antenna is

$$P = 100\pi^4 I_o^2 \left( \frac{\pi a^2}{\lambda^2} \right)^2$$

$$= 100\pi^6 I_o^2 \left( \frac{a}{\lambda} \right)^4$$  \hspace{1cm} (3a)

where $I_o$ is the current in the loop antenna and $a$ is the radius of the loop antenna. This radiated power can also be expressed in terms of the operating (or carrier) frequency as

$$P = 100\pi^6 I_o^2 \left( \frac{a f_c}{c} \right)^4$$  \hspace{1cm} (3b)

It can be seen from (3b) that the radiated power depends on i) the current $I_o$ (or power of the operation), ii) the dimension (radius $a$) of the structure, and iii) the operating frequency $f_c$. The radiated power drastically increases with increasing frequency.
and the dimension of the radiating structure. According to the antenna theory [13], a good loop radiator should have a radius that is in the order of magnitude close to that of the wavelength of the radiated signal. For the transformer TR6, the radius of the outermost loop is 0.005 m. This radius is only \(0.13 \times 10^{-3}\) of the wavelength \(\lambda\) (37.5 m). The term \((a/\lambda)^4\) is in the order of \(10^{-16}\). For a current \(I_c = 1\) A, the radiated power of a single loop antenna with a radius of 5 mm is \(P = 4.86 \times 10^{-11}\) W. Therefore, the averaged radiated power of a single loop with a radius of 5 mm is negligible. Although the coreless PCB transformer has ten turns, the radiated power involved and its EMI effects are still too small to be a concern. Therefore, the calculation indicates that the transformer TR6 is an extremely poor transmitting antenna as far as far-field radiation is concerned.

By the reciprocity theorem [13], a poor transmitter is also a poor receiver for a signal of a certain wavelength. The frequency range of a receiving antenna depends on the effective dimension of the antenna. From a receiving antenna’s point of view, TR6 (with a radius of 5 mm) is a good receiver only for signals in the frequency range of tens of gigahertz. However, it is important to note that many copper tracks in a typical PCB of a power electronic circuit may have a greater dimension than 5 mm. So TR6 is not a good receiving antenna either. In addition, it has been pointed out [13] that loop antenna is not a good antenna compared with many other types of antenna. Loop antenna may be used as a search coil. However, the winding has to be wound on ferromagnetic materials such as ferrite in order that the search coil can be effective. Also, the received signal has to be amplified in the search coil application. The coreless PCB transformer under consideration has neither of these conditions and features.

III. NEAR-FIELD COUPLING

A. Three-Dimensional Simulation

The coreless PCB transformer is simulated using Ansoft 3-D EM Field Solver. Figs. 2–4 show the magnetic field plots of the coreless PCB transformer when the primary winding is excited with a current and the secondary winding loaded with a resistor. It can be seen that the magnetic field essentially concentrates inside and near the transformer structure. The field intensity drops rapidly away from the transformer structure. Fig. 4 shows clearly that most of the flux lines concentrate within the gap between the winding areas.

B. Practical Measurement

In order to practically evaluate the EMI aspects of the power converter using the proposed coreless PCB transformer gate drive, the power electronic circuit shown in Fig. 5 is constructed and tested. The carrier frequency \(f_c\) of the transformer is set at about 8 MHz. The gate drive is demodulated to switch the power MOSFET APT5040 at 100 kHz with a duty cycle of about 0.6. The converter dc voltage is 60 V. Full details of the demodulated gate drive operation and the optimal operation of the coreless transformer can be found in [9]. A precision EMC scanner with video facility was used to record the EMI emitted from the power circuit. Because of the close distance between the primary and secondary printed windings and the nature of the transformer, the near-field magnetic field is dominant in the transformer [15]. Fig. 6(a) shows the photograph of the “top side” of the power circuit and the gate drive circuit. It is important to note that the photograph of the “bottom side” of the PCB was processed with the software ‘Microsoft Photo Editor.’ The photograph of the bottom side of the PCB [Fig. 6(b)] was first taken and then “mirror-imaged” so that the positions of the all tracks and components are “as if they are actually underneath the top side of the PCB.” This allows us to examine the relative position and intensity of the EMI sources later.

On the lower left-hand side of the PCB are the integrated circuits for the electronic control of the gate drive circuit. The positions of the primary and secondary printed windings are highlighted in black square frames in Fig. 6(a) and (b), respectively. The power MOSFET is on the lower right-hand side of the PCB. A bulk dc capacitor is placed in the middle region of the top part of the PCB. Two relatively “thick” copper tracks on the upper right-hand side of the board are the tracks for the power circuit (where switching transients occur).

Initially, only the gate drive circuit was turned on and the high voltage power supply for the power circuit was disconnected.
The PCB was scanned with the precision scanner using a magnetic field probe for the frequency range from 100 kHz to 100 MHz. Fig. 7 shows the relative strength of the magnetic field distribution in the PCB under the condition that the power circuit is turned off. It indicates, as expected, that the magnetic field concentrates inside and close to the printed transformer. The magnitude plot of the magnetic field distribution of the coreless PCB transformer is re-constructed and shown in Fig. 8. It can be seen that the field is primarily in the vertical direction, i.e., perpendicular to the $x$-$y$ plane. This is a typical characteristic of a loop antenna [13], [14].

The entire power circuit was then operated and was scanned again. The IEC 1000 directive has limits on the radiated EMI emission from 30 MHz to 300 MHz. Another magnetic probe with a specified frequency range from 30 MHz to 3 GHz was then used to scan the power circuit. The frequency range of the field measurement was set for the range from 30 MHz to 300 MHz. Fig. 9 shows the relative radiation level emitted from the PCB within this specific frequency range when the power circuit is turned on. The corresponding magnitude plot of the field distribution is included in Fig. 10. It can be seen that most of the EMI emission comes from the upper left-hand region of the PCB (labeled as region ‘T’). This area contains the copper tracks that form part of the power circuit. Thus, the major source of EMI emission is the conducting path of the power circuit (upper right-hand side of the PCB) rather than the coreless PCB transformer. Even the gate drive circuit on the primary side (region “P”) and the gate drive circuit on the secondary side (region...
“S”) have higher EMI emission than the coreless PCB transformer (enclosed in the square box). The EMI emission from the coreless PCB transformer is relatively small compared with that from the power circuit and other electronic circuit in the entire circuit. Unlike the power tracks and the gate drive electronics where sharp voltage and current transients occur, the coreless transformer has some filtering effects and has no sharp rising and falling voltage and current edges. Although the coreless PCB transformer is placed fairly close to the power circuit, its normal operation is not affected by the EMI from the power circuit [9].

Coreless PCB transformers essentially operate at relatively low frequency (8 MHz in this case) by near-field magnetic coupling. This near-field magnetic coupling effect is approximately proportional to $1/r^2$ or $1/r^3$, where $r$ is the distance from the source [15]. Thus, this (relatively low frequency) magnetic coupling is only effective in a localized region as confirmed in simulations and measurements. Coreless PCB transformers, such as TR6, (i) with small radius $a$ and (ii) low operating frequency $f_o$, (iii) low power (e.g., small current $I_o$ in gate drive circuit) and (iv) no fast transients, are therefore not serious EMI source in the frequency range of 30 MHz to 300 MHz.

IV. CONCLUSIONS

Some EMI aspects of the using coreless PCB transformer in power electronic circuits have been addressed. Based on the antenna theory, it is found that the coreless PCB transformer under consideration has a radius that is much smaller than the wavelength of the operating frequency. Thus the transformer winding is an extremely poor transmitting and receiving antenna and its radiation power is negligible in gate drive applications. Unlike the conducting paths of the power circuit, the isolation coreless transformer has very small switching transients and therefore emits relatively insignificant EMI. Field measurements of the entire power circuit have confirmed that the coreless PCB transformer is not a major EMI source in the frequency range from 30 MHz to 300 MHz. The coreless PCB transformers essentially operate at relatively low frequency (8 MHz) by near-field magnetic coupling. Both theoretical estimation and experimental results indicate that the application of this transformer will cause no significant EMI problem.

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REFERENCES


Fig. 9. EMI from PCB with both the gate drive circuit and the power circuit turned on. Frequency range: 30 MHz to 300 MHz.

Fig. 10. The magnitude plot of the magnetic field distribution of the coreless PCB transformer. Frequency range: 30 MHz to 300 MHz. (Viewed from the bottom left-hand corner to the top right-hand corner of the PCB.)
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