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A Multi-Resonant Forward Converter Based on Non-Ideal Coupling of the Transformer

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Abstract

There are many transformer applications where tight coupling is difficult to achieve. Therefore an analysis of a resonant converter with a non-ideal coupling is required. In this paper a lossless forward resonant converter with a coupling ranging from 0 to 1 was studied. The peak voltage and current stress of the power switch were compared as a function of the coupling. It was found that as the coupling decreases from 1 to 0.9, the peak switch voltage reduces dramatically whilst the peak current increases slowly. Therefore, at the expense of a small increase in peak current, a coupling of 0.9 decreases the peak voltage to approximately three times the input voltage. It was also found that the traditional quasi-resonant converter becomes a multi-resonant converter when the coupling is less than one. This is because the finite switching time of the rectifying diode reduces the input inductance of the transformer to effectively give a converter that uses two different inductances during any one switching period. An experimental 48-5V 20W forward converter with a coupling of 0.9 was designed and tested. It verified the practicality of a reduced coupling transformer and yielded an extremely simple converter with a minimum parts count

1. Introduction

A common goal of transformer designers has been to increase the coupling and thereby increase the amount of energy delivered to a load. A high coupling is generally achieved when the magnetic material has a large permeability, when the air gaps in the material are kept small and the windings are in close proximity to the material. Although a coupling of close to one is physically possible, it is

becoming a more difficult task as converter frequencies increase. This is mainly because high frequency power magnetics have a lower permeability. Some examples where high coupling is difficult to achieve are printed circuit transformers and electric vehicle recharging transformers. A question then arises, is there a power supply design that actually benefits from having a lower coupling? To answer this question, a more complete analysis of a converter that includes the effects of coupling is required.

For the traditional analysis of resonant forward converters it is often convenient to model the transformer magnetizing inductance as a current source [1]. This is only accurate if the magnetizing inductance is much larger than the leakage inductance, that is, if the transformer coupling is close to unity. Another common analysis assumption is that the rectifying and freewheeling diodes are ideal and their turn on and turn off times are instantaneous [1]. This can be valid from a semiconductor point of view but it is only accurate if the secondary leakage inductance is relatively very small. This is because the rate of change of the rectifying diode current is governed by the secondary leakage inductance. Therefore both of these assumptions can not be used if the effects of transformer coupling are to be investigated.

Quasi-resonant converters use one inductor and one capacitor to achieve one resonant frequency. The common multi-resonant converter [1] uses one inductor and two capacitors to give more than one resonant frequency. This paper introduces the concept that a quasi-resonant forward converter actually becomes a multi-resonant forward converter when the transformer coupling is less than one. The main advantage of this is that the non ideal coupling of a transformer can be exploited to give a very simple converter with a minimum parts count. The transformer can be less expensive and easier to construct, and the voltage stress on the switch can be reduced when compared to a quasi-resonant converter. A lower peak

resonant voltage permits the use of a MOSFET with a lower on-resistance or input capacitance, which is important for higher efficiency and simplified drive circuitry respectively. This paper presents a multi-resonant forward converter with a non ideal coupling and an experimental 48-5V 20W converter with a coupling of 0.9 is designed and tested to confirm its practicality.

2. Theory of Operation

Figure 1 shows a typical quasi-resonant forward converter where the transformer consists of two coupled inductors, the primary inductance (L_p) and the secondary inductance (L_s).

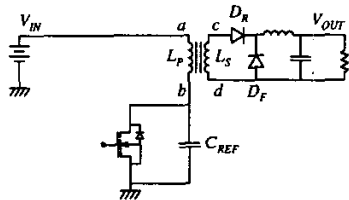


Figure 1 : A quasi-resonant forward converter.

Figure 2(a) shows this transformer as a four terminal device. Figure 2(b) shows an equivalent model of figure 2(a), derived from [2], which includes the transformer coupling (k). Figure 2(c) shows the equivalent primary input impedance (Z_{INP}) when the rate of change of current flowing out of terminal c is constant. This occurs when the rectifying diode (D_r) is completely on with constant current, or completely off with zero current. Figure 2(d) shows Z_{INP} when there is a short circuit between terminals c and d . This occurs when both D_r and the freewheeling diode (D_f) are conducting, such that their sum equals the load current. In this case the voltage between terminals c and d is clamped at around zero volts to give a virtual short circuit.

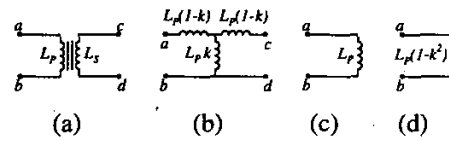


Figure 2 : A transformer as a) two coupled inductors, b) an equivalent model. The transformer input inductance when D_r current is c) constant or zero, d) changing.

Since D_r can only be fully on, fully off or partly on, then figures 2(c) and 2(d) describe the two possible equivalent input impedances of the transformer. Therefore there will be two different values of inductance resonating with the effective resonant capacitance (C_{REF}) during any one switching period. This gives rise to a multi-resonant converter with two resonant frequencies of $1/\sqrt{L_p C_{REF}}$ and $1/\sqrt{L_p(1-k^2)C_{REF}}$. C_{REF} can consist of an external capacitance in parallel with the output capacitance of the switch.

A description of operation during a steady state period is as follows. When the switch is on, D_r is fully on, Z_{INP} equals L_p and L_p has a linearly increasing current. The switch then turns off and the first resonant stage begins. D_r is still fully on so the resonant frequency is $1/\sqrt{L_p C_{REF}}$. The second resonant stage begins when D_r starts to turn off, which occurs when the voltage across the switch (V_{DS}) equals V_{IN} . Here the resonant frequency is $1/\sqrt{L_p(1-k^2)C_{REF}}$. It is the smaller equivalent inductance during this stage that lowers the peak resonant voltage when compared to a quasi-resonant converter. The next resonant stage begins when D_r is fully off, D_f is now fully on and supplying the load current. Since D_r is fully off the resonant frequency here is $1/\sqrt{L_p C_{REF}}$. The peak resonant voltage occurs during this stage. When V_{DS} lowers from its peak back down to V_{IN} , D_r starts to conduct and a new resonant stage begins.

Since D_r and D_f are both partly on, the resonant frequency is $1/\sqrt{L_p(1-k^2)C_{REF}}$. This stage continues until D_r is fully on or V_{DS} reaches zero volts. If D_r becomes fully on before V_{DS} reaches zero volts then another resonant stage of $1/\sqrt{L_p C_{REF}}$ begins.

An operation summary is that the turn on and turn off times of D_r each introduce a new stage or mode. This transforms the quasi-resonant converter into a multi-resonant converter. As k becomes smaller, these two new modes become more pronounced by occupying a larger percentage of the off time.

3. Experimental Investigation

It has been stated that when k is less than one, the quasi-resonant converter becomes a multi-resonant converter and that the peak resonant voltage can be reduced. It stands to reason that if k is reduced then more input current will be required to deliver the same output power. To investigate the effects of k , the circuit of figure 1 was studied analytically and also implemented in PSPICE for a 48-5V 20W converter. All components were ideal, no loss mechanisms were included and k was varied from 0 to 1. The peak switch voltage and peak switch current were then found as a function of k and are shown in figure 3. It can be seen that a trade off between voltage stress and current stress exists, minimum current means maximum voltage and vice versa. An optimum value of k depends solely on the application of the converter, and the relative effects for the whole system must be addressed. For example, lowering k can lower the voltage stress on a MOSFET which in turn permits the use of a MOSFET with a lower on-resistance (R_{ON}). This would reduce the I^2R loss. However, according to figure 3, the peak current stress is increased. This would increase the I^2R loss. Other tradeoffs were also present, when k was reduced the required value of L_p was reduced and that of L_s and C_{REF} were increased. Therefore if the reduction in parasitic resistance of L_p was more substantial

than the increase from L_s and C_{REF} then the total I^2R loss would be lower.

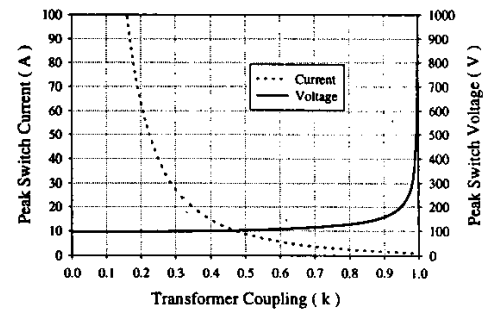


Figure 3 : The peak switch current and voltage as a function of k .

From figure 3 it can be seen that if k is chosen to be approximately at the knee of the peak voltage curve, then at the expense of a slight increase in peak current, the peak voltage can be dramatically reduced. A k of 0.9 is near the knee and also corresponds to a duty cycle of 50%, it was chosen to practically demonstrate the new multi-resonant technique. The circuit of figure 1 was built using an IRF740 as the MOSFET. C_{REF} was a 1nF capacitor in parallel with the IRF740. L_p was 14.5 μ H, L_s was 0.8 μ H and k was 0.9. Figure 4 shows the measured drain to source voltage (V_{DS}) and primary current (I_{LP}).

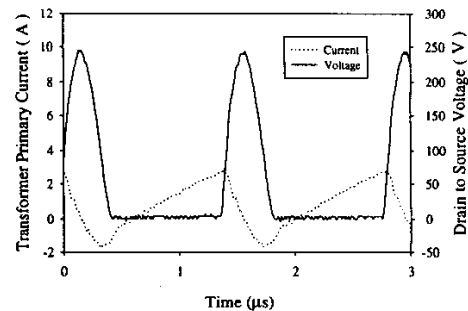


Figure 4 : Drain to Source voltage and the primary current for an output of 20W.

The peak voltage and peak current were measured as 240V and 2.5A respectively. These values are higher than the ideal case

from figure 3, with a k of 0.9, where they are 160V and 1.7A respectively. The duty cycle was also higher than the ideal case of 50%. The cause of the differences is that the input current, duty cycle and hence peak voltage had to be larger to supply the losses in the circuit. Some of the more common sources of loss that were not included in the ideal analysis of figure 3 are copper AC/DC resistances, magnetic hysteresis and eddy currents, diode voltage drop, capacitor dielectrics and R_{on} . These resistances would damp any resonant action and decrease the peak voltage. However, the output capacitance of the MOSFET is non linear and would increase the peak voltage. No fine tuning of any device was performed and no attention was given to efficiency. Therefore, as expected, the lossless analysis of figure 3 does not totally agree with the experimental results in figure 4. The experimental results did, however, provide confirmation of the theory to the first order.

Figure 5 shows the measured V_{DS} and I_{LP} for an output power of 0.1 watt. This shows that the converter can be regulated from no load to full load and still maintain zero voltage switching.

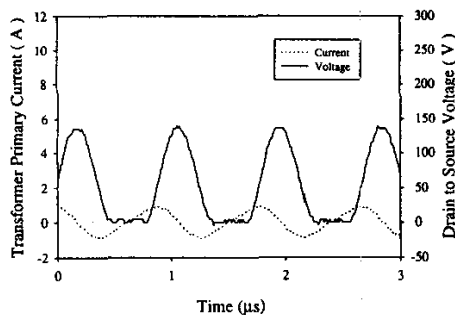


Figure 5 : Drain to Source voltage and the primary current for an output of 0.1W.

4. Conclusion

Converter frequencies are increasing to facilitate size reduction and improved efficiency. As a result, obtaining near ideal transformer coupling is becoming increasingly difficult. A power supply that benefits from leakage inductances is required. In analyzing a forward converter with non-ideal coupling, it was recognized that the magnetizing inductance should not be modeled with a current source, nor should it be assumed that the rectifying diode is switched instantaneously. When coupling is included in the analysis it is found that a quasi-resonant converter becomes a multi-resonant converter. The benefits of this are that the non-idealities of the transformer can be exploited and the peak voltage stress on the power switch can be reduced at the expense of a slight increase in the peak current. An experimental 48-5V 20W forward converter was designed and tested. The converter verified that by reducing the coupling of the transformer to 0.9 a practical converter with a realistic peak voltage and current can be designed.

5. Acknowledgment

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