THE EFFECTS OF LEAKAGE INDUCTANCE ON SWITCHING POWER SUPPLY PERFORMANCE

by

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INTRODUCTION.

Leakage inductance is often the largest single factor in degrading the performance of a switching power supply. The effects of leakage inductance in buck and boost regulators differ markedly from flyback (buck-boost) circuits.

This paper describes the effects of leakage inductance on circuit losses, load regulation and cross-regulation with multiple outputs. Methods of minimizing leakage inductance in practical transformers and coupled inductors are discussed.

Forward Converter. The first example chosen is a forward converter with multiple outputs as shown in Figure 1. Transformer mutual inductance and leakage inductances are not shown. This two-transistor version facilitates non-dissipative clamping of the energy stored in these transformer inductances and also reduces transistor voltage rating requirements. The circuit of Figure 1 is the same as in the 250 Watt Forward Converter Design Review covered separately, with a second output, V_2, providing 15 Volts at 3 Amperes in addition to the original 5 Volt, 50 Amp main output, V_1.

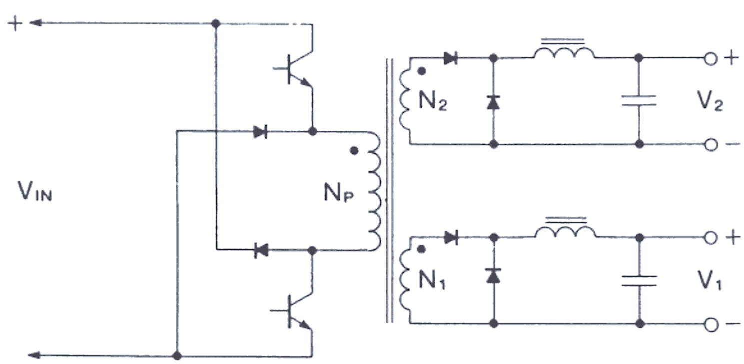
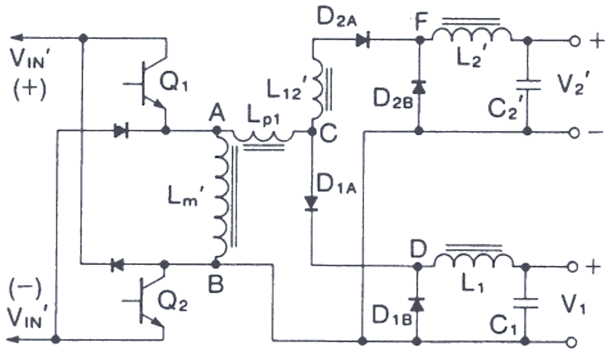


Figure 1. Forward Converter without Parasitic Inductances

In order to simplify the analysis, rectifier and transistor voltage drops are neglected. The effects of the parasitic inductances are most easily analysed in the equivalent circuit of Figure 2, in which the "ideal" transformer is eliminated. This is accomplished by normalizing the elements of the input and the #2 output according to their turns ratios with respect to the #1 main output:



$V_{IN}' = V_{IN}(N_1/N_p)$, $V_2' = V_2(N_1/N_2)$

$L_2' = L_2(N_1/N_2)^2$, $C_2' = C_2(N_2/N_1)^2$

Figure 2. Forward Converter Equivalent Circuit

L_m' is the normalized mutual inductance of the transformer. L_{p1} is the leakage inductance between the primary and the main secondary, and L_{12}' is the leakage inductance between main and #2 secondaries, all referred to the main secondary, N_1.

Operation with no Leakage Inductance. Circuit operation will first be examined with the assumptions that the leakage inductances L_{p1} and L_{12}' are zero, and the #2 output current, I_2', is also zero. This is the basic buck regulator configuration with added mutual inductance, L_m'.

Referring to the waveforms of Figure 3, filter inductor current, I_{L1}, is the familiar triangular waveform superimposed upon the DC output current, I_1. I_{L1} is carried entirely by rectifier D_{A1} during the "on" time of the switching transistors, t_{on}, and free-wheels through D_{A2} during the transistor "off" time. During t_{on}, voltage V_{DB} at the input of the L-C filter equals V_{IN}', but during the off time V_{DB} is zero. The output voltage of an inductor input filter (with continuous inductor current) always equals the time averaged input voltage, therefore:

$$V_1 = V_{IN}' t_{on}/T$$

During t_{on}, the input voltage is impressed across the transformer causing a linearly increasing current, I_{Lm}', through the mutual inductance. The maximum value of I_{Lm}' at the end of t_{on} is:

$$\max I_{Lm}' = V_{IN}' t_{on}/L_m' \qquad (2)$$

During t_{on}, normalized transistor current I_{Q1}' is the sum of the filter inductor current, I_{L1}, and the mutual inductance current, I_{Lm}'. During the off time, I_{Q1}' is zero. I_{Lm}' cannot decrease instantaneously. This causes the voltage on L_m' to reverse, forcing I_{Lm}' to flow through the clamp diodes. Thus the energy which was stored in L_m' will be recovered by pumping it back into the input source.

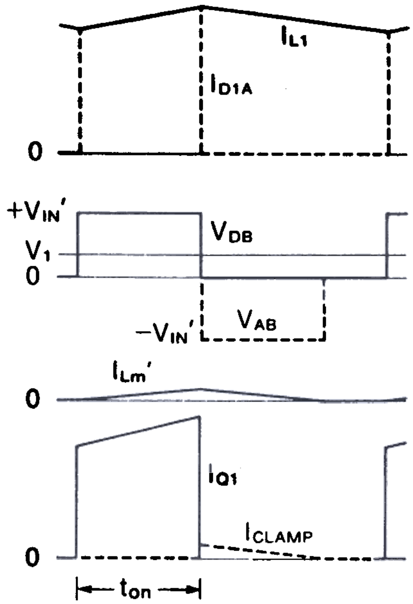


Figure 3.

Since the reverse voltage across L_m' equals V_{IN}', I_{Lm}' will decrease at exactly the same rate that it increased during the "on" time, thereby taking exactly the same time, equal to t_{on}, to reach zero again. This illustrates the fact that in order to reset the core each cycle, the reverse volt-seconds during the "off" time must at least equal the volt-seconds during the "on" time. When the reverse clamp voltage is equal to the forward voltage, as in this case, the duty cycle must be limited to 50% maximum, otherwise I_{Lm}' will continue to rise in subsequent cycles which will cause the core to saturate.

Normally, I_{Lm}' will be less than 10% of the full load current through the switching transistors causing a negligible increase in transistor losses. Likewise, I_{Lm}' has negligible effect upon the open loop line and load regulation. The energy stored in L_m' can result in significant losses if dumped into dissipative clamps. However, this energy can be recovered by clamping to input or output, or otherwise put to good use such as providing auxiliary power for the control and drive circuits.

Using the transformer design of the 250 Watt Forward Converter Design Review as an example, the 92 turn primary and 6 turn secondary result in a turns ratio of 15.33. The minimum V_{IN} of 200 Volts becomes 13 Volts V_{IN}' referred to the secondary. Primary mutual inductance, L_m, is 25mH or a normalized L_m' of 106uH referred to the secondary. From Equation 2, using a maximum t_{on} of 12.5 usec (40 kHz operation), the maximum I_{Lm}' is 1.5 Amps, negligible compared to the 50 Amp peak full load current in the secondary. The energy stored in L_m' equals 5 Watts at 40 kHz. Most of this energy is not lost, but pumped back to the input.

<u>Effects of Leakage Inductance with Single Output.</u> Figure 4 shows the result of introducing a finite value of leakage inductance, L_{p1}, in the #1 main output. Assume D_{2A} is open, completely disabling the #2 output.

L_{p1} has the effect of delaying the transfer of current between D_{1A} and D_{1B} at the beginning and end of the transistor "on" time. Referring to Figures 2 and 4, at the beginning of t_{on}, L_{p1} prevents instantaneous transfer of the filter inductor current to D_{1A}. D_{1B} must continue to conduct a diminishing portion of the filter inductor current during time t_1 while the current through L_{p1} and D_{1A} rises to finally equal I_{L1}. The time required for this current transition, t_1, is simply:

$$t_1 = I_1 L_{p1}/V_{IN}' \qquad (3)$$

Although V_{AB} jumps to V_{IN}' at the very beginning of t_{on}, V_{DB} remains at zero throughout t_1 because D_{1B} remains conducting. With t_{on} fixed (open control loop), output voltage V_1 is reduced by the volt-seconds represented in the shaded area averaged over cycle time, T. The open loop output voltage error is:

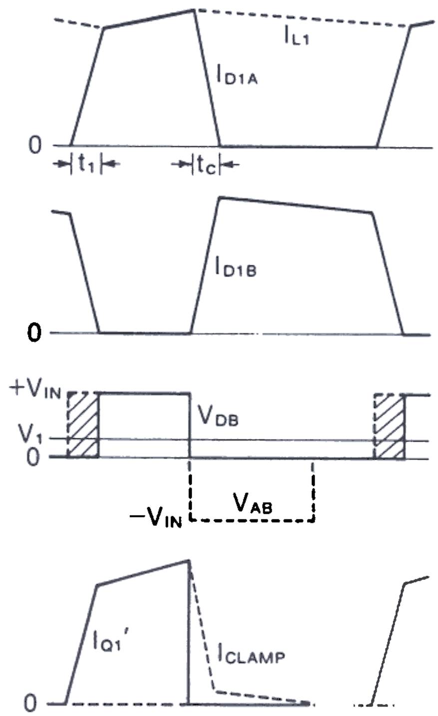


Figure 4.

$$\Delta V_1 = V_{IN}' t_1/T = V_{IN}' I_1 L_{p1}/V_{IN}' T = I_1 L_{p1}/T \qquad (4)$$

Equation 4 shows that the output voltage error varies linearly with load current. Interestingly, the value L_{p1}/T behaves just like an equivalent series resistance: "R_{p1}" = L_{p1}/T.

Energy is taken from the input source during t_1 and stored in L_{p1}:

$$W_{Lp1} = t_1 V_{IN}' I_1/2 = \frac{1}{2} L_{p1} I_1^2 \qquad (5)$$

During time t_c, L_{p1} delays transfer of current back to the free-wheeling rectifier, D_{1B}. D_{1A} and D_{1B} both conduct during t_c, and V_{DB} is zero. This has no effect on the output voltage since V_{DB} is zero in any case at the end of t_{on}.

The voltage across L_{p1} reverses during time t_c in order to maintain its current flow. V_{AB} becomes negative and the current from L_{p1} flows through the clamp diodes (in addition to the mutual inductance current discussed previously). Thus, the energy stored in the leakage inductance is also recovered back to the input.

In summary, the leakage inductance between primary and secondary hurts the open loop load regulation, but this is not usually important because it is easily brought into spec by closing the loop. The stored energy in the leakage inductance should either be recovered or put to good use, in exactly the same ways as the energy stored in the mutual inductance.

Continuing the 250 Watt Forward Converter example, the 92 turn primary consists of 4 layers of AWG19 wire, and the 6 turn secondary has 10 AWG18 wires in parallel to carry the high current. Assume the primary and secondary are <u>not</u> interleaved, that is, the entire primary is wound, then .01 cm insulation, then the entire secondary. Using the EC52 core, the primary to secondary leakage inductance, L_{p1}, referred to the secondary, is 0.52 uH. Applied to Equation 4, the open loop voltage error of the 5 Volt output will be 1.04 Volts at 50 Amp full load. For correction, a 20% increase in t_{on} will be required under closed loop control. The energy stored in the leakage inductance at full load amounts to 26 Watts at 40 kHz, which will hopefully be recovered by clamping to the input.

If the primary is interleaved with the secondary, i.e., wind two layers of the primary, insulate, entire secondary, insulate, then the remaining 2 primary layers, L_{p1} is reduced dramatically to 0.19 uH. Open loop output voltage error will be only .38 Volts and the energy stored equals 9.5 Watts at 40 kHz.

<u>Effect on Cross-Regulation of Multiple Outputs</u>. The waveforms of Figure 5 show the final step taken of drawing load current I_2' from the #2 output and with a finite value of leakage inductance, L_{12}', between secondaries.

L_{12}' has the effect of causing an <u>additional</u> delay in the transfer of current between #2 output rectifiers D_{2A} and D_{2B}. At the beginning of the "on" time, while current is increasing in L_{p1}, D_{1A} and D_{1B} are both conducting, holding voltage V_{CB} to zero. This means that throughout time t_1 there is no voltage across L_{12}' so that its current cannot start to increase. At the end of t_1, when the current through L_{p1} finally equals I_{L1}, the current through D_{1B} becomes zero and V_{CB} is allowed to rise. Current through L_{12}' and D_{2A} then starts to increase toward I_{L2}', throughout the interval t_2.

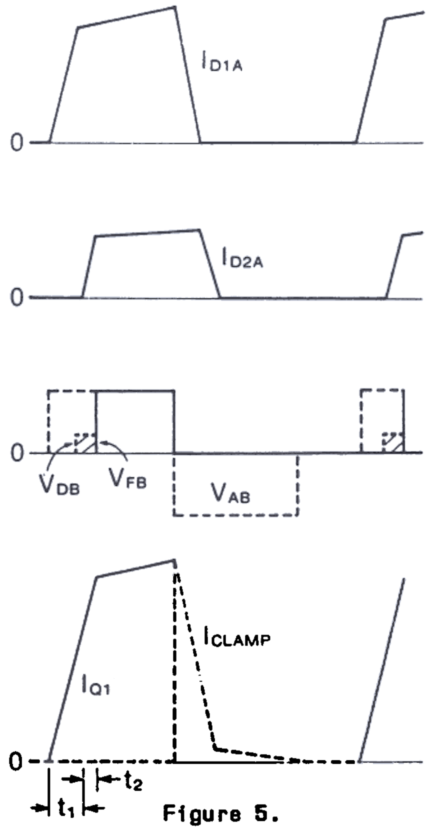


Figure 5.

During t_2, D_{2A} and D_{2B} both conduct, sharing I_{L2}'. V_{FB} is zero because D_{2B} is conducting. The third waveform of Figure 5 shows that during t_2, V_{FB} is zero but V_{DB} is a positive value, the same as V_{CB}. The shaded areas represent the difference in volt-seconds applied to the inputs of the two filters. When averaged over the period T, this equates to a differential or cross-regulation voltage error between outputs 1 and 2. There is no way to correct for this error, other than by post-regulation.

To quantify this error we must know V_{DB} and t_2. At the beginning of t_2, V_{CB} is allowed to rise above zero and current through L_{12}' starts to increase. This same increase in current must also occur through L_{p1}. Thus the two inductors are directly in series during t_2, so that the voltage across each is in direct proportion to its inductance value:

$$V_{DB} = V_{CB} = V_{L12}' = V_{IN}'L_{12}'/(L_{p1}+L_{12}') \qquad (6)$$

$$t_2 = (L_{p1}+L_{12}')I_2'/V_{IN}' \qquad (7)$$

$$\Delta V_{12}' = V_{DB}t_2/T = I_2'L_{12}'/T \qquad (8)$$

Note the similarity to Equation 4. The equivalent series resistance: "R_{12}'" = L_{12}'/T.

In the 250 Watt Forward Converter example using an EC52 transformer core, a portion of the window area allocated to the secondary will be used to add a 15 Volt, 3 Amp winding (45 Watts). Since 6 turns are used for the main 5 Volt winding, the 15 Volt output will require approximately 3 times as many, or 18 turns. It is important that the lower power 15 volt secondary should be wound <u>on top of</u> the higher power 5 Volt winding. The normalized leakage inductance between the secondaries will always be in series with the larger diameter winding because it has greater normalized inductance. Cross regulation voltage error is minimized, because the lower power output will have smaller normalized current changes through the leakage inductance.

The leakage inductance, L_{12}' in series with the outer #2 secondary in the EC52 core is approximately 0.25 microHenries (normalized to the #1 winding). The cross regulation voltage error due to load changes in the 15 volt #2 output may be calculated using Equation 8 either normalized to the 5 volt #1 output or not normalized. The results are:

Turns Ratio, n = N_2/N_1 = 18/6 = 3
Period T = 25 μsec

Not Normalized		Normalized
$V_2 = 15$ V	$1/n$	$V_2' = 5$ V
$I_2 = 0\text{–}3$ A	n	$I_2' = 0\text{–}9$ A
$L_{12} = 2.25$ μH	$1/n^2$	$L_{12}' = 0.25$ μH
$\Delta V_{12} = 0.27$ V	$1/n$	$\Delta V_{12}' = .09$ V

It is worth mentioning a few additional points. In the example chosen, the leakage inductance between the secondaries is physically located in series with the low power #2 secondary. The effect of changing output #2 load current on cross-regulation has been demonstrated above. However, the cross-regulation due to changing #1 main output load is theoretically perfect. Both outputs will track each other perfectly when load #1 changes, and if #1 is closed loop regulated, both are regulated. This is because there is no intervening impedance to impair cross-regulation in series with the #1 output from the common feed point C in Figure 2. This is why it is important to locate this leakage inductance in series with the low power output which has less effect on cross-regulation.

Cross-regulation can be improved dramatically by winding the secondaries together (multifilar). That is, the wires of all secondaries are co-mingled in the same winding volume, rather than seperate discrete secondaries wound on top of each other. This can make the leakage inductance between secondaries so small it becomes negligible. It is sometimes not practical to wind the secondaries multifilar, such as when copper foil is used for one or more secondaries.

It would be desireable to include the primary in the multifilar bundle to reduce the primary to secondary leakage inductance, but this is not practical in off-line applications because of the large turns ratio and the need for high voltage isolation between primary and secondaries.

Wiring inductance between the transformer secondaries and the filter inductor inputs (points D and F in Figure 2) has exactly the same effect as leakage inductance between secondaries; that is, wiring inductance has an adverse effect on cross-regulation. It is vital to minimize wiring lengths wherever the current is discontinuous. This is especially important with low voltage outputs and at higher power levels.

Be aware of the fact that after minimizing leakage and wiring inductances, the DC cross-regulation may be excellent, but the dynamic, or AC cross regulation will be pitifully bad if individual filter inductors are used in each output. This is true for any multiple output buck regulator, because a disturbance on any output is almost perfectly decoupled from all other outputs because of the high AC impedance of the filter inductors.

The solution to this problem is to put all output filter inductor windings on a common single core. This provides excellent AC coupling between the multiple outputs. The turns ratios between these windings must be the same as the voltage ratios between the respective outputs. The only problem with this technique is that slight offsets in voltage caused by rectifier forward drop variations will cause large circulating currents and output ripple at the switching frequency. The problem is solved by deliberately introducing a few percent of leakage inductance between the multiple windings of the filter inductor, which absorbs the voltage variations yet does not interfere significantly with the AC cross-coupling.

IMPORTANT NOTICE

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