9x.6 Transformer + Rectifier + Capacitor = Giant Spikes!

Most designers don't realize that a simple linear unregulated dc supply can (and often does) generate large microsecond-scale spikes, at the powerline frequency; these generate a buzzing sound in low-level audio circuits, and generally create havoc. They're easily tamed, once you know about them.

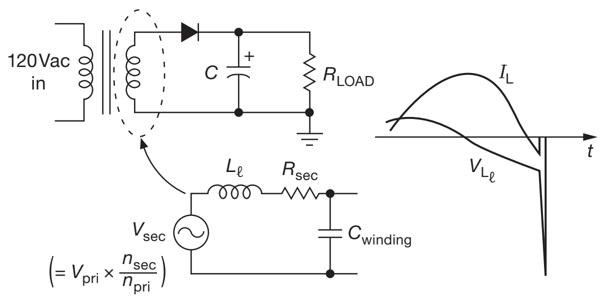

Figure 9x.23. Half-wave rectifier with transformer leakage inductance.

9x.6.1 The effect

We can understand this under-appreciated effect by looking at a half-wave supply (Fig. 9x.23). The problem is caused by the combination of the transformer's leakage inductance (see §§1.5.2 and 9.5.2 and the L_L values listed in Table 9x.1) and the rectifier's reverse recovery time (§1x.7.2): first, the (series) leakage inductance causes the current through the rectifier to lag the voltage across the inductor, so by the time the rectifier current reaches zero there is a significant reversed voltage across the inductor; that means that the current is decreasing at a significant rate, according to $V = LdI/dt$. Now, if the diode had no stored charge (zero reverse recovery time) there would be no problem – diode conduction would cease at zero current; but the diode, with its stored charge, continues to conduct as the current through it goes negative, until the stored charge is removed, whereupon the current stops abruptly.

This is the essential combination: the diode abruptly stops conducting with reversed current flowing through the inductor. Inductors don't like to have their current stopped abruptly ($V = LdI/dt$ again), and respond by increasing the voltage to maintain continuity of current. In this case that means a negative voltage spike at the transformer secondary.

The effect can be quite large. Fig. 9x.24 shows measured waveforms for a 10 V unregulated half-wave rectifier circuit. We used a Signal Transformer Co. "split bobbin" type, designed for good isolation (low inter-winding capacitance, high breakdown voltage), whose reduced winding coupling results in significant leakage inductance. The diode was a 1N4001 (1 A conventional rectifier), the filter capacitor was 3,300 μF electrolytic, and the load was a 20 Ω resistor. You can see the flattening of transformer output (with its series L_L and winding resistance), and the diode current causing capacitor charging; the mischievous spike occurs when the current goes to zero. The expanded trace (Fig. 9x.24B) shows that the diode current goes negative for about 8 μs before abruptly ceasing (or trying to, anyway!), at which point the spike erupts.

9x.6.2 Calculations and cures

For low-voltage unregulated supplies you can use Schottky rectifiers to prevent this effect. In addition (and more generally) you can suppress the spike by putting a capacitor (or series *RC* combination) across the transformer secondary; this provides a conduction path for the leakage inductance's suddenly orphaned current, as seen in Fig. 9x.24C.[24]

To choose values for a damping *RC* circuit, we can use the measured leakage inductance L_L to estimate spike size, slew rate, and resonant *Q*; we'll illustrate with the transformer used for the waveforms above (Signal 241-4-10: 10 Vrms, 0.5 A), which has a measured secondary $L_L = 2$ mH. The energy stored in the leakage inductance at the moment of snapoff ($\frac{1}{2}L_L I_{snap}^2$) is transferred to the capacitor ($\frac{1}{2}CV_{pk}^2$), so the peak voltage is

$$V_{pk} = I\sqrt{L/C}.$$

For our circuit, where the measured $I_{snap} = 13$ mA (Fig. 9x.24B), a 1μF damping capacitor results in $V_{pk} = 0.6$ V (compared with the 35 V undamped spike, whose size is set by the effective shunt capacitance of the transformer secondary winding and the rectifier, here roughly 300 pF). With that damping capacitor[25] the slew rate is

[24] You sometimes see a small ($\sim 0.1\mu$F) capacitor across each diode of a transformer-powered bridge rectifier.

[25] A 1μF capacitor might seem large, but the (reactive) current through

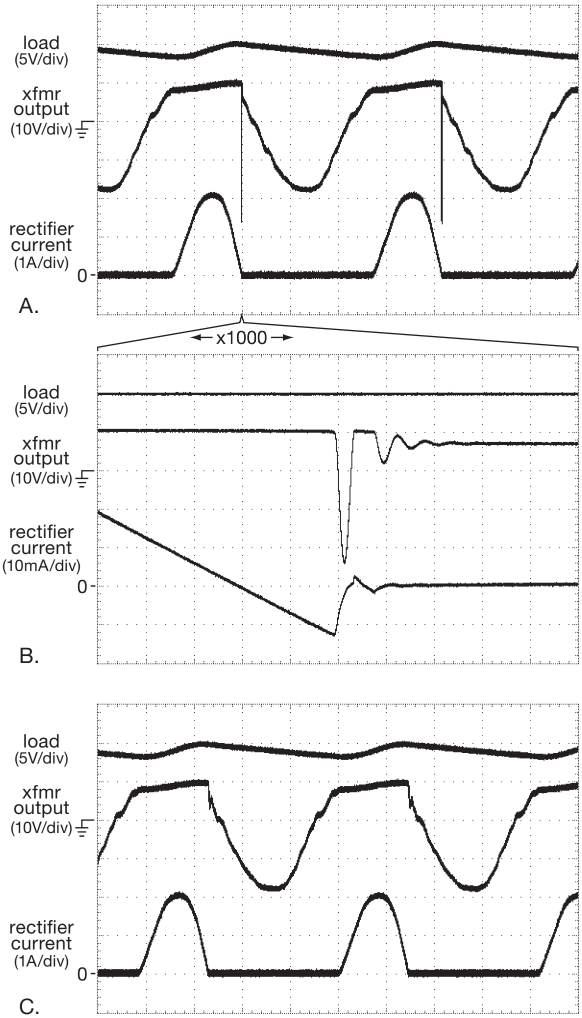

Figure 9x.24. Measured waveforms for the circuit of Fig. 9x.23, showing transformer output voltage, dc output voltage, and diode current. A. two full cycles (4 ms/div); note large negative spike at transformer output. B. expanded view (4 μs/div and 10 mA/div), showing detail of current reversal and of 35 V, 1 μs spike. C. addition of snubber (10 Ω and 1 μF in series) across secondary.

given by

$$\mathrm{SR} = dV/dt = I_{\mathrm{snap}}/C_{\mathrm{total}}$$

which evaluates to 13 V/ms; this is harmless, being only a factor of 4 greater than the secondary ac waveform's SR = $2\pi fA = 3.8$ V/ms. Finally, the series resistor R is chosen for adequate damping of the series RLC circuit, whose Q is given by $Q = \omega L/R$: our value of 10 Ω gives $Q \approx 3$, somewhat underdamped (even including the secondary winding resistance, which was measured to be 1.3 Ω); an external resistor of $R = 39\,\Omega$ would produce critical damping, though the added impedance would nearly double the voltage spike, by adding a ~0.4 V step ($I_{\mathrm{snap}}R$); perhaps of greater concern, that step is characterized by high slew rate.

Table 9x.1: Small Transformer Parasitics[a]

V_{sec} (V_{rms})	I_{sec} (A_{rms})	R_{pri} (Ω)	R_{sec} (Ω)	$R_{\mathrm{sec}}^{\mathrm{eff}}$ (Ω)	L_{L}(pri) (mH)	L_{L}(sec) (mH)	Part #
24	0.1	372	23.8	47.8	377	25.1	241-3-24
24	0.2	138	8.33	17.0	178	11.3	241-4-24
24	1.25	21.5	1.31	2.59	59	3.42	241-6-24
24	2.4	9.6	0.55	1.09	40	2.18	241-7-24
24	4.0	4.2	0.24	0.46	25	1.34	241-8-24

Notes: (a) All are Signal Transformer 241-series "split bobbin" power transformers, 120Vac primary, 24V secondary.

Table 9x.1 lists measured parasitic parameters (R_{winding}, L_L) for a series of typical small ac power transformers of successively larger frame sizes (thus power ratings). The leakage inductances were measured with an impedance meter, in each case with the other winding shorted. For resistive losses it's often convenient to assign a single "effective winding resistance" to the secondary, by combining a reflected primary resistance: $R_{\mathrm{eff}}(\mathrm{sec}) = R_{\mathrm{sec}} + R_{\mathrm{pri}}/N^2$, where N is the turns ratio $n_{\mathrm{pri}}/n_{\mathrm{sec}}$; that way, you have just one resistance value for calculations. Here, where the open-circuit output voltage for the transformers went from 30 Vrms down to 28 Vrms (going down the table), the turns ratio N went from 4.0 to 4.3. Normal transformer design typically chooses wire sizes to equalize resistive losses in primary and secondary; and that is the case with this series of transformers, where $R_{\mathrm{sec}}^{\mathrm{eff}}/N^2$ is very closely equal to twice R_{sec}.

it is 4 mA, negligible compared with the power transformer's 500 mA current rating.