RCD Snubber Revisited

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***Abstract*— The use of the polarized RCD turn-off snubber configuration across switching devices is popular because of its simplicity and use of only passive components. This configuration is limited by the fact that all capacitor-stored energy is dissipated in the discharge resistor.**

In this paper it is shown that with the addition of a ferrite transformer to the standard RCD arrangement, in excess of 70% of the energy stored on the snubber capacitor may be passively recovered into the dc supply. Performance of this passive recovery snubber is supported by theoretical, simulated and practical results.

I. Introduction

A TURN-OFF snubber capacitor is frequently used in power switching applications to limit the rate of rise of voltage across the switching device at turn off; thereby controlling the switching loss and voltage overshoot. A commonly used configuration is the passive polarized RCD snubber shown in Fig. 1. The principal disadvantage of this arrangement is that, usually, all the energy stored on the capacitor is dissipated in the resistor after the switch turns on. If the circuit is operating at a switching frequency f_s, then the power dissipation (P_d) in the snubber resistor will be

$$P_d = \tfrac{1}{2} C V_s^2 f_s. \quad (1)$$

This energy is fixed and independent of load current. For high frequency or high voltage operation this loss can prove to be a limit on the size of snubber capacitor that may be employed.

Various methods exist for the passive recovery of snubber energy [1]–[3]. The energy is usually recovered into the load, thereby affecting the load voltage regulation and makes recovery, load current-dependent. The circuit proposed in this paper is a simple modification to the RCD turn-off snubber arrangement that will allow a significant proportion (>70%) of the stored capacitor energy to be returned to the supply rail. This is achieved by the use of a transformer catch winding [4]–[6].

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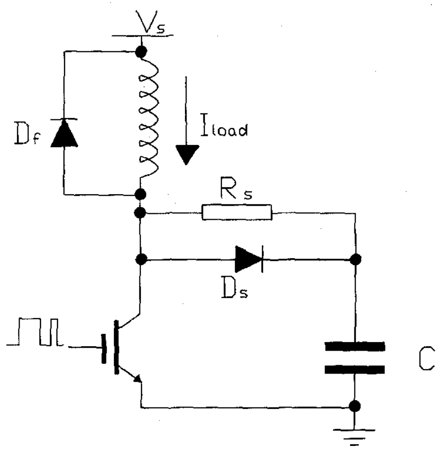


Fig. 1. The RCD snubber.

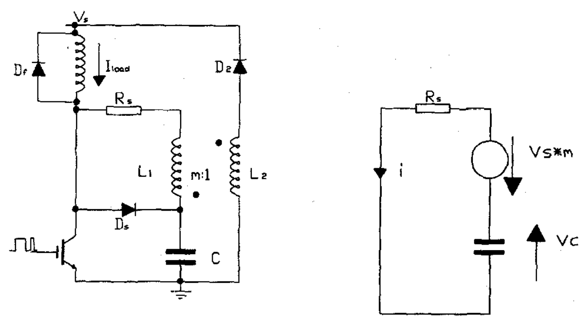


Fig. 2. The catch winding energy recovery circuit with resistor rest: (a) circuit and (b) equivalent circuit.

II. Circuit Description

A. Basic Circuit

In the circuit shown in Fig. 2(a) a ferrite step-up transformer is added into the discharge path. The turns ratio (m) is chosen such that when the switch turns on the secondary voltage is sufficient to cause D_2 to conduct, thereby transferring energy back to the supply. The equivalent circuit for this operation is shown in Fig. 2(b). For ideal circuit elements and a turns ratio of less than one ($m < 1$), the governing equation for the circuit is

$$\frac{dv_c}{dt} + \frac{v_c}{R_s.C} = \frac{V_s.m}{R_s.C}. \quad (2)$$

Given the initial conditions $v_c(0) = V_s$ and $i_c(0) = V_s(1 - m)/R_s$, the solutions to this differential equation are given by

$$v_c(t) = V_s\left[m + (1-m)e^{-(t/R_sC)}\right] \quad (3)$$

$$i_c(t) = \frac{V_s}{R_s}(1-m)e^{-(t/R_sC)}. \quad (4)$$

From these equations it may be shown that the recovered energy (E_R) is related to the turns ratio by the formula

$$E_R = 2E_0m(1-m) \quad (5)$$

where E_0 is the initial capacitor stored energy ($1/2CV_s^2$). Inspection of this formula shows that in theory 50% recovery could be obtained with $m = 1/2$. The basic circuit described here has two principal draw backs: i) because of the exponential shape of the discharge current flow, the on-time of the switch must be significantly greater than the R_sC time constant and this imposes a restriction on the minimum on-time for the switch; ii) at the end of the energy recovery phase a residual voltage of mV_s remains on the capacitor and is dissipated relatively slowly. This restricts the energy that may be recovered. These two restrictions may readily be overcome.

B. Improved Circuit

Fig. 3(a) shows a circuit with an improved energy recovery characteristic, over that in Fig. 2(a). Inductance is added to the capacitor discharge path. The effect is to cause the energy recovery phase to occur as a half sinusoidal pulse, the duration of which is essentially defined by the period of the resonant components C and L_r. The governing equation for the circuit during this resonant period is given as

$$\frac{d^2v_c}{dt^2} + \frac{R_s}{L_r}\cdot\frac{dv_c}{dt} + \frac{v_c}{L_r.C} = m.V_s. \quad (6)$$

Given the initial conditions $v_c(0) = V_s$ and $i_c(0) = 0$, the solutions to this differential equation are

$$v_c(t) = mV_s + V_s(m-1)e^{-\alpha t}\frac{\omega_0}{\omega}\cos(\omega t - \phi) \quad (7)$$

$$i_c(t) = \frac{V_s}{Z_0}(1-m)\left(\frac{\omega_0}{\omega}\right)^2 e^{-\alpha t}\sin(\omega t) \quad (8)$$

where

$$\omega = \omega_0\sqrt{1 - \frac{\alpha^2}{\omega_0^2}}$$
$$\phi = \arctan\left(\frac{\alpha}{\omega}\right)$$
$$\omega_0 = \sqrt{\frac{1}{L_r.C}}$$
$$\alpha = \frac{R_s}{2L_r}$$
$$Z_0 = \sqrt{\frac{L_r}{C}}. \quad (9)$$

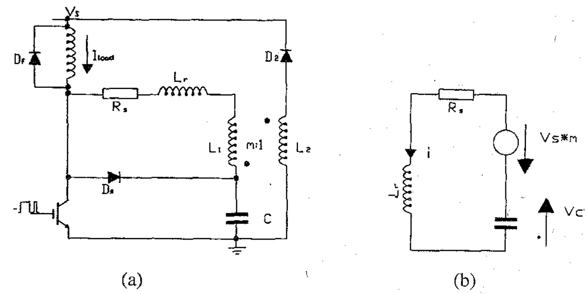


Fig. 3. The improved catch winding energy recovery circuit with resistor reset: (a) circuit and (b) equivalent circuit.

Mode I: Equations (7) and (8) hold for $v_c > 0$ and $i_c > 0$. For the case when $v_c > 0$ when $\omega t = \pi$ in (8), energy recovery will cease when the current reaches zero. The recovered energy, for this case, may be calculated analytically and is given by

$$E_r = 2E_0m(1-m)\left[1 + e^{-(\alpha\pi/\omega)}\right]. \quad (10)$$

In this mode of operation charge will be left on the capacitor at the end of the energy recovery phase, and this portion of the stored energy is not recovered. Some of this energy will discharge through the path provided by the magnetizing inductance (L_{mag}), L_r, R_s, and the switch, and this energy will be lost as heat in the resistor R_s. Any energy not recovered or dissipated in the resistor will be seen as a residual voltage on the capacitor (C) when the switch next turns off. In this case a soft voltage clamp suitable for IGBT's results.

Mode II: A second mode of operation, and that which is desirable for GTO's, occurs when the capacitor voltage reaches zero while there is still resonant current flowing. The stored energy in L_r causes the current to divert into the path provided by the diode D_s. In this case, transformer action continues and the energy stored in the inductor is recovered. If the time at which the capacitor voltage reaches zero is t_1 and the current flowing at this time is i_{t_1}, the current in the resonant inductor will decay exponentially according to (11), which holds until the resonant inductor current reaches zero. Even though energy recovery is incomplete at t_1, the capacitor is fully discharged and the switch may be turned off, if desired. The governing equation for the current during this period is derived from

$$\frac{di_{L_r}}{dt} + \frac{R_s}{L_r}.i_{L_r} = \frac{V_s.m}{L_r}. \quad (11)$$

If the origin is shifted to $t = t_1$ and the initial current condition is $i_{L_r} = i_{t_1}$, the solution to this differential equation is given by

$$i_{L_r} = -\frac{mV_s}{R} + \left(\frac{mV_s}{R} + i_{t_1}\right)e^{-(Rt/L_r)}. \quad (12)$$

If the current in the inductor falls to zero at time t_2, then the energy recovered by this mode of operation will be defined by

$$E_r = mV_s\int_0^{t_1} i_C\,dt + mV_s\int_0^{t_2} i_{L_r}\,dt. \quad (13)$$

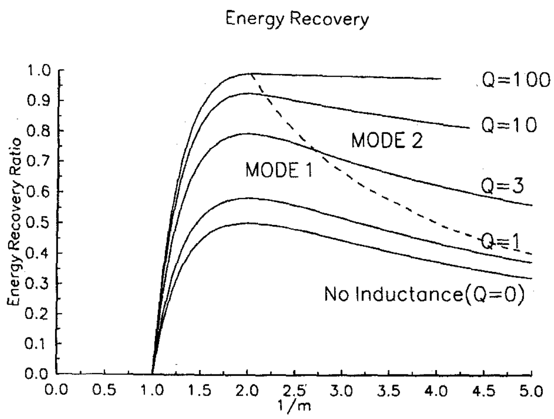


Fig. 4. Curves of the energy recovery ratio E_1/E_o for varying Q factor and turns ratio. The dashed line shows the boundary between mode 1 and mode 2 recovery.

The curves in Fig. 4 show the theoretical recovered energy for varying values of Q factor ($Q = Z_0/R_s$) and transformer turns ratio (m). These plots show that the peak energy transfer occurs for $m = 1/2$ and that the maximum recovery approaches 100% as the Q factor becomes large. For low values of Q factor the recovery rate approaches that for the basic circuit in Fig. 2. A high Q is achieved by removing circuit resistance added as part of the RCD network in the original circuit, shown in Fig. 1.

C. Modified Improved Circuit

A further modification that may be made to the circuit is that shown in Fig. 5. In this circuit the transformer secondary is connected to the positive side of the snubber capacitor. The behavior of the circuit is now governed by

$$v_c = m.(V_s - v_c) + L_r \frac{di_1}{dt} + i_1.R_s \tag{14}$$

$$i_1 = \frac{1}{1+m} i_c. \tag{15}$$

Again these equations may be solved to give the energy returned to the supply as the snubber capacitor discharges. In this case it is found that the recovered energy is given by

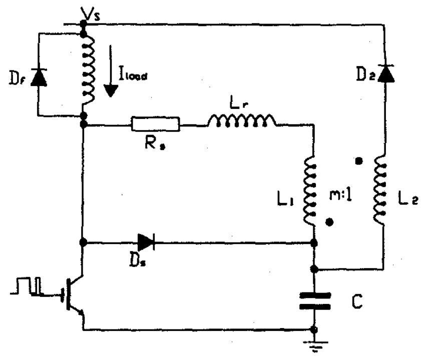
$$E_{2r} = 2E_0 . \frac{m}{(1+m)^2}\left[1 + e^{-(\alpha\pi/\omega)}\right]. \tag{16}$$

This gives rise to a similar set of curves to those shown in Fig. 4 except displaced one unit to the left on the $1/m$ axis.

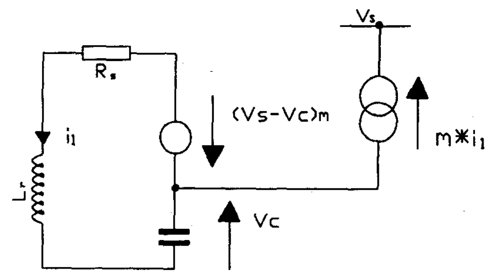
The principal difference between this and the arrangement shown in Fig. 3 is that the maximum energy transfer now occurs for m equal to one. This means that the potential reverse voltage seen by the secondary diode D_2 is halved.

III. Practical Limitations

In practice, the theoretical behavior will be degraded by a number of factors. A real transformer will posses a finite magnetizing inductance; during energy recovery the magnetizing



(a)



(b)

Fig. 5. The modified catch winding energy recovery circuit with resistor reset: (a) circuit and (b) equivalent circuit.

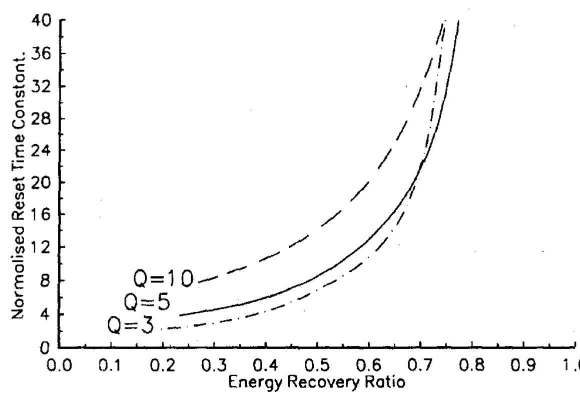


Fig. 6. Normalized reset time constant ($\omega_0 L_{mag}/2\pi R_s$) against energy recovery ratio ($m = 1/2$).

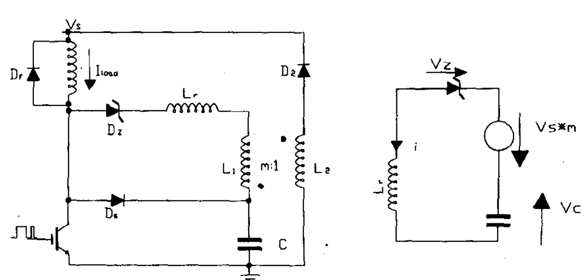
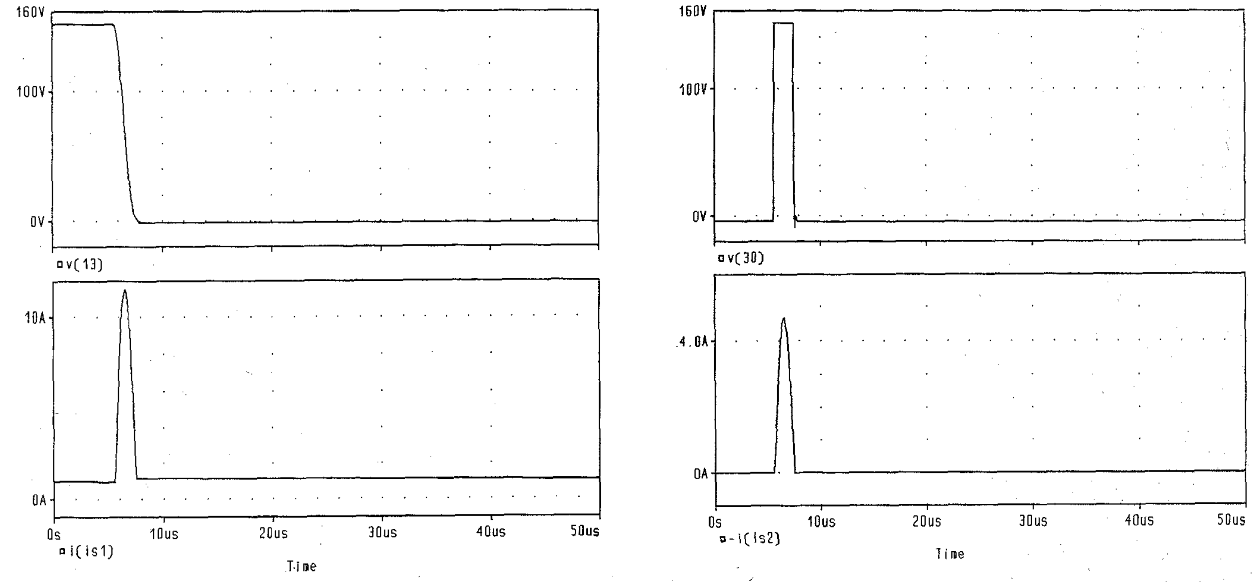
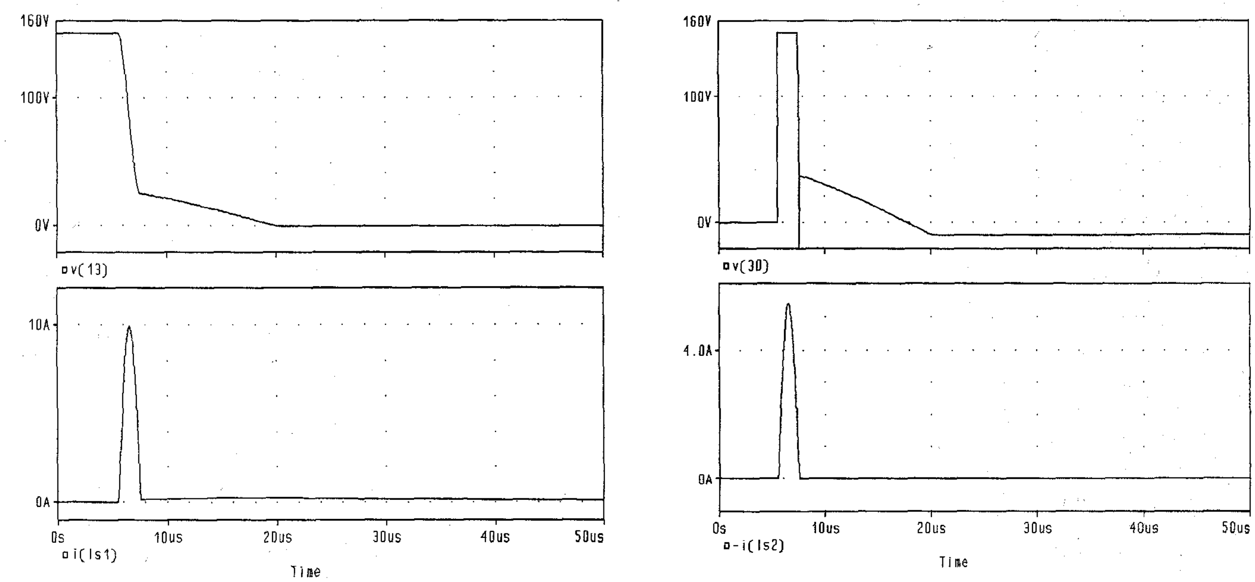


Fig. 7. The catch winding energy recovery circuit with Zener diode (D_z) reset: (a) circuit and (b) equivalent circuit.



(a) (b)

Fig. 8. Pspice simulations for resistor reset, $m = 0.5$. (a) Capacitor voltage v(13) and primary current $i(ls1)$. (b) Secondary voltage v(30) and secondary current $i(ls2)$.



(a) (b)

Fig. 9. Pspice simulations for Zener diode reset, $m = 0.5$. (a) Capacitor voltage v(13) and primary current $i(ls1)$. (b) Secondary voltage v(30) and secondary current $i(ls2)$.

current will ramp linearly according to

$$i_{mag} = \frac{mV_s t}{L_{mag}}. \tag{17}$$

For a real transformer, transformer action is lost when the magnetizing current i_{mag} rises to the circuit current given by (8) or (11) (depending on the operating mode).

For circuits operating in mode 1; once transformer action ceases, any voltage remaining on the capacitor will tend to discharge resonantly through the magnetizing inductance of the transformer. This gives rise to a low frequency (relative to ω) resonant increase in magnetizing current. This increase ends when the capacitor voltage reaches zero and diode D_s conducts. For circuits operating in mode 2 transformer action is lost after the capacitor voltage has reached zero and the magnetizing current is defined by (17). For the circuit to operate correctly the transformer core must reset before the next energy recovery operation and, in particular, before the next switch turn-on. During the reset phase the reset voltage is provided by the potential drop across R_s in Fig. 3(a) and the

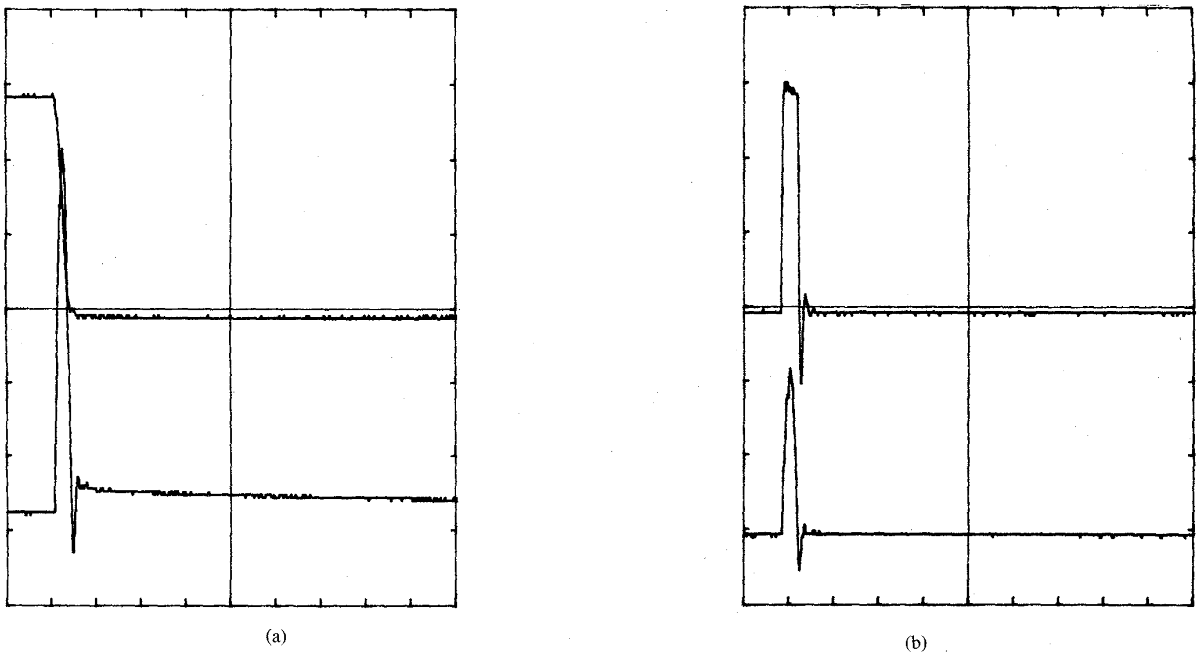


Fig. 10. Experimental waveforms for resistor reset, time base 5 μs/division. (a) Upper trace, capacitor voltage (50 V/division); lower trace, primary current (2.5 A/division). (b) Upper trace, secondary voltage (50 V/division); lower trace, secondary current (2.5 A/division).

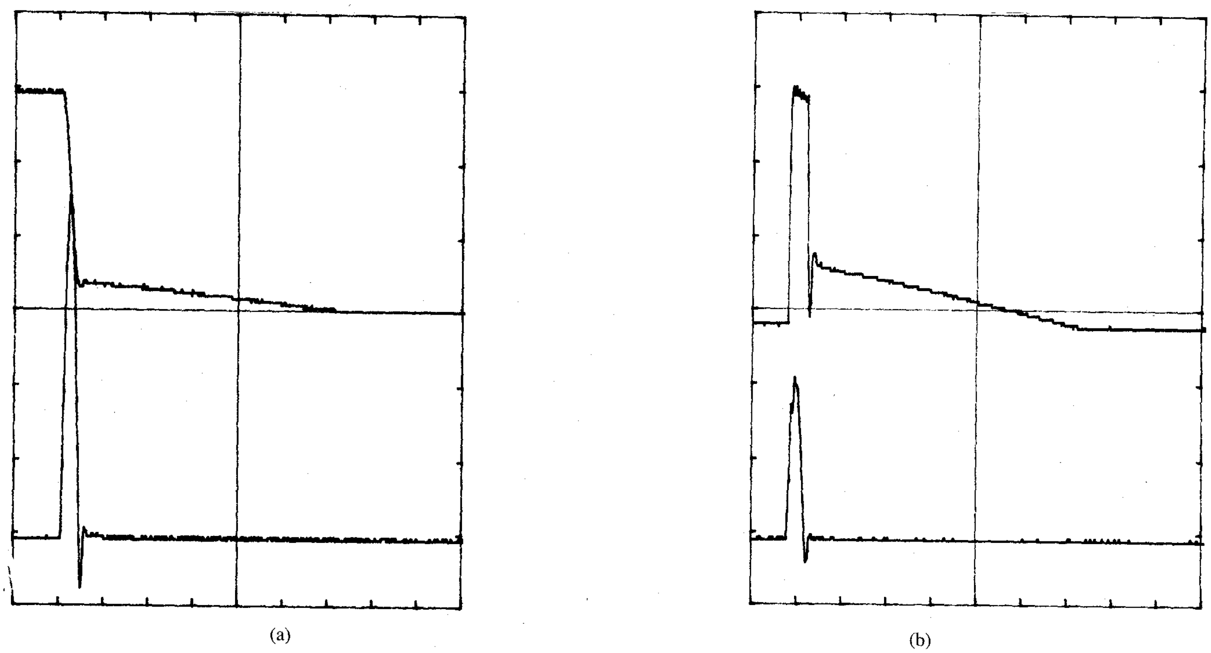


Fig. 11. Experimental waveforms for Zener diode reset, time base 5 μs/division. (a) Upper trace, capacitor voltage (50 V/division); lower trace, primary current (2.5 A/division). (b) Upper trace, secondary voltage (50 V/division); lower trace, secondary current (2.5 A/division).

magnetizing current decays according to the $(L_r + L_{mag})/R_s$ time constant. The time for the magnetizing current to decay to a negligible level will limit the switching frequency that may be employed. It may be seen that there is a conflict here between the need to use a high Q circuit for high energy recovery and the need for a low Q for a short magnetizing current reset time constant. The curves shown in Fig. 6 show the effect of the trade off between reset time and energy recovery for a turns ratio of $m = 0.5$.

The problem of transformer core reset may be resolved, in many cases and particularly at low powers, by replacing the resistor with a Zener diode as shown in Fig. 7. This allows a very high Q circuit to be employed while the Zener diode provides a constant voltage source (V_z) for reset. The consequence of this is a well defined reset time but with losses occurring in the Zener diode; both during reset and during the energy recovery phase when it will appear as a parasitic voltage source in series with the transformer. During the recovery phase the ratio of the energy lost in the Zener diode to that recovered is given by V_z/mV_s It should be noted that, in practice, the components R_s and L_r may be provided by the winding resistance and leakage inductance of the transformer primary. In any event inductance is usually added as wire length into the R-C discharge path of an R-C-D snubber so as to limit and delay the peak discharge current through the switch at turn-on.

IV. SIMULATIONS

The snubber circuits have been modeled using PSpice, for both resistive and Zener diode core reset. The results are shown in Figs. 8 and 9. Fig. 8 shows the simulation for resistive reset with the circuit operating at the boundary of mode 1 and mode 2 so that the resonant current and voltage reach zero simultaneously. Fig. 9 shows the simulation for Zener diode reset, in this case the circuit operates in mode 1 and the capacitor voltage is greater than zero at the end of the resonant current pulse.

Calculations based on these simulations show levels of energy recovery to be in line with those predicted in theory.

V. EXPERIMENTAL RESULTS

The waveforms shown in Figs. 10 and 11 show the practical results for the energy recovery circuits employing an IGBT at a switching frequency of 6.6 kHz. The component values were $R_s = 2\,\Omega$, $C = 0.1\,\mu$F 1 kV metallized polypropylene, $L_r = 4.1\,\mu$H (including transformer leakage); the transformer was bifillar wound on a ferrite toroid core (Thompson T22) with a turns ratio of 40 : 80. Under these conditions it was found that a circuit using Zener diode reset ($V_z = 0.05\,V_s$ with a theoretical maximum recovery of approximately 95% results in recovery ratios of around 80%, while a resistive reset circuit realizes recovery ratios of around 70%. The degradation in performance of the latter is due to the incomplete reset of the magnetising current, seen in Fig. 11. It is found that the stresses experienced by the catch winding diode D_2 are well controlled, with a maximum reverse voltage just in excess of V_s, and approximately $V_s + V_z/m$ when Zener diode reset is used.

VI. CONCLUSIONS

The results for the proposed passive turn-off snubber energy recovery circuits show that a relatively simple modification to the commonly used RCD snubber may result in excess of 70% of the snubber capacitor stored energy being recovered into the d.c rail. In practice the RCD snubber resistor is replaced by a ferrite transformer and a secondary diode. Theoretical, simulated and practical results substantiate the viability of this simple but effective turn-off snubber.

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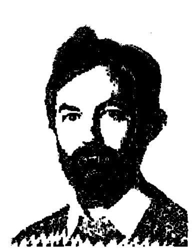

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