

# Lossless Active Clamp for Secondary Circuits

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**Abstract** - In recent years, lossless snubbers have been developed with the emphasis on snubbing the primary side switches. With the switching losses in the primary being minimised, the secondary diode losses become a major limiting factor of converter operating frequency and total efficiency. To address this problem, a new active lossless clamp for secondary diodes of switch mode converters is proposed. The clamp recycles diode reverse recovery energy stored in the transformer leakage inductance and allows diodes with smaller reverse voltage to be used in output circuits. A double reduction of power loss is obtained by recovering the leakage inductance energy and through lower conduction loss of the output diodes. The clamp operates over the full range of load from open circuit to short circuit and is fully compatible with resonant transition type circuits. This paper analyses the operation of the proposed regenerative clamp and discusses the application to various secondary circuits. Finally, the clamp operation is verified by experimental results obtained from the application of the regenerative clamp on a compact 3kW rectifier.

## I. INTRODUCTION

When diodes in the secondary side of isolated converters recover, a large current spike flows in the transformer and stores energy in the transformer leakage inductance. The energy stored in the leakage inductance will cause ringing on diode voltage waveforms with large overshoots, necessitating the use of high voltage rated diodes, and causing heating of the transformer as the ringing is primarily damped out by transformer resistance. Furthermore, the resultant high  $dv/dt$  and peak voltages cause significant amounts of electromagnetic interference (EMI) to be generated.

In medium to higher power converters the loss is substantial and limits the operating frequency making the use of relatively large transformers necessary. If this energy is recovered instead of dissipated, a substantial increase in switching frequency is possible, allowing smaller energy storage components with an associated cost saving to be used. Besides being able to operate at higher frequencies, the converter requires less cooling.

Several methods are available to process the leakage inductance energy. The most common method is to

dissipate the energy using passive RC snubbers placed in parallel with each diode [1,2]. Besides dissipating the energy, these snubbers cause additional loss apart from the damping that is provided, and typically limit the voltage overshoot to around twice the transformer secondary voltage. Another common method is the dissipative clamp [2,3] which consists of a diode connected in series with a parallel RC circuit. The dissipative clamp is also lossy since the discharging resistor in parallel with the clamp capacitor is dissipating a constant amount of power to reset the capacitor each switching cycle. The designer is often forced to limit the operating frequency in order to limit the amount of heating caused by such snubbers.

Several lossless methods have also been developed. One particular method used in conjunction with a secondary full bridge rectifier, provides clamping of the voltage across the rectifier diodes and regenerates the leakage energy to the load each half-cycle [4] with the addition of a clamp capacitor and a MOSFET. This circuit relies on the clamp capacitor being large enough to resonate with the transformer leakage inductance at the desired frequency for proper operation and is limited to converters with a secondary full bridge rectifier. Another variation of this uses an auxiliary winding on the output choke to reset the clamp capacitor voltage [5].

Another method designed for use with a forward converter [6] clamps the reverse voltage of the freewheel diode only and recycles the stored energy to the output using an auxiliary switch connected to an auxiliary winding on either the main transformer or the output choke. This circuit also requires a small dissipative element in series with the auxiliary switch to prevent the auxiliary winding from conducting the output current.

In order to have a useful clamp, it must be able to operate over the full load range and should clamp the voltage on the main rectifying diodes. The new regenerative clamp presented here clamps the reverse voltage on the main diodes and recycles all of the energy stored in the transformer leakage inductance due to reverse recovery while dissipating very little power. The action of the clamp allows devices with a lower voltage rating to be used for the main diodes, as compared to the unclamped case, resulting in less conduction loss. The loss savings result in a very significant increase in efficiency compared to the

unclamped circuit. Furthermore, because the leakage inductance energy is fully recovered, it allows the insertion of additional inductance in series with the transformer to facilitate a well-controlled di/dt, resulting in lower EMI, as well as reducing the loss in the transformer due to the lower high frequency current harmonics.

This paper describes the clamp as applied in a conventional PWM forward converter and discusses the possibilities of applying it to other topologies.

## II. REGENERATIVE SECONDARY CLAMP

Figure 1 shows a forward converter with the new regenerative clamp (patent pending) arranged for use during the off period of the primary switch. The additional components in the regenerative clamp can be separated by their primary function into a clamp circuit and a regeneration circuit. The voltage clamp consists of two diodes D3 and D4, and a clamp capacitor C5, while the regeneration circuit consists of an inductor L5, a unidirectional switch (D7 and S5) and a diode D6.

The operation of the clamp captures the voltage overshoot energy of both switching transitions of the converter, storing the energy in the clamp capacitor, thereby clamping the reverse voltage of the main secondary diodes. The regenerative switch is operated to reset the clamp capacitor voltage, resulting in a transfer of the corresponding energy to the primary side.

The regeneration of the energy stored in capacitor C5 is achieved by turning on switch S5 during the period when freewheel diode D2 is on. The unidirectional switch is formed by connecting diode D7 in series with switch S5. Inductor L5 is chosen to be typically much larger than the transformer leakage inductance and permits the turn on of S5 under zero current conditions.

Figure 2 shows the timing waveforms for the continuous conduction mode operation of the regenerative clamp in a forward converter with a 1:1:1 turns ratio transformer. The full cycle operation of the clamp and regeneration circuit is described as follows:

- t0: the primary switch S1 is turned on, forward biasing main diode D1. Magnetising current I(Mag) in the transformer increases linearly.
- t0 - t1: current in D1 increases with a di/dt proportional to voltage  $V_{Lsec}$  divided by the transformer leakage inductance L2. Current in freewheel diode D2 decreases at the same rate.
- t1: D2 reverse recovers and turns off, supporting reverse voltage. Current in L2 is equal to the

output choke L1 current plus the diode reverse recovery current. The energy in L2 due to diode reverse recovery increases the voltage on D2 until clamp diode D4 turns on clamping the diode voltage to the voltage on clamp capacitor C5.

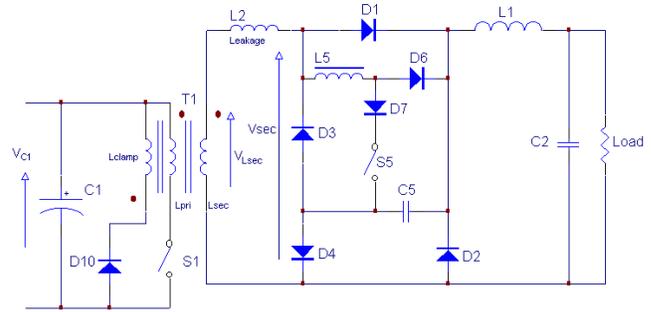


Figure 1. Lossless regenerative clamp

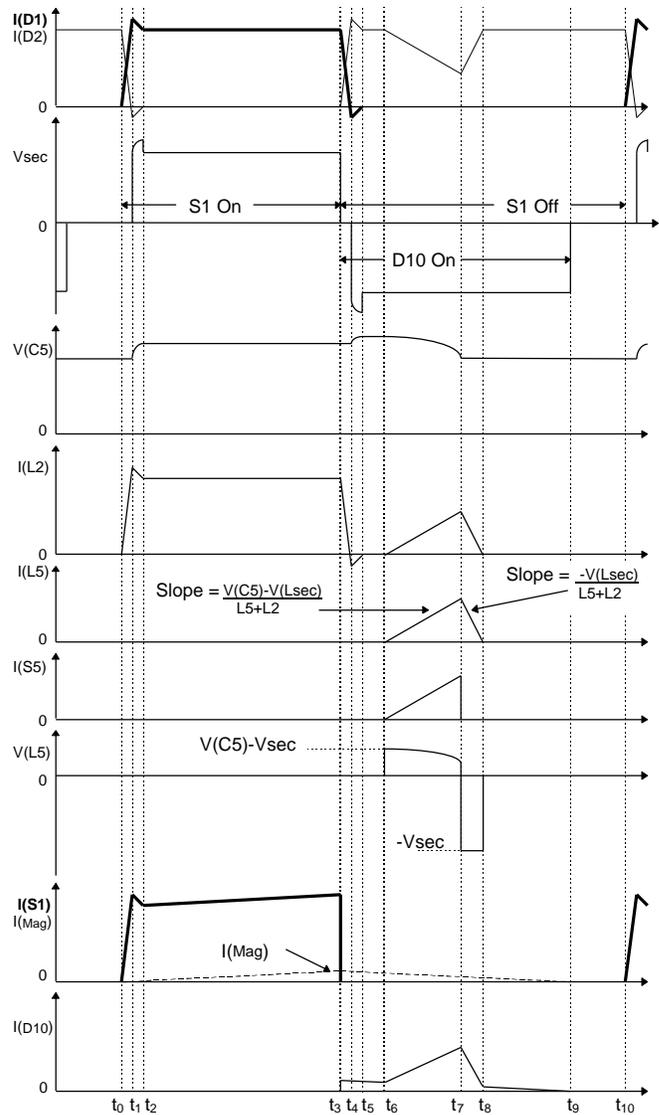


Figure 2. Timing waveforms for regenerative clamp

- t1 - t2: the reverse recovery energy stored in L2 is transferred to clamp capacitor C5 as the current in L2 reduces to the load current at a rate proportional to the voltage difference between C5 and the ideal transformer secondary  $V_{Lsec}$ . At the end of this period, clamp diode D4 turns off, enabling the voltage across the freewheel diode to fall to the ideal transformer secondary voltage  $V_{Lsec}$ .
- t2 - t3: Primary switch S1 delivers energy to the load via forward diode D1 and output choke L1. Voltage on clamp capacitor C5 remains unchanged from the peak value obtained at time t2.
- t3: Primary switch S1 is turned off. Voltage on the primary winding  $L_{pri}$  swings positive due to the magnetising current  $I(Mag)$  and load current until clamp winding  $L_{clamp}$  and clamp diode D10 operate to clamp the primary switch voltage  $V_{Lpri}$  to twice  $V_{C1}$ . Magnetising current  $I(Mag)$  then begins to decrease linearly as the magnetising energy is transferred back to primary storage capacitor C1. The secondary terminal voltage  $V_{SEC}$  similarly collapses, forward biasing freewheel diode D2.
- t3 - t4: Current in freewheel diode D2 increases with a  $di/dt$  proportional to the leakage inductance L2 and  $V_{Lsec}$ . Current in forward diode D1 decreases at the same rate until the reverse recovery current of D1 is reached at t4.
- t4: D1 turns off and supports reverse voltage. The current in L2 is equal to the diode reverse recovery current. The reverse voltage on D1 increases until clamp diode D3 turns on clamping the diode voltage to the voltage on clamp capacitor C5.
- t4 - t5: The loop formed by D2, C5, D3 and the secondary  $L_{sec}$  transfers some of the energy in leakage inductance L2 to the primary storage capacitor C1 via clamp winding  $L_{clamp}$  and diode D10. The rest of the energy is transferred to clamp capacitor C5 as the current in L2 reduces to the load current at a rate proportional to the voltage difference between C5 and the ideal transformer secondary  $V_{Lsec}$ . At the end of this period, clamp diode D3 turns off, enabling the voltage across forward diode D1 to fall to the secondary voltage  $V_{Lsec}$ .
- t5 - t6: D2 is conducting the full current in output choke L1. Voltage on clamp capacitor C5 remains unchanged from the peak value obtained at time t5.
- t6: The regenerative circuit is activated by turning on switch S5. Since inductor L5 is carrying zero

current, the turn on of S5 is under zero current conditions. With S5 on, the voltage difference between  $V_{Lsec}$  and C5 is applied across  $L5+L2$  via conducting diode D2. This is illustrated by the equivalent of the regeneration circuit shown in Fig. 3, where  $L_{sec}$  is replaced by the transferred primary capacitor C1'. The effect of the increase in current in  $L5+L2$  is a net decrease in the current flowing in freewheel diode D2.

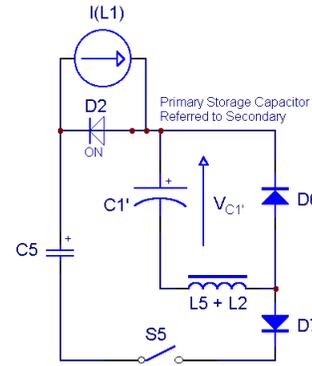


Figure 3. Equivalent of regeneration circuit

- t6 - t7: Current increases in  $L5+L2$ . A portion of the energy in C5 is transferred to primary capacitor C1 via  $L_{clamp}$  and D10, adding to the magnetising current, while another portion is transferred to L5. The on time for S5 can be either a constant or a period determined by the time for the peak current in S5 to reach a predetermined value.
- t7: S5 is turned off. Current continues to flow in  $L5+L2$ , turning diode D6 on. A negative voltage equal to  $V_{Lsec}$  is applied across  $L5+L2$ , reducing the current at a rate equal to the  $V_{Lsec}$  divided by the inductance of  $L5+L2$ .
- t7 - t8: All of the energy in L5 and L2 is returned to the primary via the loop formed by D6, D2, the transformer secondary  $L_{sec}$  and series inductors L5 and L2. Winding  $L_{clamp}$  and diode D10 transfer the energy to C1. This loop is also shown in the equivalent circuit of Fig. 3. When the current in L5 reaches zero, D6 turns off, disconnecting the regeneration circuit. Freewheel diode D2 again conducts the full current of output choke L1. Switch S5 must be turned off early enough so that time t8 is reached before the magnetising current has reset and primary switch S1 is again turned on.
- t8 - t9: Magnetising current continues to flow in the clamp winding  $L_{clamp}$  and diode D10 until it reaches zero at t9. The freewheel diode D2 is still in conduction due to the continuous current flowing in output choke L1.

t9: The transformer core is reset and the primary and secondary voltages collapse to zero. D2 continues conducting output choke L1 current until the next cycle begins at time t10.

The amount of energy to be recycled is a function of the peak diode reverse recovery current and the leakage inductance. This energy can be recycled in a short period of time if  $L5 + L2$  is small, requiring a high peak current to flow in S5 over a short on time. A more beneficial approach is to use a larger value of L5, so that for the same peak energy stored in  $L5 + L2$ , the peak current in S5 is significantly smaller.

The operation of the regeneration circuit requires that the transformer is still magnetised in the forward direction. Hence, under normal operation this equates to an available on time for S5 equal to the on time of primary switch S1, which is typically  $0.4 \sim 0.5$  the switching period. From this limit, it is clear that operation during short circuit of the output, requires the on time of S5 to be less than the minimum on time of S1. The regeneration circuit can be made to operate under short circuit conditions by designing L5 to allow sufficient energy to be recycled for the minimum on time of S1. This will result in a higher peak current in L5 and S5, but will guarantee operation of the clamp to protect main diodes D1 and D2.

To do this, the value of energy to be recycled each cycle and the minimum on time define the maximum value of L5. Assuming the voltage on C5 does not change by a large amount, the energy delivered to the primary during the on time ( $T_{ON} = t7-t6$ ) of S5 is:

$$E_{ON} = V_{Lsec} \int_0^{T_{ON}} i(t) dt = \frac{V_{Lsec} [V_{C5} - V_{Lsec}] T_{ON}^2}{2[L5 + L2]} \quad (1)$$

and the energy delivered during the reset time ( $T_{OFF} = t8-t7$ ) of L5 is:

$$E_{OFF} = \frac{V_{Lsec}^2 T_{OFF}^2}{2[L5 + L2]} = \frac{[V_{C5} - V_{Lsec}]^2 T_{ON}^2}{2[L5 + L2]} \quad (2)$$

Hence the total energy recycled is:

$$E_{TOT} = E_{ON} + E_{OFF} = \frac{V_{C5} [V_{C5} - V_{Lsec}] T_{ON}^2}{2[L5 + L2]} \quad (3)$$

This can be rearranged for  $L5+L2$  in terms of the reverse recovery energy by selecting the maximum value of voltage on C5 and making the recycled energy equal the worst case reverse recovery energy.

$$(L5 + L2)_{Max} = \frac{V_{C5(Max)} [V_{C5(Max)} - V_{Lsec}] T_{ON}^2}{2E_{Irr}} \quad (4)$$

The available reverse recovery energy can be calculated from the expected secondary winding ( $L_{sec}$ ) current waveform in terms of the energy during the turn on and turn off of S1 as:

$$E_{S1(ON)} = \frac{1}{2} (L2) \left[ \left( I_{L1(min)} + I_{rr} \right)^2 - I_{L1(min)}^2 \right] \quad (5)$$

$$E_{S1(OFF)} = \frac{1}{2} (L2) I_{rr}^2 \quad (6)$$

$$E_{Irr} = E_{S1(ON)} + E_{S1(OFF)} \cong (L2) \left[ I_{rr} \left( I_{rr} + I_{L1(min)} \right) \right] \quad (7)$$

where  $I_{rr}$  is the component due to diode reverse recovery current, assumed to be equal for D1 and D2, and  $I_{L1(min)}$  is the current flowing in the output inductor L1 at the time the forward conversion begins.

### III. ALTERNATIVE REGENERATIVE CLAMP ARRANGEMENTS FOR CONVERTERS

Figure 4 shows the same regenerative clamp circuit of Figure 1 rearranged to permit operation of the regeneration circuit during the period when the primary switch is on. The operation of the clamp components D3, D4 and C5 are the same as previously described as is the regeneration circuit except that the energy is delivered to the load instead of being returned to the primary energy storage capacitor C1. The limitation of this arrangement is the same as for Figure 1, in that the period available to operate the regeneration circuit is dependent on the *on time* of the primary switch, which varies with converter load demand.

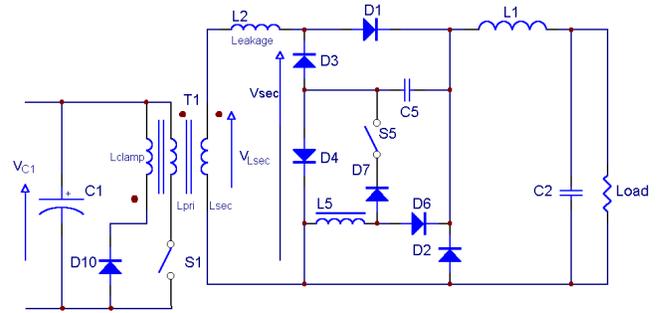


Figure 4. Arrangement of regenerative clamp for operation during the on time of S1.

Figure 5 shows the circuit arrangement for the regenerative clamp in the isolated converter family: flyback, full-bridge rectifier, center-tap secondary, and current doubler. In all the converters shown, the arrangement of the regenerative clamp is made so that regeneration of the clamp energy occurs during the on period of the primary side switch(es). Furthermore, for the center-tap arrangement, full bridge and current doubler, the regeneration circuit can be operated during each of the non-free-wheeling periods. This allows the peak current in L5 to be smaller since energy is recycled twice as often.

### IV. EXPERIMENTAL RESULTS

A 3kW, 200kHz compact 48V rectifier was built using the new regenerative clamp and tested to verify the principle of operation and the associated power loss saving. Figure 6

shows the experimental secondary circuit with the component values used.

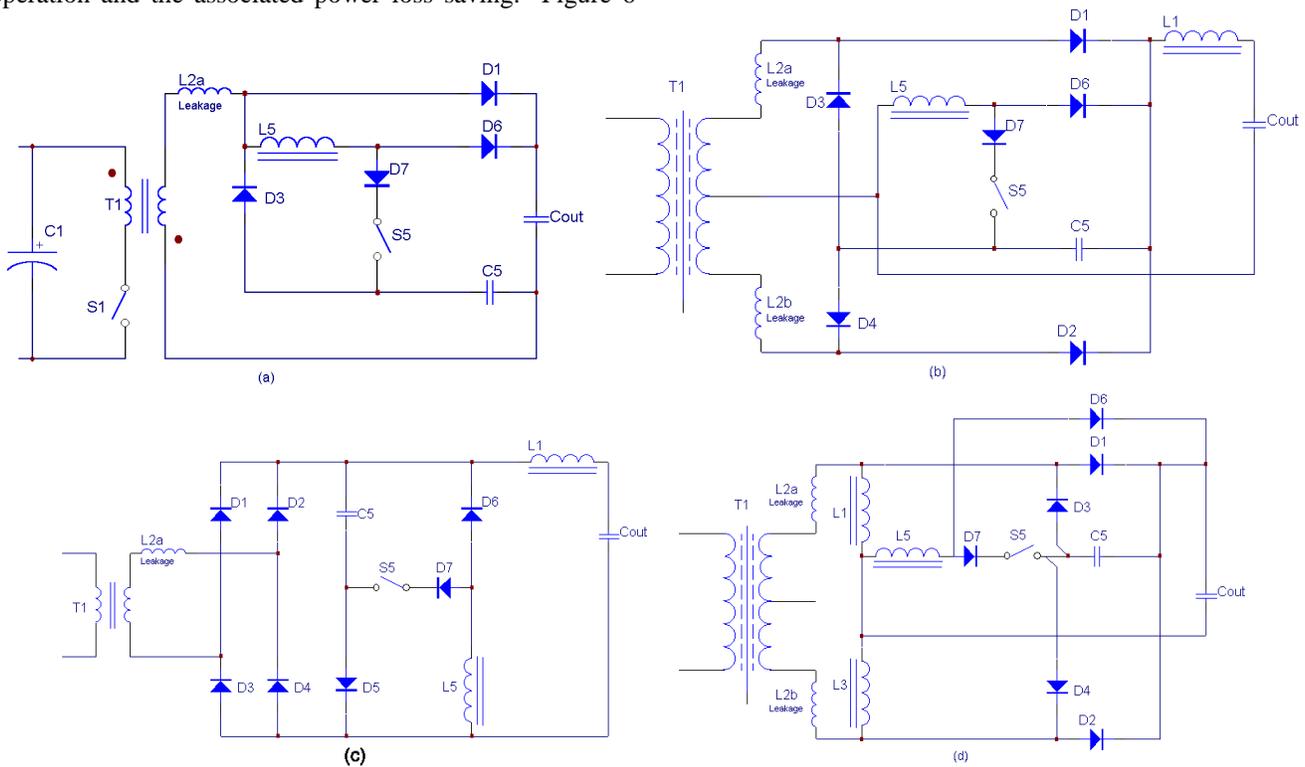


Figure 5. Alternative arrangements of regenerative clamp for: (a) flyback, (b) center-tap secondary, (c) full bridge and (d) current doubler.

Figure 7 shows the operational waveforms of the regenerative clamp under full load, indicating the secondary transformer voltage and L5 inductor current. Figure 8 gives detail of the clamping of the voltage across the freewheel diode and the transformer secondary current showing the reverse recovery current amplitude requiring to be clamped.

It is important to note that the combination of the RC snubber with the 400V diodes is normally used because of its simplicity. The losses are usually acceptable in lower powered converters, but this is not the case at higher power levels where the dissipation of the RC snubber becomes a serious thermal consideration. The improvement in converter losses using the regenerative clamp as compared to the RC snubber solution is 97W or 3% in efficiency.

The table of Figure 9 lists the important differences between a number of suitable diodes for use in the secondary. Clearly the 200V diodes have a lower on-voltage compared to the 400V diodes. It is interesting to note that the regenerative clamp is insensitive to the reverse recovery characteristics of the secondary diodes and the leakage inductance of the transformer, since the operation of the clamp will recycle all the reverse recovery energy captured each cycle.

Figure 10 shows a table of results for energy recovered with various arrangements for snubbing or clamping of the secondary diodes. The improvement in efficiency using the regenerative clamp and 200V diodes over a dissipative clamp and 400V diodes is clearly illustrated yielding up to 139W reduction in total loss.

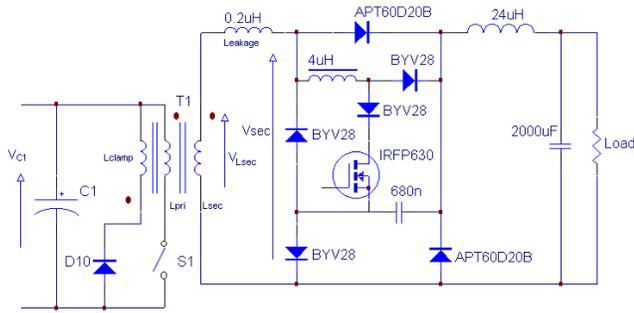


Figure 6. Experiment regenerative clamp circuit values.

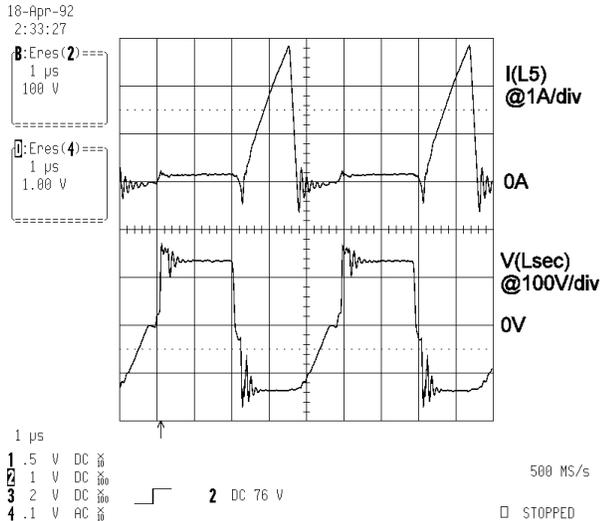


Figure 7. Clamp operation at full load. Top: I(L5) @ 1A/div, Bottom: V(Lsec) @ 100V/div

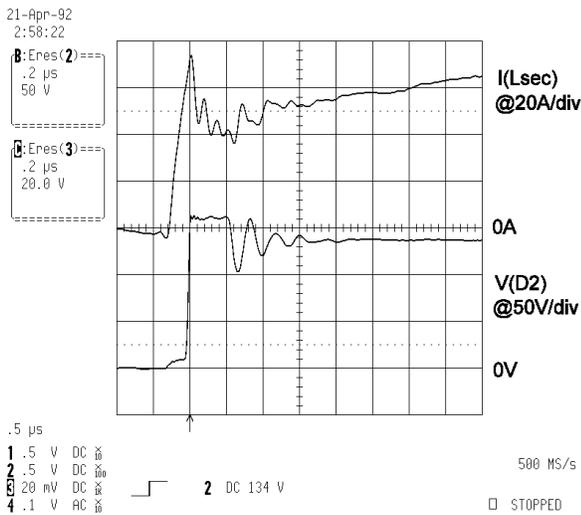


Figure 8. Capture of reverse recovery energy.

Top: I(sec) @ 20A/div. [Peak = 77A]

Bottom: Clamping of freewheel diode voltage, @ 50V/div.

Device	$V_{rrm}$	$I_{rr}^1$	$V_f^2$	$Q_{rr}^3$
APT60D40B	400V	30A	1.3V	900nC
BYT60P-400	400V	32A	1.3V	1100nC
RHRG5040	400V	34A*	1.7V	760nC*
60CPF04 (IR)	400V	60A*	1.2V	5000nC*
APT60D20B	200V	35A	0.9V	1100nC

BYV52/PI	200V	36A*	0.9V	680nC*
<sup>1</sup> Peak reverse recovery current for $di_f/dt=-480A/\mu s$ , $T_j=100^\circ C$				
<sup>2</sup> Maximum forward drop @ $I_f=60A$ , $T_j=150^\circ C$				
<sup>3</sup> Reverse recovery charge for $di_f/dt=-480A/\mu s$ , $T_j=100^\circ C$				
* Device data not quoted above $di_f/dt=-100A/\mu s$ , values estimated				

Figure 9. Diode properties that affect total secondary losses.

Configuration	Reduction in Loss
400V Diode, Dissipative Clamp (280V Zener)	0W
400V Diode, RC Snubber, under damped	42W
400V Diode, Regenerative Clamp	103W
200V Diode, Dissipative Clamp (180V Zener)	18W
200V Diode, Regenerative Clamp	139W

Figure 10. Energy recovered with various snubbing or clamping arrangements of the secondary diodes.

## V. CONCLUSIONS

A new regenerative clamp for secondary diodes has been presented which recycles diode reverse recovery energy stored in the transformer leakage inductance and allows diodes with smaller reverse voltage to be used. The regenerative clamp can be implemented in many of the isolated topologies, providing a significant improvement in efficiency. Operation of the regenerative clamp was verified experimentally on a compact 3kW rectifier providing an improvement of total loss of up to 97W or approximately 3% in efficiency, over a typical RC snubber.

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*Note: The regenerative clamp for secondary diodes described in this paper is the subject of international patent applications.*