Three Phase Power Factor Corrected Isolated Buck for 48V/100A Rectifier with Secondary Active Clamp

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Abstract:

A novel active clamp circuit for the secondary diodes of an isolated three phase buck converter is presented. The voltage spike on the diodes is clamped to permit the use of lower voltage rating diodes and the energy trapped in the transformer leakage inductance due to the reverse recovery current of the diodes is recycled to the output. The principle of operation of the active clamp with the three phase buck is analyzed and verified on a 6kW prototype.

1.0 Introduction

A common approach to implement unity power factor, isolated AC-DC conversion is to have two stages - a power factor corrected AC-DC converter stage followed by an isolated DC-DC stage. Three phase versions of this theme are sometimes implemented using three delta- or star-connected single-phase units, with an artificial neutral network to eliminate the neutral connection and ensure stability [1].

Another approach is to directly convert the three phase AC to DC in a single isolated buck-derived stage, since it is possible to draw constant power at any point in time on a three phase supply. Such a single stage isolated converter, as shown in Figure 1, can be efficiently implemented by splitting the conversion process into a three phase-to-high frequency single phase cyclo-conversion section followed by a high frequency rectification section, and placing a small high frequency transformer between the conversion processes [2], [3].

By using such a configuration, and drawing constant power, a low output ripple AC-DC stage with sinusoidal input currents is achieved. The switching sequence of this type of converter can be implemented from either a look-up table based approach or an analog derived PWM circuit with distribution logic. The operation of the cyclo-conversion section has been previously described for hard-switching [2] and soft-switching operation [3] and will not be discussed here.

One problem of implementing the high frequency cyclo-conversion is that the power devices must be AC switches (2 or 4-quadrant operation) and must be able to withstand the peak-to-peak of the phase-to-phase voltage, including any mains transient voltages.

Another problem concerns the transformed input voltage that appears across the output diodes. Since there is no large capacitor bank to store energy in the primary, line transients such as lightning (6kV/3kA) and switching surges, although attenuated by MOVs and primary clamp circuits, are transferred to the secondary and increase the peak voltage stress across the secondary diodes. Consequently it becomes important to limit the peak voltage stress of the secondary diodes due to surges to a level similar to the maximum switching stress.

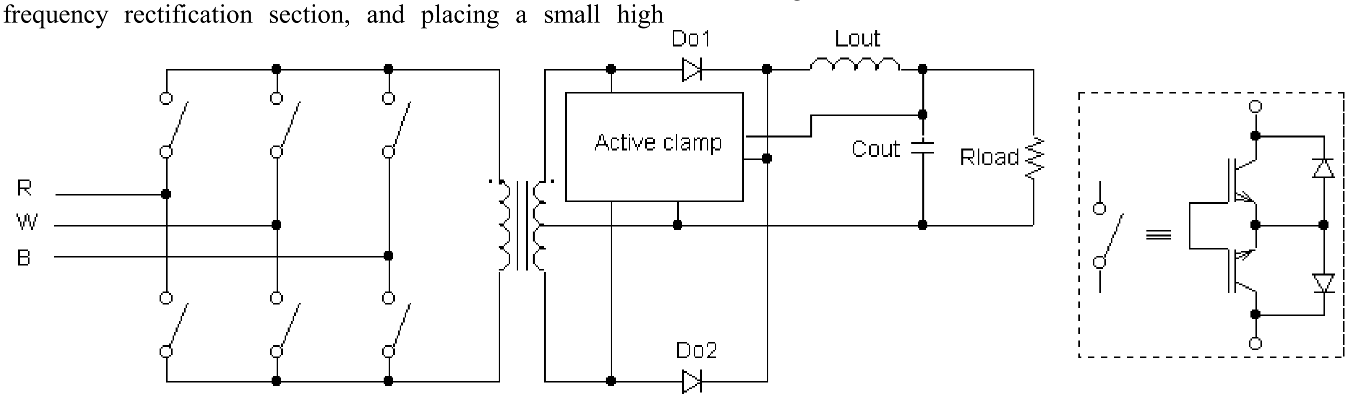

Figure 1. Three phase isolated buck converter with a secondary active clamp. AC switch realization using anti-parallel IGBT-diode combinations.

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Additionally, isolated switch mode power converters typically use secondary rectifier diodes that are hard switched when the converter operates in continuous conduction mode (CCM). As a result of the hard switching, the diode reverse recovery current stores energy in the leakage inductance of the isolation transformer that can result in large transient voltages being applied to the diode turning off. Methods of controlling the transient voltage can either be dissipative [4], [5], [6] or use energy recycling techniques that have minimal losses [7], [8]. A technique to reduce or eliminate reverse recovery current has been reported in [9], where two separate DCM currents are summed together to form a CCM current.

This paper presents a secondary active clamp that provides a method of limiting the transient voltage across the secondary diodes of an isolated three phase buck converter while recovering the reverse recovery energy stored in the leakage inductance in a lossless manner. The active clamp is a variation of an active clamp previously reported [10], [11], and is applicable to any converter with rectification on a center-tapped secondary of a high frequency isolation transformer. The clamp limits the peak voltage stress on the diodes to less than 350V for a 48VDC output, thereby enabling 400V diodes to be used in place of 600V devices. The use of lower voltage diodes and the recycling of the diode reverse recovery energy to the output terminals in a substantially lossless manner, improves the efficiency by over 0.5%.

2.0 Active Lossless Clamp Circuit Principles

2.1 Circuit Configuration

The circuit implementation for the active clamp embedded in the secondary circuit of a buck-derived converter is presented in Figure 2. The active clamp is implemented for a secondary side center-tapped transformer.

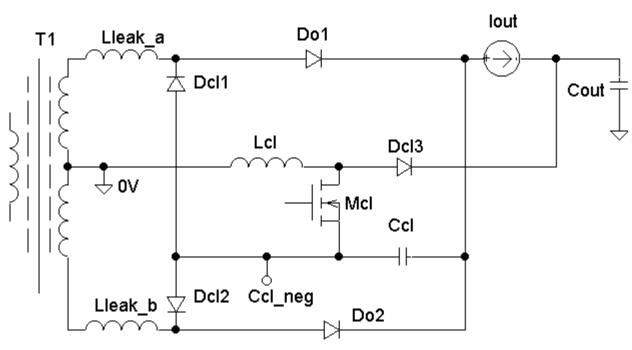

Figure 2. Basic active clamp circuit configuration.

2.2 Circuit Description

The active clamp can conveniently be broken into two separate parts: the *clamp circuit* and the *recycling circuit*.

The clamp circuit forms, together with the main output diodes D_{O1} and D_{O2}, a full bridge. The bridge comprises D_{O1}, D_{O2}, D_{CL1}, and D_{CL2}. The AC ports of the bridge are connected to the transformer secondary side, while the rectifiying ports of the bridge are connected to the clamp capacitor C_{CL}.

The key property of a bridge in its application here is the fact that all diodes are clamped to the capacitor C_{CL} voltage. The same voltage rating can be used for all diodes in the bridge. The only parameter that needs to be controlled is the clamp capacitor voltage.

The recycling circuit comprises L_{CL}, M_{CL} and D_{CL3}. The recycling circuit effectively forms a buck-boost converter. With this configuration, the captured energy in C_{CL} is recycled to the output. The buck-boost converter is operated in discontinuous conduction mode (DCM).

There are several options to drive the gate of MOSFET M_{CL}, which have been described in [10]. In this implementation, a separate independent controller is used to control the voltage on C_{CL}.

2.3 Circuit Operation

The total circuit consists essentially of two independent circuits, which will be described separately. For simplicity the currents and voltages are approximated to straight-line sections and any second order effects such as current rise times are ignored. For this approximation to be valid, it is assumed that the variation in the voltage on C_{CL} is small compared to the DC value.

2.3.1 Clamp Circuit

A clamping cycle begins when any one of the two main output diodes undergoes reverse recovery and switches off after freewheeling.

As soon as the current in D_{O2} has dropped to zero, reverse current due to the reverse recovery of D_{O2} begins to flow, as shown in Figure 3a. This current will continue to increase until D_{O2} has recovered. The rate of current increase is given by:

$$\frac{di}{dt} = \frac{2V_{SEC}}{L_{LEAK}} \tag{1}$$

where V_{SEC} is the transformer secondary voltage per winding, and L_{LEAK} the sum of the transformer leakage inductances referred to the secondary.

When D_{O2} switches off, the excess current in the leakage inductance commutates from D_{O2} to C_{CL} and D_{CL2} as shown in Figure 3b. The clamp capacitor C_{CL} voltage will increase as long as the current flows through it. The excess current decreases until the current in D_{O1} drops to the level of I_{OUT}.

At this point, the current in D_{CL2} reaches zero, and it blocks any reverse current and the clamp cycle is complete.

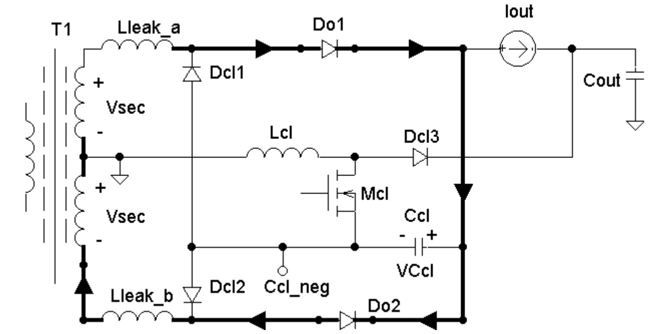

Figure 3a. Reverse recovery current starts flowing in the shown circuit as soon as the current in D_{O2} drops to zero.

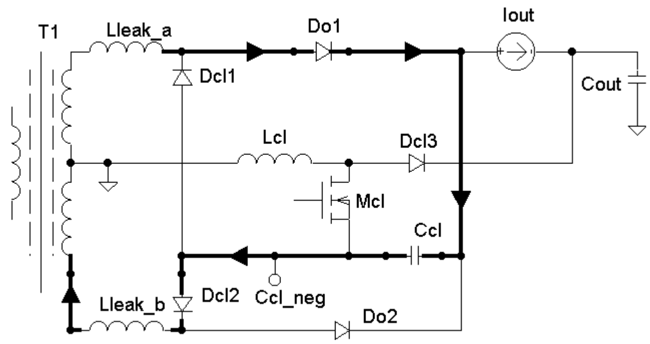

Figure 3b. Excess current in leakage inductance absorbed by C_{CL}.

The rate of current decrease through C_{CL} is given by:

$$\frac{di}{dt} = \frac{V_{CL}}{L_{LEAK}} \qquad (2)$$

where V_{CL} is the clamp margin voltage defined as:

$$V_{CL} = V_{C_{CL}} - 2V_{SEC} \qquad (3)$$

and Vc_{CL} is the clamp capacitor voltage.

2.3.2 *Energy Equations for the Clamp Circuit*

At the moment that diode D_{O2} recovers, the excess energy stored in the leakage inductance is given by:

$$E_{excess} = \frac{L_{LEAK} I_{RR}^2}{2} + L_{LEAK} I_{RR} I_{OUT} \qquad (4)$$

where I_{OUT} is the output load current, and I_{RR} is the amplitude of the diode reverse recovery current. The second term of equation (4) can be shown to be energy being transferred to the output choke. The first term energy is absorbed by C_{CL} from the leakage inductance.

During clamping of the freewheel diode, energy dumped into the clamp capacitor C_{CL} can be derived from the integration of the capacitor current (charge) and is given by:

$$E_{CL}(in) = \left[\frac{V_{C_{CL}}}{V_{CL}}\right] \frac{L_{LEAK} I_{RR}^2}{2} \qquad (5)$$

One important point highlighted by equation (5) is the value of the total energy absorbed by C_{CL}. This energy is bigger than the leakage energy by a factor of Vc_{CL}/V_{CL}.

When V_{CL} ($=Vc_{CL}-V_{SEC}$) approaches zero, the straight line approximations become invalid and the energy equations are no longer accurate. However, inspection of (5) shows that in the limit, the energy into C_{CL} approaches infinity, and that in the accurate case the energy in C_{CL} approaches the total converter energy. This implies that when the clamp margin voltage V_{CL} becomes small, the clamp has to process a substantial portion of the total output power, something that is clearly undesirable. This observation only holds while there is reverse recovery current in the main diodes. In the absence of such current for example during DCM, the clamp circuit processes no power and V_{CL} is zero.

To reduce the power processed by the clamp circuit, the clamp voltage must be as large as possible, otherwise the conduction loss of the clamp circuit cancels out any gain in efficiency obtained by recycling the leakage energy and using better main diodes.

2.3.3 *Recycle Circuit*

A recycling stroke begins when MOSFET M_{CL} switches on, as shown in Figure 4a. The current in L_{CL} ramps up from zero at a rate given by:

$$\frac{di}{dt} = \frac{V_A - V_{C_{CL}}}{L_{CL}} \qquad (6)$$

where V_A is the voltage at node A at any time in the main switching cycle.

The current flows through C_{CL} in the opposite direction to the clamp cycle current, thus removing charge. The current flows into node A and into the output circuit. A small portion of the load current is sourced by this action, decreasing the main transformer current by this amount. The majority of the stored energy is removed during this part of the recycling action.

A small amount of energy is stored in L_{CL} during the time when MOSFET M_{CL} is on. This energy is dumped to the output terminals when M_{CL} switches off, as shown in Figure 4b. Note that by connecting D_{CL3} to node A it is possible to dump this energy into node A during the time when node A is not at zero volts. However, in this application, due to the MOSFET M_{CL} not being synchronized with the main switches, dumping the energy to the output ensures that the current in L_{CL} decreases at the maximum rate to ensure it reaches zero. The rate of current decrease in L_{CL} is given by:

$$\frac{di}{dt} = \frac{V_{OUT}}{L_{CL}} \tag{7}$$

where V_{OUT} is the output voltage.

2.3.4 Energy Equations for the Recycling Circuit

The energy drawn out of the clamp capacitor during the conduction of M_{CL} is:

$$E_{CL}(out) = \left[\frac{V_{C_{CL}}}{V_{CL}}\right]\frac{L_{CL}I_{CL}^2}{2} \tag{8}$$

where I_{CL} is the peak current flowing in M_{CL} at the moment of turn off.

Equation (8) has exactly the same form as (5). This indicates that the peak current in L_{CL} can be chosen by careful selection of L_{CL} and that this current will proportionally track I_{RR}.

The energy delivered to the output when M_{CL} is turned off is given by:

$$E_L(out) = \frac{L_{CL}I_{CL}^2}{2} \tag{9}$$

An analysis of the energy equations yields the surprising result that the clamp voltage V_{CL} is independent of the load current I_{OUT}. It is mainly determined by the amplitude of the diode reverse recovery current I_{RR}. This is different to the case of passive snubbing, where the leading edge reverse voltage spike is strongly dependent on load current. In the case of the clamp circuit, this means that the energy processed by the clamp remains roughly constant regardless of load, tracking only the amplitude of the reverse recovery current's dependency on forward current and junction temperature.

The idealized waveforms are shown in Figure 5. Only two reverse recovery events are shown to simplify the figure, corresponding to the special case where one phase voltage is zero. Typically, there are four reverse recovery events per switching cycle. The top diagram shows the current in D_{O1} as it becomes forward biased. The current ramps up from the freewheel value (assumed to be 50% of the output current) until it reaches the output current I_{OUT}. It then continues to increase at the same rate to I_{RR}. At t_0 D_{O2} switches off. The excess current in L_{LEAK} commutates to C_{CL} and drops to I_{OUT} at time t_1. At t_3 the primary side IGBTs switch off, and the current drops to the freewheel value for the rest of the cycle. At t_5 diode D_{O1} recovers and switches off. The excess current again commutates to C_{CL}, charging it up to t_6.

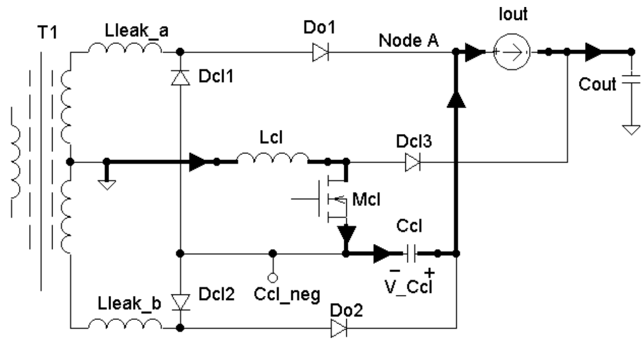

Figure 4a. Recycling current begins to flow in the indicated path. The majority of the energy is recycled during this part of the recycling stroke.

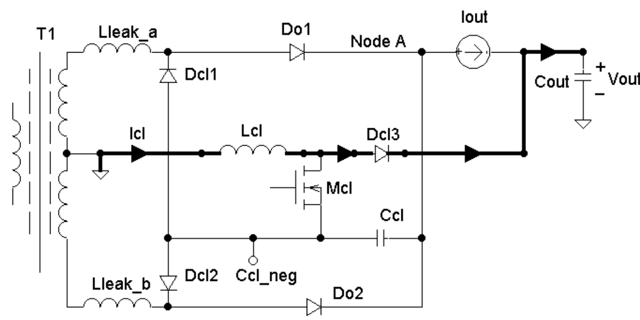

Figure 4b. Recycling current in L_{CL} decreases in this path.

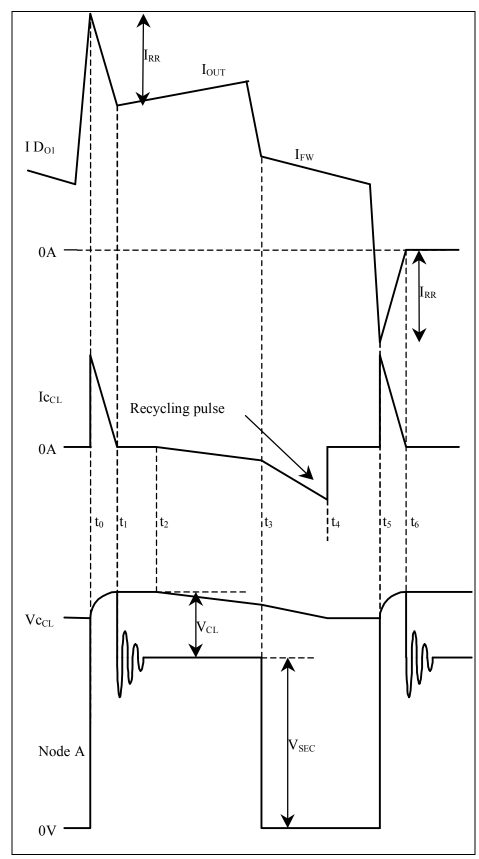

Figure 5. Waveforms for the clamp circuit. The recycling current in C_{CL} is also shown for a typical case. Not to scale.

The resetting action starts at t_2 (not synchronized). The current in L_{CL} rises at a certain rate. At t_3 the voltage across L_{CL} changes, resulting in an increase in the rate of rise of current in L_{CL}. At t_4 the clamp MOSFET turns off and the current in C_{CL} drops to zero.

3.0 Experimental Results

The active clamp circuit was implemented in a 6kW three-phase single stage power factor corrected rectifier as per Figure 1. The IGBTs on the primary were 1200V devices with switching frequencies alternating between 25kHz and 50kHz. The output diodes were 400V, 100A soft recovery devices with an I_{RRM} varying between 30A when cold to 60A when hot. The primary control circuit was DSP based and controlled the switch pulsewidths to draw resistive currents from the supply.

Figures 6 through 9 show the operation of the active clamp at arbitrary points on the three-phase supply. Figure 6 shows the clamping action on the leading edge spike of the transformer secondary voltage being applied to the output diodes. Parasitic elements in the clamp circuit cause a small amount of ringing on the clamped waveform. In this three-phase converter, clamping takes place four times in every cycle due to the switching action of the primary side switches.

Figure 7 shows the current in one of the transformer secondary windings. Note the two reverse recovery current spikes from D_{O2} labeled "A", and the spikes from D_{O1} labeled "B".

Figure 8 shows the reverse recovery current of a cold junction diode as measured in one of the secondary windings. Note the different slopes in the current reverse recovery spike. The down-slope is smaller because the voltage across the leakage inductance is V_{CL}.

The operation of the clamp capacitor reset circuit is shown in Figure 9. The bottom trace is the drain-source voltage of M_{CL}, switching asynchronously to the main converter at a frequency of 130kHz. Note the different base voltages corresponding to different voltages on the negative terminal of C_{CL} (C_{cl_neg} in Figure 4). The top trace is Vc_{CL}, the voltage on C_{CL}. Corresponding to every time M_{CL} is on, there is a small reduction in the voltage, while with every reverse recovery, there is an increase.

The 400V diodes selected have 0.2V less forward voltage drop than their 600V counterparts. For a load current of 100A, this translates directly into a 20W conduction loss saving. Switching loss, although poorly characterized in diode manufacturer's data sheets, is also substantially less for lower voltage diodes. This is due to the presence of a tail current, which dominates switching loss in higher voltage diodes.

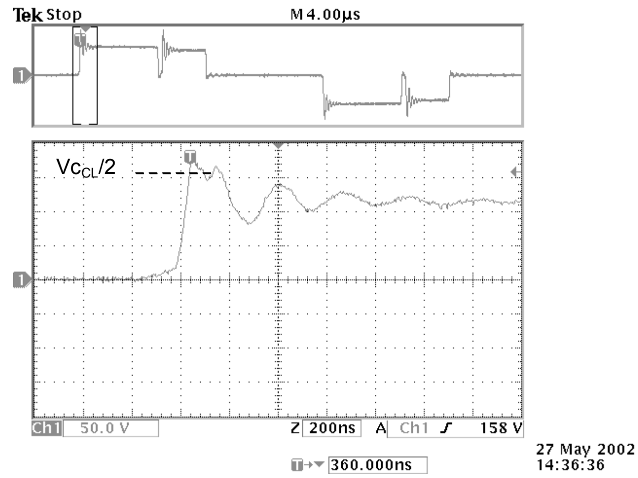

Figure 6. Clamping action on the leading edge spike of the transformer secondary voltage.

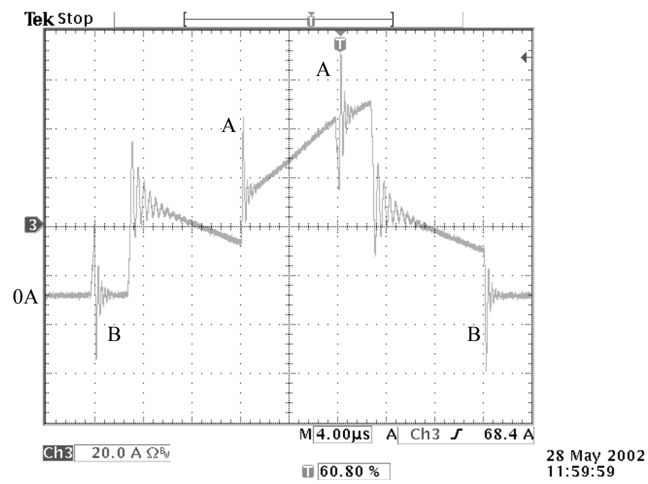

Figure 7. High Frequency transformer secondary winding.current

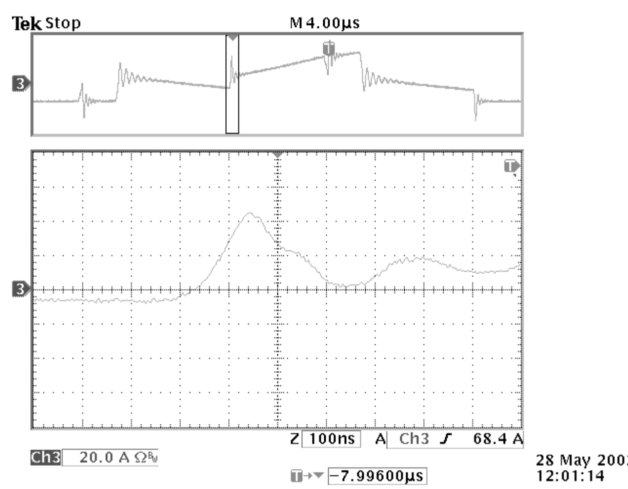

Figure 8. Reverse recovery current measured in the transformer secondary.

Figure 10 shows a plot of the power factor and efficiency of the three-phase converter at 400VAC. A peak efficiency of 92.5% was achieved at 65A load for the complete rectifier. Figure 11 shows the layout of the prototype converter with the two main heatsinks taking the primary IGBTs and the secondary diodes. The 6kVA high frequency transformer is shown in the foreground.

4.0 Conclusion

The theory of operation of an active clamp for secondary circuits as applied in a center-tapped secondary circuit was presented.

The active clamp was successfully applied to a three-phase single stage rectifier where the mains voltage and surges appear transformed across the output diodes, necessitating a strong clamping action to protect output diodes. The recycling property of the clamp increases efficiency by recovering leakage energy, and allows diodes of lower voltage rating to be used, a very important consideration for efficiency.

5.0 References

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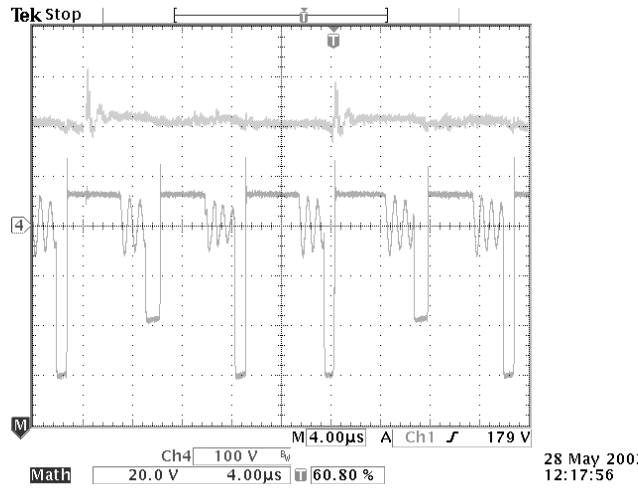

Figure 9. Action of the recycling circuit. Bottom trace: M_{CL} drain-source voltage. Top trace: Vc_{CL}, the ripple voltage on C_{CL}.

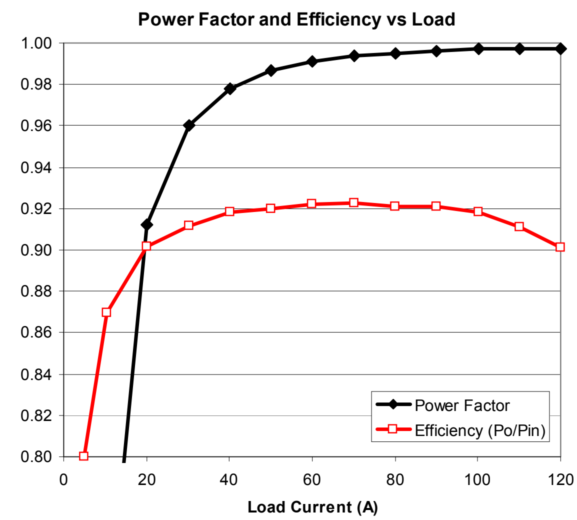

Figure 10. 6kW prototype power factor and efficiency versus load current.

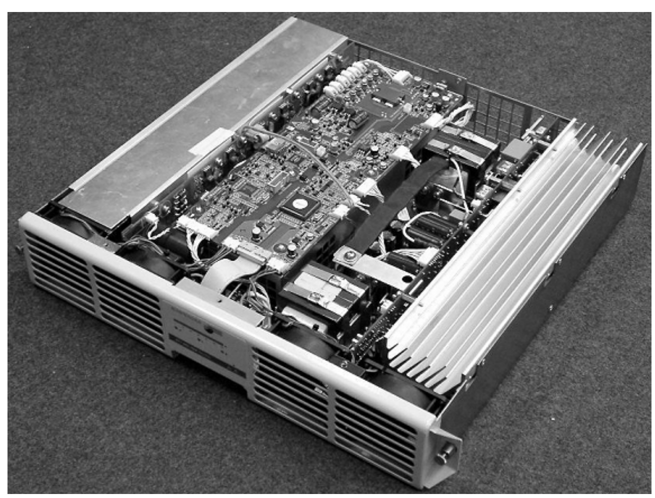

Figure 11. A 2U high prototype 6kW three phase single stage telecommunications rectifier in which the secondary active clamp is used. .