ACTIVE CLAMP FOR OUTPUT RECTIFIER STAGES OF ISOLATED DC-DC CONVERTERS

Carlos H. Illa Font, Eduardo F. R. Romaneli(*) and Ivo Barbi
Power Electronics Institute – INEP
Department of Electrical Engineering
Federal University of Santa Catarina – UFSC
P. O. Box 5119 – Fax +55-48-234-5422
88040-970 – Florianópolis – SC – Brazil
Internet: www.inep.ufsc.br – E-mail: carlos@inep.ufsc.br, romaneli@cefetpr.br, ivo@inep.ufsc.br

Abstract: **This paper presents a new active clamping circuit employing a Forward converter from medium to high power applications. The proposed active clamping can be implemented in the Full-Wave Rectifier, Center-Tap Rectifier and Hybridge Rectifier. The active clamping circuit clamps the voltage across the rectifier and delivers the reverse recovery energy to the output of the DC-DC converter, increasing the overall efficiency. A method to control the clamping voltage is also presented which ensures a regulated clamping voltage. This approach provides an increase in the reliability of the converter since in high power applications, the rectifier diodes both turn on and turn off with several hundred volts and even several hundred amps. The paper presents the analyses of the active clamping circuit and experimental results from an isolated DC-DC Three Level-ZVS-PWM converter with a Hybridge output rectifier operating at 24kW rated power.**

KEYWORDS

DC-DC Converter, Output Rectifier, Active Clamp, High Power Application

I. INTRODUCTION

When the rectifiers diodes in the secondary side of DC-DC isolated converters recover, the reverse recovery current flows in the transformer and stores energy in the leakage inductance. As a result of interaction between the leakage inductance of transformer and parasitic capacitance of rectifier diode, several ringing and large overshoots will appear on the diode voltage waveform.

The ringing across the rectifier diode voltage waveform can generate significant amount of electromagnetic interference and the overshoots generally destroy the rectifier diodes. To solve that problem several methods are available [1], [2], [3], [4], [6], mainly as a function of the rated power processed by the DC-DC converter and the voltage levels.

(*) Eduardo F. R. Romaneli is a Professor at Federal Center of Technological Education of Paraná, Curitiba – PR – Brazil.

In low power applications with low voltages, the use of schottky diodes as rectifier diodes can be the solution for this matter. However, if the voltage levels increase this solution will not be appropriated, because there is no schottky diode that supports several hundred reverse voltages.

Another solution for low power applications is the use of ultra fast diodes with high reverse voltage sometimes can be acceptable. But, in the medium to high power applications, this manner decrease significant the overall efficiency of the DC-DC converter.

A different way to clamp the voltage across the rectifier diodes is connecting in series with the diode a saturable reactor [2]. This approach is able to operate in high power applications with very good clamping voltage effectiveness. However, the saturable reactors have elevated cost and their temperature rise is high due to the tape-wound core structure.

The solution that has the best compromise between cost, performance and application is the use of clamping circuits. Clamping circuits can be passives, when they have just capacitors, resistors and diodes or actives, when they have capacitors, diodes and a controlled switch.

The passive clamping circuits, like RCD clamping circuit, present low cost, simplicity and good clamping effectiveness. By the way, they present high losses in medium to high power applications. This feature will imply the use of a specific heat transfer system for the clamping resistor, by the increase of converter's heatsink or by the use of forced coolers. In both ways the volume of the converter will increase and consequently decrease the power density of the converter. Other limitation for passive clamping circuits is the search for high efficiency in converter requirements. Therefore, the passive clamping circuits present good features in low power applications.

To address the problem in high power applications, active clamps must be employed. This paper proposes an active clamping circuit employing a Forward converter. Experimental results from a DC-DC Three Level-ZVS-PWM converter with Hybridge output rectifier stage in a 24kW rated power applications will be presented. A discusses the possibilities of applying the active clamping circuit in other output rectifier stages topologies will be presented as well.

II. THE PROPOSED ACTIVE CLAMP

The proposed active clamp structure is based on two different actions of the whole active clamp circuit. The first one is the clamping action and the second one is the action of recycling the reverse recovery energy from the clamping capacitor to the output of the DC-DC converter.

A good approach to realize the first action is configuring the clamping diodes, the clamping capacitor and the rectifier diodes like a Full-Wave rectifier with output capacitor. Fig. 1 shows the topology of that rectifier. When the diodes turn off, the output capacitor C clamps the voltage across the diodes naturally.

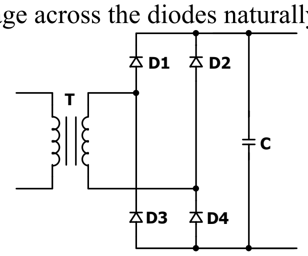

Fig. 1 – The Full-Wave rectifier topology.

A DC-DC converter connected between the clamping capacitor and the output of the high power DC-DC converter can realize the second action. A block diagram of this approach is presented in Fig. 2.

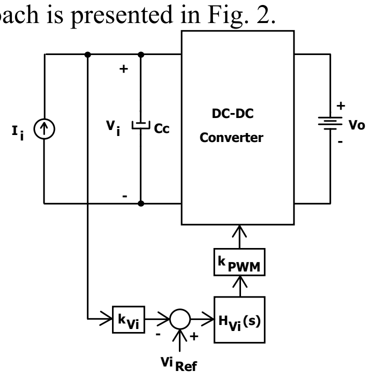

Fig. 2 – Block diagram of the DC-DC converter connections in the clamping circuit.

The presence of a DC-DC converter in the clamping circuit brings some interest advantages compared with others active clamping circuits:

- The independent operation of the clamping circuit;
- No isolated drivers are necessary;
- Possibility to control the clamping voltage because the clamping voltage is equal to DC-DC converter input voltage;
- This approach makes easier the active clamping circuit generalization to the output rectifier stages topologies.

Some disadvantages of this active clamping circuit are:

- Increase of the component count in the clamping circuit;
- Volume increasing of the clamping circuit.

Fig. 3 shows the active clamping circuit connected to the most common output rectifier stages used in DC-DC converters for high power applications. In Fig. 3 a) is presented the Full-Wave rectifier, in Fig. 3 b) is presented the Center-Tap rectifier and the Hybridge rectifier is presented in Fig. 3 c).

The Forward converter was choose because the active clamping circuit in the Center-Tap needs isolation, to control the clamping voltage Forward switch and the clamping capacitor will be in the same ground and the power process by the clamping circuit. The Forward converter topology is the same employed in switching mode power supplies.

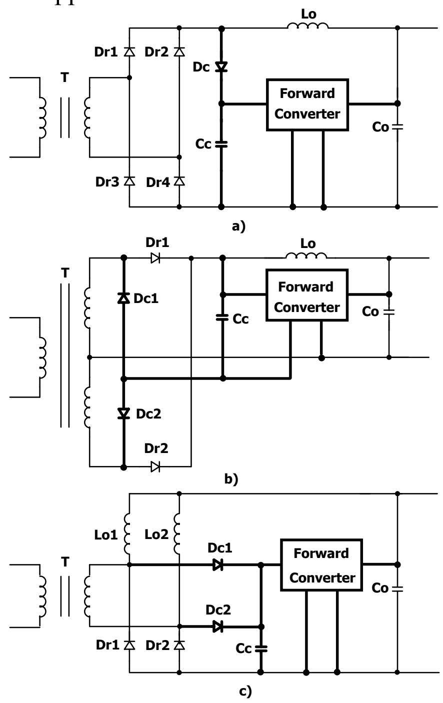

Fig. 3 – The active clamping circuit connected to the output rectifiers stages: a) Full-Wave rectifier, b) Center-tap rectifier and c) Hybridge rectifier.

III. CLAMPING CIRCUIT ANALYSIS

When the rectifier diodes turn off, the reverse recovery current flows in the secondary side of the transformer, through the clamping diode and the clamping capacitor creating a new loop on the secondary side. The equivalent circuit is showed in Fig. 4, where V_s represents the voltage in the secondary side of the transformer, L_{ls} represents the leakage inductance plus the resonant inductance referred to the secondary side and C_c represents the clamping capacitor.

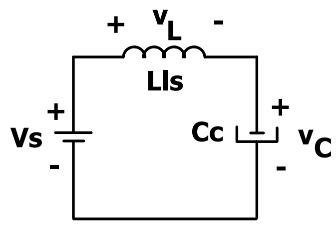

Fig. 4 – Equivalent circuit for analysis.

The initial conditions for the circuit presented in Fig. 4 are presented in (1) where I_{rr} represents the peak reverse recovery current and V_{Ccmin} the minimum voltage in the clamping capacitor.

$$\begin{cases} i_L(0) = I_{rr} \\ v_C(0) = V_{Ccmin} \end{cases} \tag{1}$$

The voltage in the clamping capacitor C_c can be expressed by (2).

$$v_C(t) = V_S + (V_{Ccmin} - V_S).\cos(\omega.t) + I_{rr}.\sqrt{\frac{L_{ls}}{C_c}}.\text{sen}(\omega.t) \tag{2}$$

Where ω represents the natural frequency of the equivalent circuit and it is given by (3).

$$\omega = \frac{1}{\sqrt{L_{ls}.C_c}} \tag{3}$$

At the end of reverse recovery time t_{rr}, the clamping capacitor C_c will be charged with the maximum voltage V_{Ccmax}, yielding:

$$V_{Ccmax} = v_C(t_{rr}) = Vs + (V_{Ccmin} - Vs).\cos(\omega.t_{rr}) + I_{rr}.\sqrt{\frac{L_{ls}}{C_c}}.\text{sen}(\omega.t_{rr}) \tag{4}$$

The voltage V_{Ccmax} defines the maximum voltage across the rectifiers diodes.

The equation (4) can be represented as function of clamping capacitor, since the variables L_{ls}, V_s, t_{rr} and I_{rr} are known. The minimum clamping voltage V_{Ccmin} must be adopted and verify the restrictions of (5), for the Full-Wave and Hybridge rectifiers and (6) for the Center-Tap rectifier.

$$V_{Cc_{min}} > V_S \tag{5}$$

$$V_{Cc_{min}} > 2.V_S \tag{6}$$

The clamping capacitor value is obtained through the curve generated by (4). With the clamping capacitor choosen the maximum clamping voltage can be calculated by (4) again.

The power processed by the clamping circuit can be estimated across the energy stored in the clamping capacitor (W_{Cc}) in a half commutation period of the DC-DC converter. The equation yields:

$$W_{Cc} = \frac{1}{2}.C_c.\left(V_{Cc_{max}}{}^2 - V_{Cc_{min}}{}^2\right) \tag{7}$$

The energy stored in the clamping capacitor can also be written by (8), where P_{Cc} is the power in the clamping circuit.

$$W_{Cc} = P_{Cc}.\frac{T_{sDC\text{-}DC}}{2} \tag{8}$$

Solving (7) and (8) for P_{Cc} leads to:

$$P_{Cc} = f_{sDC\text{-}DC}.C_c.\left(V_{Cc_{max}}{}^2 - V_{Cc_{min}}{}^2\right) \tag{9}$$

Therefore, the power in the clamping circuit is an important specification to design the Forward converter.

The stresses on clamping capacitor are given by (10) and (11). The rms current through the clamping capacitor can be obtained by numerical simulation.

$$V_{Cc_{pk}} = V_{Cc_{max}} \tag{10}$$

$$I_{Cc_{pk}} = I_{rr} \tag{11}$$

The stresses on clamping diodes are given by (12) and (13). The average current flow through the clamping diode is also obtained by numerical simulation.

$$V_{Dc_{pk}} = V_{Cc_{max}} \tag{12}$$

$$I_{Dc_{pk}} = I_{rr} \tag{13}$$

The stresses on Forward converter components are the same of the Forward converter in switching mode power supplies application.

To control the clamping voltage, the Forward converter model for input voltage control must be found, because the clamping voltage is equal to the Forward input voltage. The Fig. 5 shows the Forward converter circuit used to obtain the model.

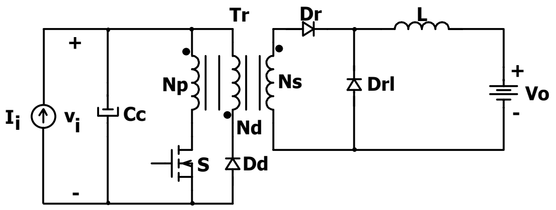

Fig. 5 – Forward converter circuit used to obtain the model.

The Forward converter was modeled by the model of PWM switch [7] and the transfer function resultant is given by:

$$\frac{\hat{v}_i(s)}{\hat{d}(s)} = \frac{-I_o.R_{SE}}{n}.\frac{\left(s + \frac{1}{R_{SE}.C_c}\right).\left(s + \frac{D_{max}.V_i + D_{max}{}^2.\frac{I_o}{n}.R_{SE}}{I_o.n.L}\right)}{\left(s^2 + \frac{D_{max}.R_{SE}}{n^2.L}.s + \frac{D_{max}{}^2}{n^2.L.C_c}\right)} \tag{14}$$

Where I_0 is the Forward output current, R_{se} is the clamping capacitor series resistance, n is the Forward transformer turns ratio, D_{max} is the maximum duty cycle, V_i is the DC input voltage or DC clamping voltage and L is the Forward inductance.

IV. DESIGN METHODOLOGY

The necessary specifications to design the active clamping circuit are:

- Input voltage: V_{cc} = 900V;
- Output voltage: V_o = 60V;
- Output current: I_o = 400A;
- Output power: P_o = 24kW;
- Switching frequency: $f_{sDC\text{-}DC}$ = 35 kHz;
- Efficiency: $\eta_{DC\text{-}DC}$ = 96%;
- Output ripple voltage: ΔV_o = 100mV;
- Output ripple current: ΔI_o = 20A;
- Turns Ratio: $n_{DC\text{-}DC}$ = 2.5;
- Leakage Inductance: L_{lp} = 2uH;
- Resonant Inductance: L_r = 5uH;
- Peak Reverse Recovery Current: I_{rr} = 30A;
- Reverse Recovery Time: t_{rr} = 440ns.

In the Three Level-ZVS-PWM converter, the voltage in primary side is given by:

$$V_p = \frac{V_{cc}}{2} = 450V \tag{15}$$

In the secondary side the voltage is:

$$V_s = \frac{V_p}{n_{DC\text{-}DC}} = 180V \tag{16}$$

The minimum clamping voltage adopted is 5% greater than the secondary side voltage. The equation (17) shows this result.

$$V_{Cc_{min}} = 1.05.V_s = 189V \quad (17)$$

The equivalent inductance in the secondary is given by:

$$L_{ls} = \frac{L_{lp} + L_r}{n_{DC\text{-}DC}^{\;2}} = 1.12\mu H \quad (18)$$

The equation (4) can be represented as function of the clamping capacitor value, resulting in the curve plotted in Fig. 6. A good region of the curve to choice the clamping capacitor value is where the clamping voltage is constant.

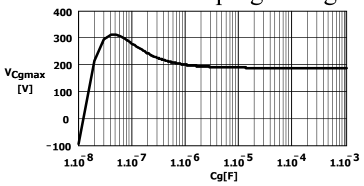

Fig. 6 – Maximum clamping voltage as a function of clamping capacitor value.

The choose clamping capacitor was 1mF. Then, the maximum clamping voltage is 189,012V and the voltage ripple in the clamping capacitor is 12mV. The power processed by the clamping circuit is about 160W.

With the power in the clamping circuit and the set of specifications above, the Forward converter can be designed.

- Forward input voltage: $V_i = 189V$;
- Forward output voltage: $V_o = 60V$;
- Forward input power: $P_{Cc} = 160W$;
- Forward switching frequency: $f_s = 35kHz$;
- Maximum duty cycle: $D_{max} = 0.4$;
- Forward efficiency: $\eta = 85\%$;
- Forward output ripple current $\Delta I_{L\%} = 15\%$.

To regulate the clamping voltage just a proportional compensation was implemented. The Fig. 7 shows the circuit that realize the proportional compensator and Fig. 8 shows the Bode plot of converter transfer function (G(s)), compensator transfer function (H(s)) and the open-loop transfer function (GH(s)).

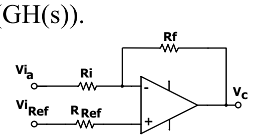

Fig. 7 – The proportional compensator circuit.

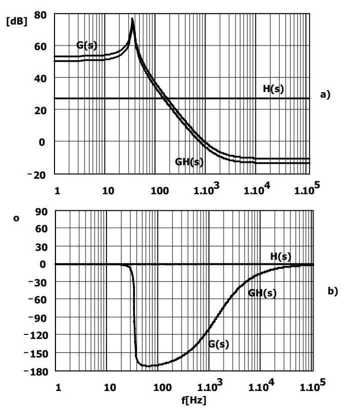

Fig. 8 – Bode plots: a) Module and b) Phase.

The compensator gain was equal to 33 resulting in a phase margin equal to 42°.

V. EXPERIMENTAL RESULTS

The active clamping circuit was implemented in a Hybridge output rectifier stage of an isolated DC-DC Three Level-ZVS-PWM converter. The DC-DC converter is designed to operate in a power supply for telecommunications systems.

The converter's secondary side is presented in Fig. 9. The whole active clamping circuit appears in details. The integrated circuit UC3525A was implemented to control and driver the active clamping circuit.

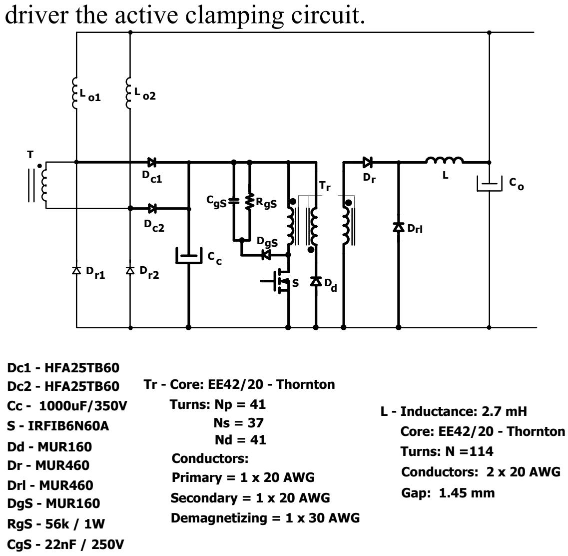

Fig. 9 – Implemented active clamping circuit.

The clamping voltage and the voltage across the rectifier diode are showed in Fig. 10. During the rectifier diode turn off, the voltage across it is clamped with low ringing amount. A detail of the rectifier diode turn off is showed in Fig. 11.

The Fig. 12 shows the voltage across the Forward switch and the current through the Forward inductor. The current through Forward inductor is the reverse recovery current recycled to the output.

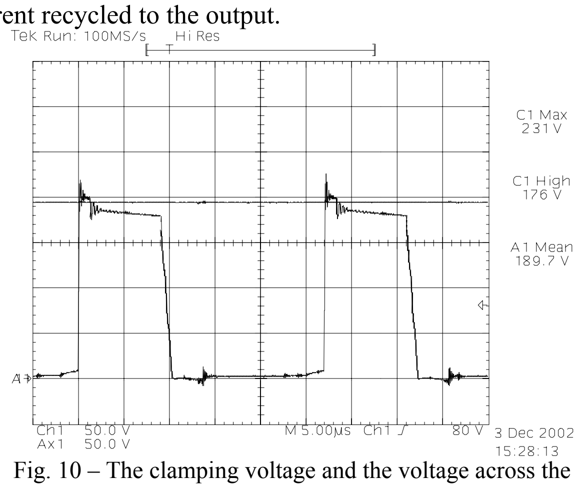

Fig. 10 – The clamping voltage and the voltage across the rectifier diode.

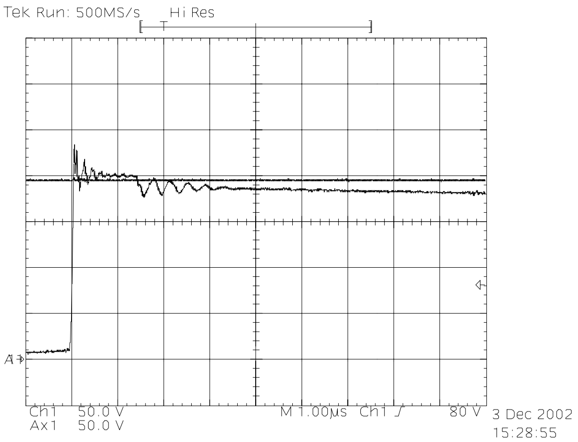

Fig. 11 – Detail of the rectifier turn off.

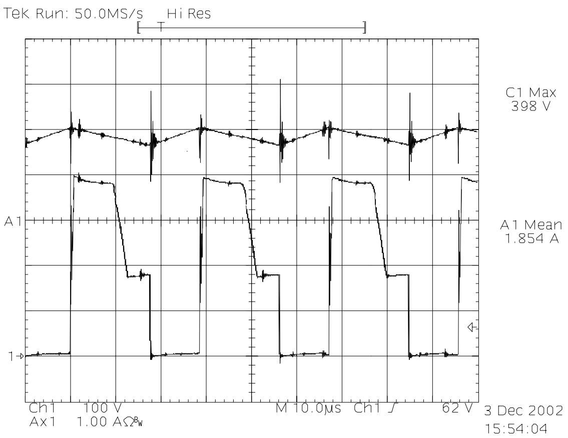

Fig. 12 – The voltage across the Forward switch and the current in the Forward inductor.

A comparative experimental efficiency curves between this active clamping and the traditional RCD passive clamping are shown in Fig. 13. The active clamping increases the overall converter efficiency. At rated power an improvement of approximately 0.5% in efficiency was reached over.

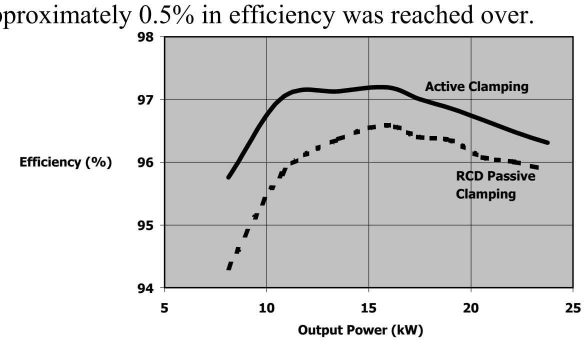

Fig. 13 – The efficiency curves.

VI. CONCLUSIONS

The proposed active clamping circuit showed a new application to the Forward converter.

The experimental results confirm the clamp effectiveness and the regenerative feature of this active clamping circuit. This approach has interesting advantages as the closed-loop control of the clamping voltage, independent operation and the possibility to use in the most common output rectifier stages. The increase of clamping circuit component count justifies its application in medium to high power applications.

The control of the clamping voltage ensures a regulated clamping voltage. This feature provides an increase in the reliability of the converter. As a matter of fact, in high power applications the rectifier diodes both turn on and turn off with several hundred volts and even several hundred amps. Finally, the practical results show that the active clamping circuit increases the overall efficiency of the converter.

REFERENCES

[1] R. Sheely; J. Dekter; N. Machin. *“Improved Active Clamp for Secondary Circuits”*. In: INTELEC 2000 – International Telecommunications Energy Conference. Proceedings, Phoenix, Arizona, USA: 2000, p.130-134.

[2] R. Liu. *“Comparative Study of Snubber Circuits for DC-DC Converters Utilized in High Power Off-line Power Supply Applications”*. In: APEC´99 – Applied Power Electronics Conference and Exposition. Proceedings, v. 2, Dallas, Texas, USA: 1999, p.821-826.

[3] J. Dekter; N. Machin; R. Sheely. *“Lossless Active Clamp for Secondary Circuits”*. In: INTELEC´98 – International Telecommunications Energy Conference. Proceedings, San Francisco, California, USA: 1998, p.386-391.

[4] D. B. Dalal; Fu-Sheng Tsai,. *“A 48V, 1.5kW, Front-end Zero-voltage-switched, PWM Converter with Lossless Active Snubber for Output Rectifiers”*. In: APEC´93 – Applied Power Electronics Conference and Exposition. Proceedings, San Diego, California: 1993, p.722-728.

[5] P. C. Todd. *“Snubber Circuits: Theory, Design and Application”*. Unitrode Power Supply Design Seminar SEM-900, Unitrode, 1993.

[6] J. A. Sabaté; V. Vlatkovic; R. B. Ridley; et al. *“High-voltage, High-power, ZVS, Full-bridge PWM Converter Employing an Active Snubber”*. In: APEC´91 – Applied Power Electronics Conference and Exposition. Proceedings, Dallas, Texas, USA: 1991, p. 158-163.

[7] V. Vorpérian. *“Simplified Analysis of PWM Converters Using the Model of the PWM Switch”*. VPEC Seminar Tutorials, Blacksburg, Virginia, 1989.

[8] Carlos Henrique Illa Font. *“Grampeamento Ativo para Estágios Retificadore de Saída de Conversores CC-CC Isolados”*. Florianópolis – SC, 2003. Dissertação (Mestrado em Engenharia Elétrica) INEP/EEL. Universidade Federal de Santa Catarina. (in Portuguese).