ANALYSIS OF AN ADJUSTABLE, DC-LINK- BASED, REGENERATIVE ELECTRONIC LOAD

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Abstract **– This paper presents a novel, Regenerative Electronic Load, which allows laboratory experimentation of power electronic equipment to be done with quite low losses, since the energy flow is essentially directed back to the grid. It is based on the rectifier/inverter configuration of a DC-DC transmission system, here called DC-link, where its main purpose is to allow the energy to flow from the source side (converter in the rectifier mode) to the load side (converter in the inverter mode), through a small line resistor, in series with a power inductor, with minimum losses. Implemented by means of thyristor technology, at mains frequency, it can be applied both to DC- and AC-output equipment, allowing the biggest part of the energy, that would be dissipated in the form of heating, in usual resistive loads, to be injected back to the electric grid. The proposed Electronic Load is capable of drawing full range load current, from the equipment under test, in a smooth manner, by adjusting a simple potentiometer. The working principle, applications consideration, main equations and some simulation results of the proposed Electronic Load are also presented.**

KEYWORDS

Electronic load, Power converters, HVDC transmission system, Regenerative electronic load.

I. Introduction

Power electronics laboratories are always involved with the need of testing power electronic equipment, many times with high power loads (some kilowatts). These loads are usually made up of power resistors, what means that a significant amount of energy is lost during the test phase. Another problem is that such a load is not always present, at least in the desired value, making it difficult to test some DC-DC or AC-DC converters. Adjust of the resistive load is usually made by steps instead of a smoothing variation, what makes difficulty the full range test of the equipment.

The need for a kind of load that satisfies the load requirements of the various types of converters usually tested in power electronics laboratories, has led to the proposed Regenerative Electronic Load. It is intended to act as an adjustable electronic load, suitable for being used with equipment such as DC-DC or AC-DC converters.

Switched electronic loads intended to test power equipment in power electronics laboratories are present in the market, though they are usually not regenerative [1], what means they allow the test to be done, with versatility, but without economy. In the technical literature one can find some regenerative Electronic Load (*E-Load*), but for low power, single-phase applications [2].

A revision of the high voltage direct current power transmission (HVDC) theory is presented to show how the power flow control is reached in that scheme. As is known, the HVDC transmission system is a reality worldwide, making it possible to transmit great blocks of energy in high DC voltage such as the double bipolar ± 600kV (plus and minus 600kV), which is the case of the Itaipú hydroelectric plant, HVDC system. This DC transmission system is a tie line between the 50Hz, AC electric system of Ciudad del Este, Paraguay, and the 60Hz, AC electric system of Ibiúnas in south-eastern Brazil. In the light of such a kind of DC transmission system involving a thyristor controlled rectifier in the source terminal and a similar topology operated in the inverter mode [3], an electronic load system can be thought of to do the same thing between any converter and the own electric grid of the laboratory. The similarities and the differences between these systems are to be studied in order to establish the best way of controlling the current drained by the electronic load when connected to the output terminals of the electronic equipment under test.

II. HVDC Transmission System – A Revision

A typical HVDC bipolar system is shown in Fig. 1, constituted by two converter groups in series in each side. The left side can be considered as the source of power or rectifier converter, whereas the right side plays the role of inverter, injecting the power to the AC system. As the mid point of each terminal station is at ground potential the lower and upper halves of the system are symmetrical, and therefore only one half need to be considered [4].

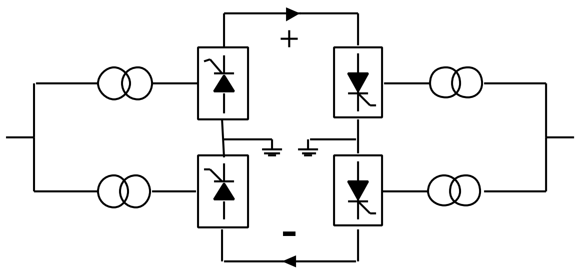


Fig. 1 Typical HVDC transmission system.

The equivalent circuit of Fig. 2 can conveniently represent this basic transmission system.

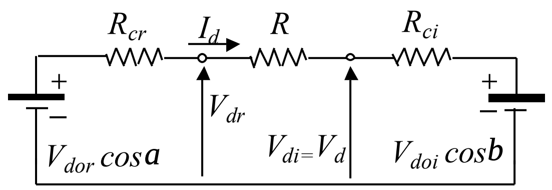


Fig. 2 DC transmission system equivalent circuit.

The equations below allow one to determine the current flowing in the line:

$$I_d = \frac{V_{dr} \quad V_{di}}{R} \tag{1}$$

By substituting the appropriate expressions for V_{dr} and V_{di} yields:

$$I_d = \frac{V_{dor} \cdot \cos a \quad V_{doi} \cdot \cos b}{R + R_{cr} + R_{ci}} \tag{2}$$

Where R is the line resistance; R_{cr}=3.X_{cr}/ is the non-dissipative equivalent resistance due to the commutating reactance (X_{cr}=2. .f.L_c) linked to the existence of leakage inductance in transformer rectifier and source; R_{ci} is the same, but for the inverter [5].

A change of current and therefore of power transfer can be achieved by altering any one of four possible parameters:

a) The delay angle or control angle of the rectifier, ;
b) The advance angle or control angle of the inverter, ;
c) The rectifier transformer winding voltage;
d) The inverter transformer winding voltage.

The last two items (c) and (d) generally involve the use of an on load tap changing (OLTC) transformer or change of a source voltage, whereas the first two items refer to the control angles of the rectifier ( ) and inverter ( ), respectively.

Neglecting the overlap angle (or commutation time) it can be shown that the relation between the RMS value of the fundamental-frequency component of AC line current and the DC line current is:

$$I_{L1} = \frac{\sqrt{6}}{p} \times I_d \tag{3}$$

In addition, the following expression allows one to figure out the power factor:

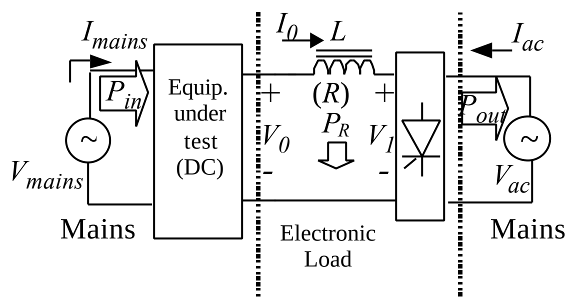
$$pf = \cos f = \cos a \tag{4}$$

Thus, the delay angle ( ) control displaces the fundamental component of the current by an angle equal to . Therefore the converter, in the rectifier mode, draws reactive power from the AC system proportional to the delay angle   [3]. That's the reason why the delay angle , as well as its counterpart, the advance angle , is kept in a small range: between 15 to 18 degrees [4].

Based on this HVDC transmission system, an Electronic Load may be developed: any DC- or AC-output equipment could be power experimented by means of a connection of its (DC) output to an inverter-mode, Rectifier Bridge through a very small resistance, like the line resistance of the HVDC system. This resistance will be implemented by means of the equivalent series resistance of a smoothing reactor (L) that will be put between both converters, since the sending and ending terminal voltages will not be constant, nor instantaneously equal.

III. Electronic Load Basic Operating Principle

There are two possible basic types of this Regenerative *E-Load*: one for DC-output and another for AC-output. Fig. 3 and Fig. 4 show the basic configuration involving the equipment under test, the electronic load and the electric grid, for both types.



P_{in}: processed power, P_R: dissipated power,
P_{out}: regenerated power

Fig. 3 Electronic load for DC-output equipment.

The basic operating principle establishes that the power to be drained from the equipment under test will be dissipated partially in the resistor R, of small value, and in its biggest part yielded back to the grid. The effective energy consumption is then that in the resistor R plus the energy lost in the equipment devices. The lost energy in the experiment is therefore only a fraction of the total developed electric power. The biggest part of that power is being injected back to the utilities without any problem since the electronic load is based on a line-side commutated, controlled rectifier.

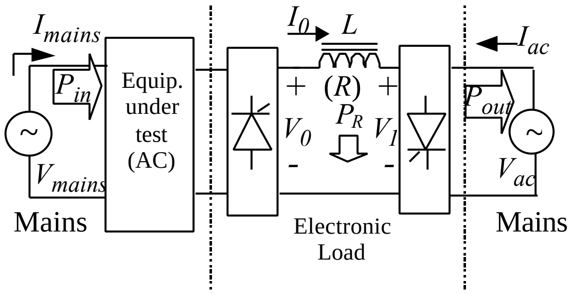


Fig. 4 Electronic load for AC-output equipment.

A simple potentiometer is capable of controlling the load level, which can be adjusted by means of the advance angle ( ) of the controlled output inverter [6]. In this way the load level is continuously varied in full load range, from light to heavy load, without the need of any mechanical switching.

IV. Basic Equations Governing The Electronic Load

The main equations governing the *E-Load* can be derived from the simplified, single-phase circuit of Fig. 5, which is the case 1: *E-Load* for DC output equipment.

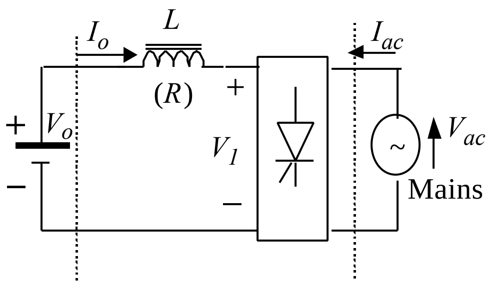


Fig. 5 Simplified *E-Load* circuit.

Under the consideration of a smoothed, continuous conduction mode line current I_0, the power lost in line resistor R is given by:

$$P_R = R \times I_0^2 \tag{5}$$

Where I_0 stands for the smoothed, DC-line current through the line resistor R. The total power delivered by the DC source is expressed by:

$$P_o = P_R + P_1 \tag{6}$$

Where $P_1 = V_1.I_0$ is the power injected (back) to the mains by means of the inverter-mode, controlled rectifier.

Since the DC source output power is also the product $V_0.I_0$, one can get to the following normalized equation:

$$P_{on} = R_n \cdot \left[\frac{(1 - V_{1n})}{R_n} \right]^2 + V_{1n} \cdot \left[\frac{(1 - V_{1n})}{R_n} \right] \tag{7}$$

Where:

V_{1n} is the normalized V_1 voltage (related to the base, rated voltage V_{0r});

R_n is the normalized load resistance (in the base resistance $R_b = V_{0r}/I_{0r}$, with I_{0r} being the dc-source rated, output current.

The power lost in the line resistor R is just a fraction of the total power P_0, and is given by:

$$P_{Rn} = R_n \cdot \left[\frac{(1 - V_{1n})}{R_n} \right]^2 \tag{8}$$

Where $I_{0n} = I_0/I_{0r}$ is the normalized line (or load) DC current, which is also equal to:

$$I_{on} = \frac{1 - V_{1n}}{R_n} \tag{9}$$

These two important power equations (7 and 8) are now plotted together, in order to a better visualization of the amount of power that is dissipated as heat, and that amount injected back to the mains.

Letters (a) and (b) in Fig. 6 indicate the amount of power lost and injected in the mains, respectively, for an R_n=0.1 per unit (in a base, rated resistance R_b). This percent power dissipation in R (indicated by letter b in Fig. 6) is the maximum possible, related to the rated power of the equipment under experimentation, and it will occur in the operating point of nominal power. Thus, for an R_n=0.1 (or 10%) the power effectively dissipated in R is equivalent to 10% of the rated output power of the equipment in this operating point. Therefore, the amount of power that is not lost in heat form and is injected back to the electrical network arises to 90%! For light load the percent of dissipated power is still smaller than the R_n (less than 10% in this example).

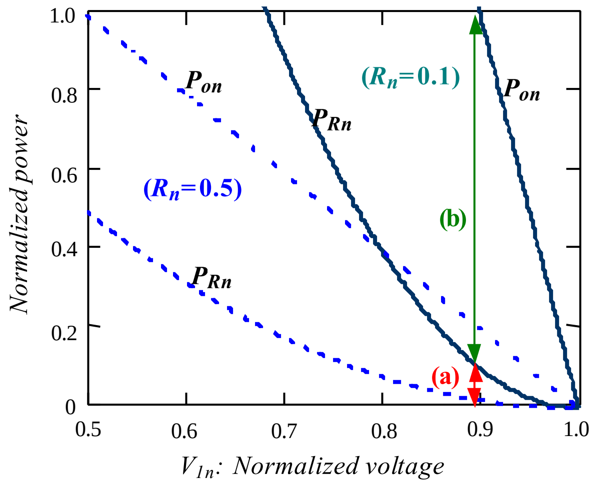


Fig. 6 Normalized power: lost (P_{Rn}), and injected in the mains (P_{on}).

This basic analysis shows the utility of such a regenerative electronic load. For output power greater than 2kW, the three-phase Rectifier Bridge topology is the more indicated, because of the equally distributed power among the phases.

V. Main Simulation Results

Based on the above operating principle's considerations, some simulation studies have been made both for DC- and AC-output equipment.

First, a DC voltage source played the role of the DC-output equipment (circuit shown in Fig 5). Fig. 7 shows the *E-Load* drawing a heavy, single-phase load (2kW) by means of an advance angle equal to 23.5 degrees, with an average load current equal to 10.4A. The peak-to-peak I_o current *(DI$_0$)* is around 1.7A. The I_{ac} current (11.2A rms) is a square waveform.

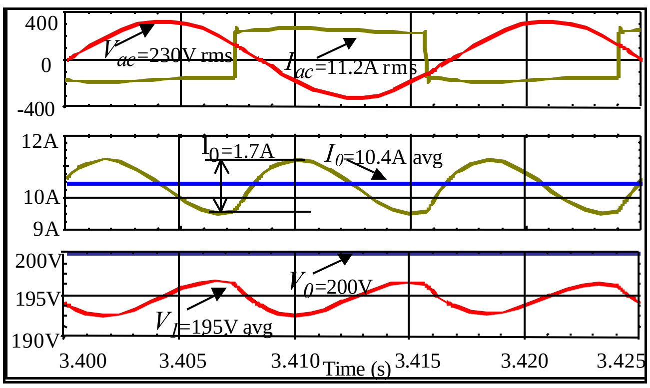


Fig 7 Waveforms of voltages and currents for a DC output equipment using an *E-Load* with heavy load

In Fig. 8 the same equipment is shown being controlled by means of an advance angle ( ) of 20.1 degrees, with an average load current around 0.74A (light load 150W). In this case there is discontinuous conduction mode in I_o current. So, the I_{ac} current waveform is no longer rectangular.

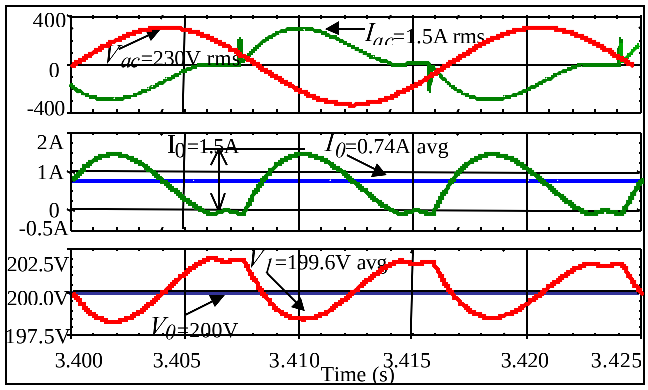


Fig 8 Voltages and currents for a DC-output equipment using an *E-Load* with light load (discontinuous conduction mode)

In the second case, an AC-output voltage, single-phase equipment is under test. Fig. 9 shows the simulation results for the circuit of Fig 4, using control angles of the rectifier ( ) equal to zero degree and inverter ( ) equal to 25 degrees, respectively.

One can see the AC-output equipment's voltage and non-filtered, line current (in the top of Fig. 9). The *E-Load* makes the role of a resistive load, since the fundamental line current is in phase with the voltage. The high frequency filtering was not implemented in this simulation. By means of its implementation, this quasi-square wave line current becomes a sinusoidal one.

The current I_{ac} , in the middle of Fig. 9, represent the current injected back to the mains, if its sign is taken negative. The voltages in the bottom of the figure compare the average voltages of the sending-end Rectifier Bridge (V_o) and that of the receiving-end Rectifier Bridge (V_I). As it is expected, the sending-end voltage (V_o) is greater than the other one.

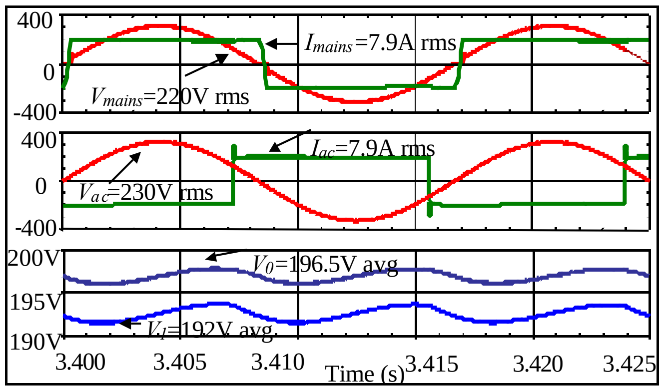


Fig 9 Voltages and currents for an AC-output equipment using an *E-Load*, with =0° and =25°

Now, the same circuit is shown in Fig 10, using control angles equal to 30 degrees and equal to 15 degrees, respectively. Similar comments made for Fig. 9, can be made for these variables of Fig. 10. The main difference is the fact that in this case the *E-Load* makes the role of a lagging impedance, as one can check by the displacement of the current concerning the voltage, in the top of the figure.

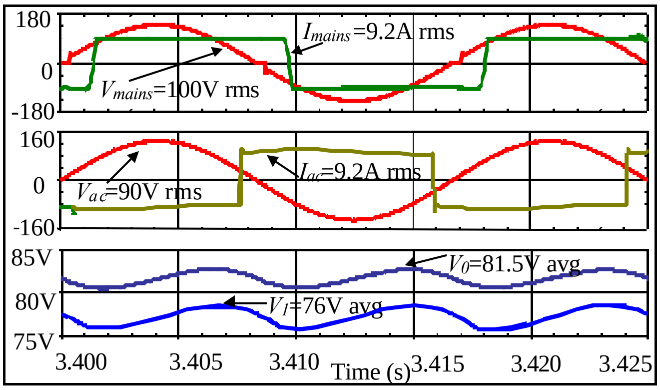


Fig 10 Voltages and currents for an AC-output equipment using an *E-Load*, with =30° and =15°

VI. Applications Considerations

The Electronic Load can be used to draw load current from either DC-output or AC-output electronic converters. In the first case the Rectifier Bridge (on the left) of the *E-Load* will not be necessary, since de equipment under test provides the adequate DC source to be connected, through an adequate line resistor *R* (implemented by means of the equivalent series resistance of a smoothing reactor), to the converter bridge controlled in the inverter-mode. If the electric grid feeds the equipment, its developed power will be injected back to the own grid during the experimentation, except for a small amount of energy, which will be dissipated in the line resistor *R*.

In the second case, the *E-Load* being used to draw power from AC-output equipment, the Rectifier Bridge will be necessary. A controlled, Rectifier Bridge will then rectify the equipment's AC output voltage, with its DC-output being linked to the inverter-mode converter bridge through the line resistor *R*. Once more the inverter-mode Rectifier Bridge is to be controlled by its advance angle control to adjust the load level of the equipment under test.

At any case, a step down, isolating transformer may be used to match the equipment and the mains voltages.

VII. Need Of Reactive Compensation And Harmonic Filtering

The voltage source V_{ac} can be considered as a power receptor, if the negative of the I_{ac} current in Fig. 5 is taken. In addition, if this current is decomposed in its two Cartesian components I_r (reactive current), and I_a (active current), then one can redraw the figure to represent these two currents as shown in Fig. 11.

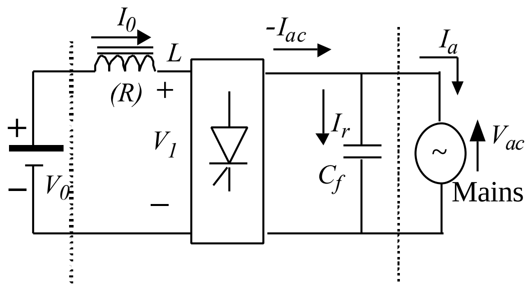


Fig 11 Current I_{ac} decomposed in components I_r and I_a

Now, the I_a current enters the voltage source and characterizes the active power ($V_{ac}.I_a$) being regenerated; the I_r current enters the filtering capacitor C_f and characterizes the leading reactive power being drained by the original voltage source, or the lagging reactive power being injected by it. Therefore, a filtering capacitor C_f is to be inserted in parallel to the mains in order to implement a source of lagging reactive power needed by the inverter-mode, thyristor Rectifier Bridge. If this capacitor is not present, the amount of lagging reactive power needed by the rectifier should be provided by the mains, what would require a bigger line current (I_{ac}). This process may be called reactive compensation, since the Rectifier Bridge requires lagging reactive power for its operation with smoothed DC current. This analysis does not consider the harmonic content of the I_{ac} line current, but just its 60Hz, sinusoidal, fundamental current.

Syntonized filter, active filter or low-pass filter may be considered to implement the filtering of the high harmonic content of the I_{ac} line current. They should be inserted in parallel to the Rectifier Bridge, according to Fig. 12. This filtering is needed to avoid harmonic currents enter the electric network.

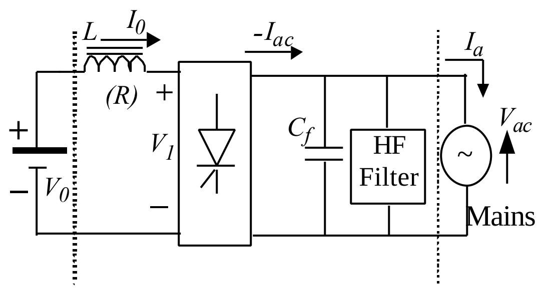


Fig 12 Single-phase *E-Load* with high frequency filter and reactive compensation

VIII. AC-Output Voltage Equipment Considerations

In the case of AC-output equipment, the *E-Load* is implemented according to Fig. 13. Typical loads for an AC source can be constituted by *R-L* (with lagging power factor) or *R-C* (with leading power factor) impedances. These are fed by sinusoidal voltages and currents, and there will be need of harmonic filtering and reactive compensation, in the same way that happens for the DC-output equipment, in the mains' side. Therefore, for this AC-output equipment, the *E-Load* should be implemented by means of harmonic filtering and reactive compensation both in the rectifier- and the inverter-mode Rectifier Bridges.

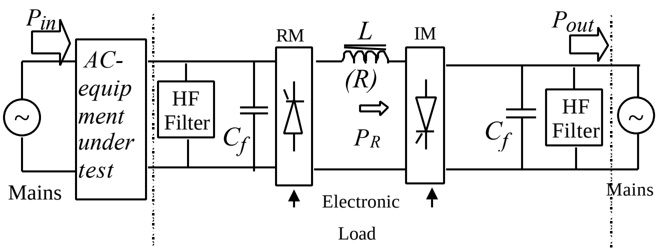


Fig 13 Complete circuit of *E-Load* for AC-output equipment

The Rectifier-Mode (RM) Rectifier Bridge can be implemented by means of the conventional thyristor technology, which is naturally capable of drawing off lagging current, in order to make the role of an inductive load. The power factor angle is then determined by the control angle . For the case of capacitive load, the RM Rectifier Bridge should be implemented by means of a transistor technology. In this way, it is capable of drawing off both lagging and leading currents, by means of an adequate modulation [6].

IX. Conclusion

A novel Regenerative Electronic Load was presented by means of its basic operating principle, main descriptive equations, simulation results, and applications considerations. It was developed to overcome difficulties concerning the use of discrete, resistive loads in laboratory tests of electronic equipment. In addition, to avoid the usual high power dissipation of conventional *E-Load*, by allowing the output power of the equipment under test to be directed back to the mains. Its operating principle is based on the HVDC transmission system operation, where a DC power flow is directed from an AC source trough a resistive line to another AC system, by using the six pulse, thyristor controlled rectifier topology in both ends, with the source end operating as a rectifier, and the load end, as an inverter.

Both DC- and AC-output electronic equipment may be tested by means of such a DC-Link, Regenerative, Electronic Load. Simulation results, for both types of these single-phase, Electronic Loads were presented.

It was also shown the need of reactive compensation and high frequency filtering, for both Rectifier Bridges of the discussed *E-Loads*. An isolating transformer is to be used in order to match the output equipment and mains voltages.

More mathematical analyses, experimental results and design considerations over the *E-Load* here presented will be dealt with in a next paper.

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