A NOVEL LOAD CURRENT CONTROL METHOD FOR A LEADING POWER FACTOR VOLTAGE SOURCE PWM RECTIFIER

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Abstract – **A novel PWM voltage source rectifier, controlled by the load dc current instead of the dc voltage has been developed. Its main characteristics are: a) there is neither input current sensors nor dc voltage sensor; b) it works with an unchangeable and predefined PWM pattern; c) it presents a very strong stability; d) its stability does not depend on the size of the dc capacitor; e) it can work at leading power factor for all load conditions and f) it can also work with zero regulation for all load conditions. Digital simulations, analyses and experiments confirm all these characteristics of the control method.**

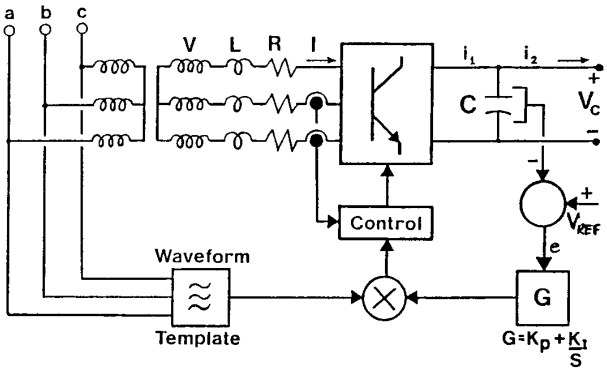

Figure 1. Direct Current Control rectifier

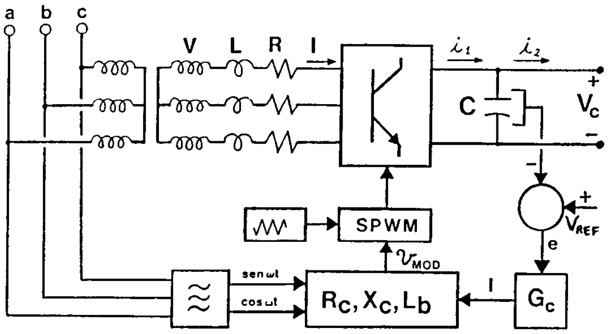

Figure 2. Indirect Current Control rectifier

1. INTRODUCTION.

The new generation of voltage source, pulse width modulated rectifiers, has reached good performance in terms of low harmonic distortion [1-3] and unity or even leading power factor operation [4]. Power reversal by current reversal and very fast dynamic response have also been some of its merits. The common factor of this kind of rectifier, is the method used in controlling the dc voltage, which is kept closed to a reference by using the error signal between that voltage and the reference. This error either controls directly the ac input currents (Direct Control) [5,6] or the input voltage modulation (Indirect Control) [7,8]. in both cases, the pattern of the pulse width modulation (PWM) is being adjusted permanently to satisfy the load requirements. For the Direct Control method, precise input current sensors and one output dc voltage sensor are required. In the Indirect Control, the current sensors are eliminated but then the system becomes more unstable. These two methods of control require a dc capacitor large enough to ensure a good stability margin, making the system transient response slower. Figure 1 shows a schematic circuit of the Direct Control rectifier and Figure 2 shows the Indirect Control configuration.

A different approach is proposed in this work. **A power rectifier without dc voltage sensor and with an unchangeable and unique PWM pattern**. The idea is based on the principle of operation for series connected, type B, PWM rectifiers proposed in [9], in which a "Master" unit controls the voltages of the other rectifiers called "slaves" without measuring their dc voltages. In the method proposed here, the rectifier is controlled in a similar form, controlling the dc voltage indirectly by adjusting the power angle through the dc load current.

This load-current-controlled rectifier can keep the dc voltage without sensing it and can operate at leading power factor for all load conditions. The stability, unlike the other rectifiers mentioned here, neither depends on the input inductance, nor on the size of the dc capacitor.

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The work analyses two methods of operation based on this principle: a "zero regulation control" and a much simpler "linear control", from which the analytical tools have been developed. Also digital computer simulations have been used to understand the behaviour of the rectifier under static and dynamic operations.

Finaly, a 2-kW prototipe has been implemented using "linear control", which has permitted the verification of the analyses and the digital simulations.

2. PRINCIPLE OF OPERATION.

The Figure 3 shows the schematic of the proposed control system.

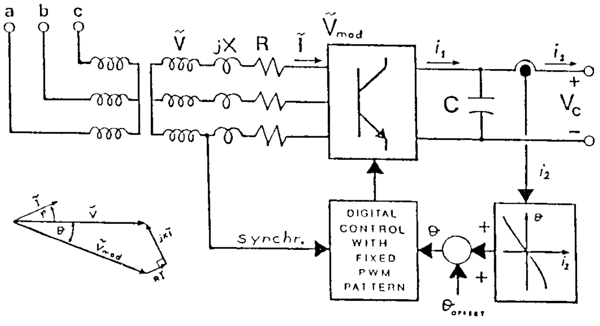

Figure 3. Load current control rectifier

The method used for controlling the rectifier is as follows: The voltage Vmod modulated by the rectifier, is produced by an unique PWM pattern, which is shifted with respect to the mains voltage V, to change the power angle **θ** and hence the amount of power flow transferred from the ac to the dc side. When the power angle is negative (Vmod lags V), the power flow goes from the ac to the dc side. When the power angle is positive, then the power flows in the opposite direction. The main idea is to control this power angle through the dc load current. One important thing that must be mentioned here is that this rectifier establishes a stable dc voltage operation for each dc current and power angle. With this characteristic, it is possible to find a relation between the dc current and the input power angle, to have zero dc voltage regulation for all load conditions. Then, without the need of measuring the dc voltage and with only one PWM pattern, the dc voltage can be kept constant. This situation may include both rectifier operation and inverter operation. A simpler control version can be implemented by making the power angle proportional to the dc current. This last version has been called "linear control".

3. ANALYSIS OF THE RECTIFIER.

The equivalent rectifier circuit for the fundamental (first harmonic and dc component at input and output terminals of the rectifier respectively), is shown in Figure 4. In this figure, V is the fundamental fase-to-neutral, mains voltage. Vmod is the fundamental of the PWM pattern. R and L are the resistance and inductance per phase located between the mains and the PWM pattern. The dc capacitor is also shown at the output terminals.

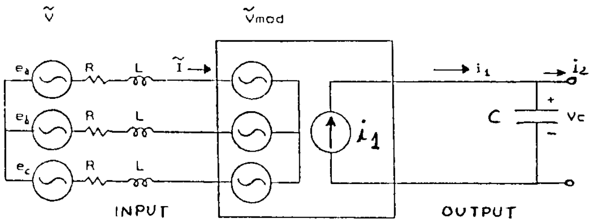

Figure 4. Equivalent circuit.

The current source i_1 is controlled by the magnitude and angle of Vmod and satisfies the power balance equations between the ac inputs and the dc output. It can be written in the d-q frame as follows:

$$v_c\, i_1 = vmod_d\, i_d + vmod_q\, i_q \qquad (1)$$

On the other hand, at the ac side, the phasor diagram establishes operating conditions between the mains and Vmod (the modulated voltage) as shown in Figure 5.

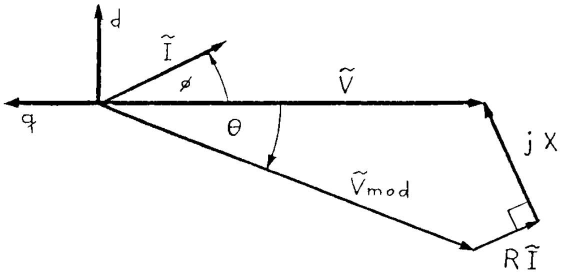

Figure 5. Phasor diagram.

This phasor diagram can also be expressed in the d-q frame as:

$$R\cdot i_d - X\cdot i_q = v_d - vmod_d \qquad (2)$$

$$X\cdot i_d + R\cdot i_q = v_q - vmod_q \qquad (3)$$

where,

$$v_d = 0 \qquad (4)$$

$$v_q = -\sqrt{3}\ V \qquad (5)$$

The rectifier works with a fixed PWM pattern, which means that there exists a linear relation between the amplitude of the modulated voltage Vmod and the dc voltage Vc:

$$|V_{mod}| = K_v \cdot V_c \qquad (6)$$

When the system is operating under steady-state, the dc capacitor reaches a particular equilibrium voltage, which means that the dc load current I_2 becomes equal to i_1. If the power angle θ (angle between V and Vmod) is kept constant, the dc voltage will take a particular and well defined value for each load current. By using equations (1) to (6) it is possible to derive an expression to see how the dc voltage Vc varies when this load current I_2 is changed.

$$V_c = (V/K_v)\cdot(\cos\theta - (X/R)\cdot \mathrm{sen}\theta) - $$
$$- I_2\cdot(R^2 + X^2)/(3\cdot K_v^2\cdot R) \qquad (7)$$

where

$$\theta = \mathrm{arctg}(vmod_d/vmod_q) \qquad (8)$$

The Figure 6 shows Vc as a function of the load current I_2 by using (7), with the power angle θ as a parameter.

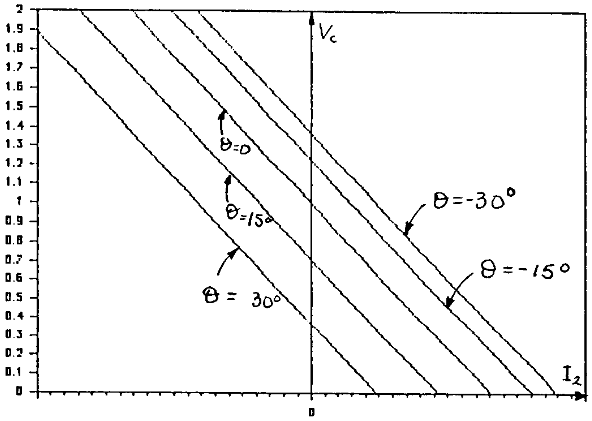

Figure 6. Vc vs I_2 for different θ angles and (X/R)=1

4. "ZERO REGULATION CONTROL".

From figure 6 it can be seen that it is possible to link the load current I_2 with the angle θ, to get zero regulation operation.

When the rectifier is unloaded (I_2=0), the mains voltage V is equal to Vmod and then, from eq.(6):

$$V_c = V/K_v \qquad (I_2=0)\ (\theta=0°) \qquad (9)$$

Replacing (9) in (7) and reorganizing terms one gets a relation θ-I_2 for zero regulation operation.

$$\cos\theta - (X/R)\cdot\mathrm{sen}\theta - 1 =$$
$$= I_2\cdot(R^2 + X^2)/(3V\cdot K_v\cdot R) \qquad (10)$$

Equation (10) allows to plot the required linking curves θ-I_2 for every load current, to obtain zero regulation, that means, the same dc voltage for all load conditions. Figure 7 shows these linking curves for different X/R rates of the rectifier.

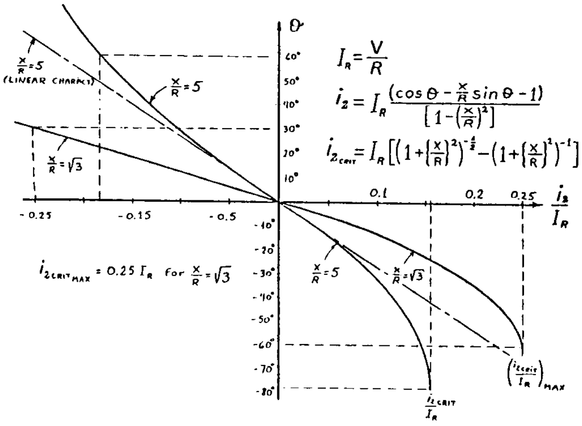

Figure 7. θ-I_2 relation for Vc=constant.

The relation plotted on figure 7 can be stored in a ROM memory. Its input is the digital value of I_2, and the output the required power angle θ to get zero regulation. A rectifier with this kind of control is shown in figure 8.

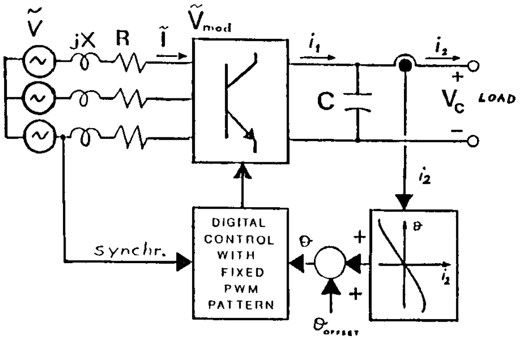

Figure 8. "Zero regulation" PWM rectifier.

It is important to realize that the rectifier cannot maintain zero regulation beyond certain limits. An overload can produce dc voltage drops mainly under rectifier operation. From figure 7 it can be observed that, depending on the X/R relation, there exists a limit for I_2, I_{2crit}. Beyond this value the dc voltage begins to fall. The figure also shows that the optimum value for X/R is $\sqrt{3}$. I_{2crit} also depends on V/R rate which is normaly bigger than 100.

5. LEADING POWER FACTOR OPERATION

One of the characteristics of the PWM rectifiers is that they can operate at leading power factor. This means they can generate reactive power. The amount of reactive power that they can generate can be expressed in the d-q frame by:

$$Q = \sqrt{3} \cdot V \cdot I_d \qquad (11)$$

Id can be evaluated through its relation with the θ angle, Kv and the parameters of the rectifier [10], getting an analytical relation which can be plotted. The figure 9 shows how the reactive power varies when the load current I_2 changes.

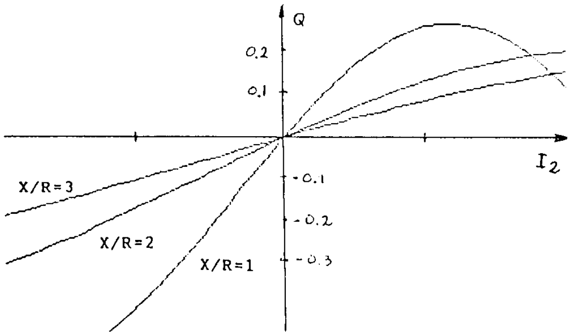

Figure 9. Reactive power vs I_2.

As it can be seen from figure 9, this converter only produces reactive power under rectifier operation. Under inverter operation, the modulator takes reactive power from the mains. This problem can be solved by adding a θ_{OFFSET} which shifts the power angle allowing leading power factor operation also for inverter operation. With the addition of θ_{OFFSET}, the rectifier is then able to operate at leading power factor for all load conditions. Figure 10 shows the implementation of θ_{OFFSET} in the control block of the rectifier.

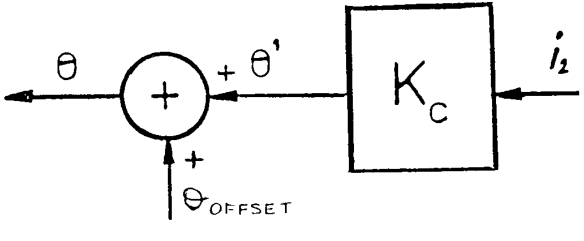

Figure 10. Control block of the rectifier with θ_{OFFSET}

As Vc is constant for all load conditions (zero regulation) then because of (6) Vmod is constant too, describing a circle when θ changes. Adding θ_{OFFSET} and looking at the "circle diagram" [10] of figure 11, it can be understood how the converter can work at leading power factor for both, rectifier and inverter operation.

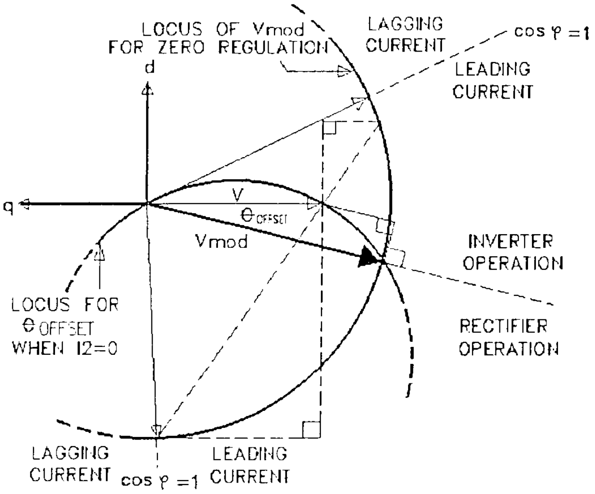

Figura 11. The circle diagram

6. LINEAR CONTROL.

Looking at figure 7 once again, it can be observed that the relation between θ and I_2 is almost linear for normal currents ($I_2 < I_{2crit}$). This behaviour allows us a simplification in the control block by changing (10) for a very simple expression:

$$\theta = -K_c \cdot I_2 \qquad (12)$$

Kc is chosen by taking the tangent to the curve of (10) in the origin. With this criterion, Kc is evaluated as:

$$K_c = (R^2 + X^2)/(3 \cdot K_v \cdot V \cdot X) \qquad (13)$$

By replacing (12) and (13) into (7) it yields:

$$V_c = (V/K_v)[\cos\{(R/X)\alpha\} + (X/R)\,\mathrm{sen}\{(R/X)\alpha\} - \alpha] \qquad (14)$$

where

$$\alpha = I_2 \cdot R \cdot [1 + (X/R)^2]/(3K_v \cdot V) \qquad (15)$$

Figure 12 shows the regulation characteristic of the rectifier, obtained with the linear control through (14). It can be noted that the regulation is good enough to justify the simplification of the circuits with respect to the zero regulation control.

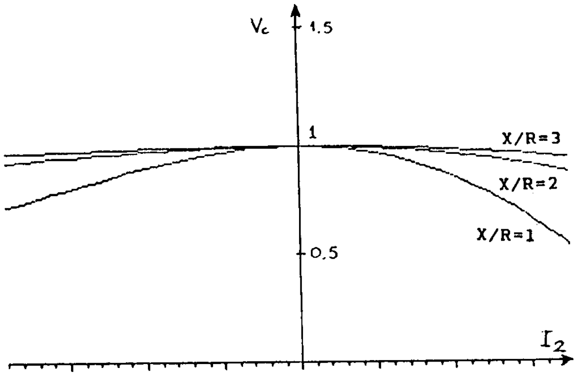

Figure 12. Vc-I_2 characteristic with linear control

7. EXPERIMENTAL RESULTS

A 2-kW prototype was implemented and tested to verify the analysis and computer simulations. Because of its simplicity, the linear control was implemented. One of the results is shown in figure 13, where a power reversal from inverter to rectifier operation is tested. The dc voltage has been adjusted to 250 volts and dc current changes from -6 to 5 amps.

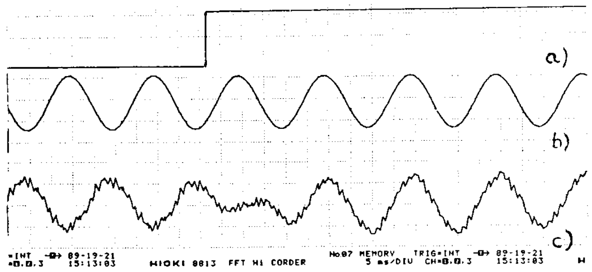

Figure 13. reversal of power operation
a) dc current from -6 to 5 A dc.
b) mains voltage, 90 V rms.
c) ac input current 5 A rms.

From figure 13 it can be seen that the current response of the rectifier at the ac side is quite fast. It is also possible to see that the system is operating at leading power factor before and after the transient, due to the addition of the θ_{OFFSET} angle already discussed. The quality of the ac currents can be improved depending on the PWM pattern stored in the EPROM. The pattern in this case has been generated from sinusoidal PWM with 15 pulses per cycle.

8. CONCLUSIONS

A 2-kW PWM voltage source rectifier controlled by the load dc current instead of the dc voltage has been developed and implemented. The rectifier has shown very fast dynamic response and strong stability, independent of the size of the dc capacitor. The simplifications introduced in this method of control with respect to the more conventional "direct current control" are: a) no need of input current sensors; b) no need of output voltage sensor; c) an unchangeable and unique PWM pattern to modulate the power transistors of the rectifier and d) power angle θ is directly controlled through the dc current load. Other interesting characteristics of this rectifier are: 1) zero regulation operation; 2) very simple control blocks and 3) leading power factor operation for all load conditions through the adjustment of the θ_{OFFSET} angle. Besides, it is possible to implement an even simpler circuit configuration by using linear control. All these characteristics were also obtained with the help of "valve-by-valve" digital computer simulations.

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