A Novel Load Current Control Method for a Leading Power Factor Voltage Source PWM Rectifier

Diego R. Veas, Juan W. Dixon, *Member, IEEE,* and Boon-Teck Ooi, *Senior Member, IEEE*

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.**

I. Introduction

THE new generation of voltage source, pulse width modulated rectifiers has reached a good performance level in terms of low harmonic distortion [1]–[3] and unity, or even leading power factor operation [4]. Power reversal by current reversal and good 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 close 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 method, the current sensors are eliminated, but then the system becomes more unstable [8]. These two methods of control require a dc capacitor large enough to ensure a good stability margin, making the system transient response slower. Fig. 1 shows a schematic circuit of the direct control rectifier, and Fig. 2 shows the indirect control

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.

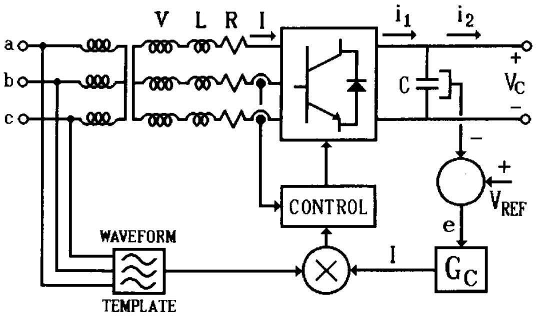

Fig. 1. Direct current control rectifier.

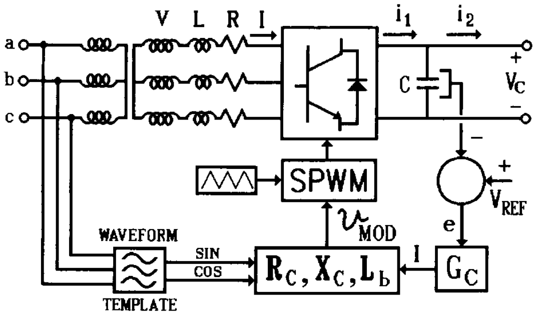

Fig. 2. Indirect current control rectifier.

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.

The work analyzes 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 behavior of the rectifier under static and dynamic operations. Finally, a 2-kW prototype has been implemented using "linear control," which has permitted the verification of the analyses and the digital simulations.

II. Principle of Operation

Fig. 3 shows the schematic of the proposed control system. The method used for controlling the rectifier is as follows:

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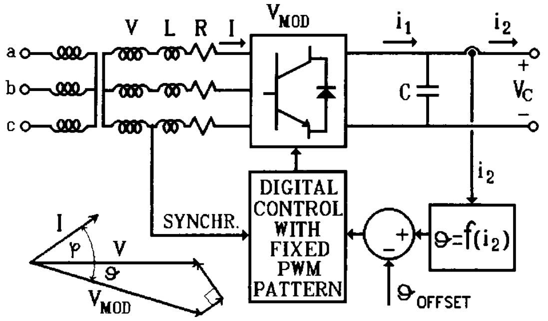

Fig. 3. Load current control rectifier.

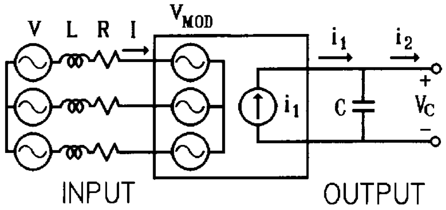

Fig. 4. Equivalent diagram.

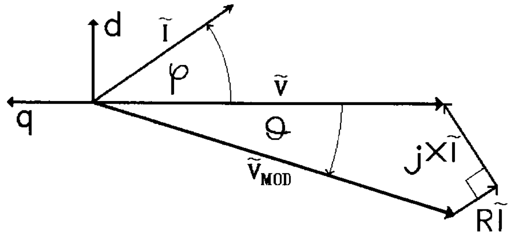

Fig. 5. Phasor diagram.

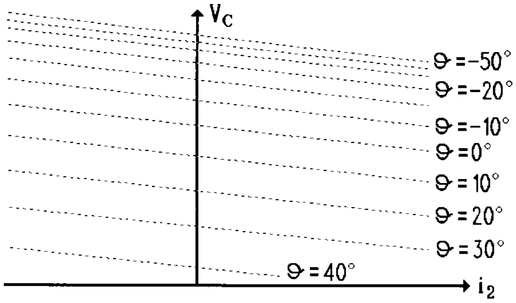

Fig. 6. Vc versus i_2 for different Θ angles ($X/R = 5$).

the voltage $V\mathrm{mod}$ 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 ($V\mathrm{\ mod}$ 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. As was already mentioned, 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."

III. 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 Fig. 4. In this figure, V is the fundamental phase-to-neutral mains voltage. $V\mathrm{\ mod}$ 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 allows us to have a defined dc voltage at the output terminals.

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

$$v_c \cdot i_1 = v\,\mathrm{mod}_d \cdot i_d + v\,\mathrm{mod}_q \cdot i_q. \qquad (1)$$

On the other hand, at the ac side, the phasor diagram establishes operating conditions between the mains and $V\mathrm{mod}$ (the modulated voltage) as shown in Fig. 5.

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

$$R \cdot i_d - X \cdot i_q = v_d - v\,\mathrm{mod}_d \qquad (2)$$

$$X \cdot i_d + R \cdot i_q = v_q - v\,\mathrm{mod}_q \qquad (3)$$

where

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

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

The rectifier works with a fixed PWM pattern, which means that there exists a linear relation between the amplitude of the modulated voltage $V\mathrm{mod}$ and the dc voltage Vc:

$$|V\ \mathrm{mod}\ | = Kv \cdot Vc. \qquad (6)$$

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 $V\mathrm{mod}$) is kept constant, the dc voltage will take a particular and well-defined value for each load current. By using (1)–(6), it is possible to derive an expression to see how the dc voltage Vc depends on the load current i_2 and the power angle Θ.

$$\begin{aligned} Vc = (V/Kv) \cdot [\cos\Theta - (X/R)\sin\Theta) \\ - i_2 \cdot (R^2 + X^2)/(3 \cdot Kv^2 \cdot R) \end{aligned} \qquad (7)$$

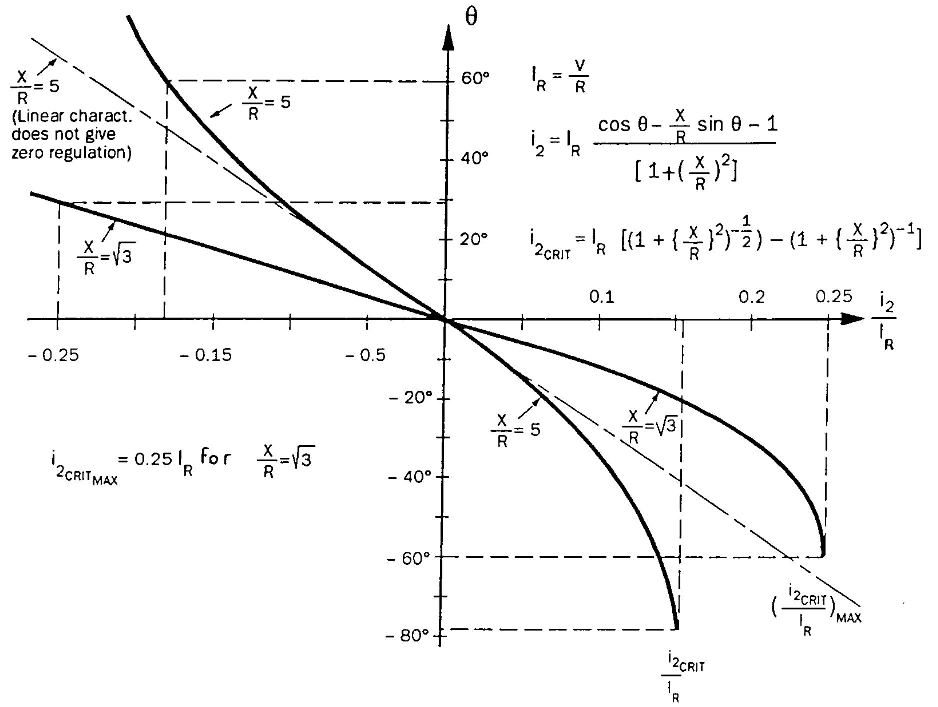

Fig. 7. $\Theta - i_2$ relation for Vc = constant.

where

$$\Theta = \mathrm{arctg}\,(v\,\mathrm{mod}_d/v\,\mathrm{mod}_q). \tag{8}$$

Equation (7) can be plotted to show how Vc is affected by the load current i_2, keeping the power angle Θ constant. Fig. 6 shows Vc versus i_2 curves, for different Θ angles.

IV. "ZERO REGULATION" CONTROL

From Fig. 6, it can be seen that it is possible to link the load dc current i_2 with the angle Θ to get zero regulation operation. To do that, Θ have to be modified each time the load current i_2 changes to ensure that Vc will be kept at the same value. First, it is required to choose an arbitrary value of voltage Vc. For example, $\Theta = 0$ for $i_2 = 0$ can be selected and, then, because of (7), the voltage Vc takes the value

$$Vc = V/Kv \qquad (\text{for } i_2 = 0 \quad \text{and} \quad \Theta = 0). \tag{9}$$

This arbitrary value of Vc form (9) can be replaced in (7) to get a $\Theta - i_2$ relation for zero regulation operation. Under these conditions, the voltage Vc will always be equal to V/Kv and also, because of (6), $|V|$ will be equal to $|V \bmod|$.

$$\begin{aligned}\cos\Theta - (X/R)\cdot\sin\Theta - 1 \\ = i_2\cdot(R^2+X^2)/(3V\cdot Kv\cdot R).\end{aligned} \tag{10}$$

Equation (10) allows us to plot the required $\Theta - i_2$ curves to get zero regulation operation, which means the same dc voltage for all load conditions. Fig. 7 shows these curves for two different values of X/R and $Kv = 1/3$.

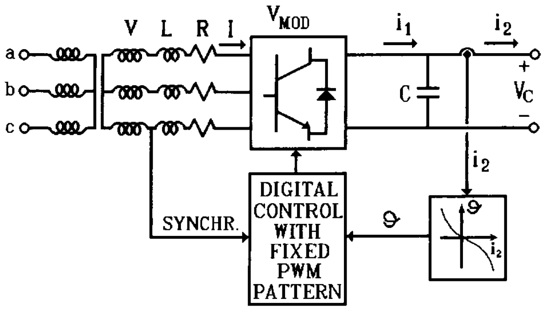

Fig. 8. "Zero regulation" PWM rectifier.

The relation plotted on Fig. 7 can be stored in a ROM memory, where the input is the digital value of i_2, and the output is the required power angle Θ to get zero regulation. A rectifier with this kind of control is shown in Fig. 8.

It is important to realize that the rectifier cannot maintain zero regulation beyond certain limits. From Fig. 7, it can be observed that there exists a limit for $i_2, I_{2\mathrm{CRIT}}$. Beyond this value, the dc voltage begins to fall. $I_{2\mathrm{CRIT}}$ is evaluated through $(di_2/d\Theta)$ and depends on the X/R relation. The optimum value for X/R, in terms of higher $I_{2\mathrm{CRIT}}$, is $\sqrt{3}$. $I_{2\mathrm{CRIT}}$ also depends on the V/R rate, which is normally greater than 100. For example, a rectifier working with $V =$ 110 V and $R = 0.5\,\Omega$ is able to keep zero regulation condition until $I_{2\mathrm{CRIT}} = 55$ amp for $X/R = \sqrt{3}$.

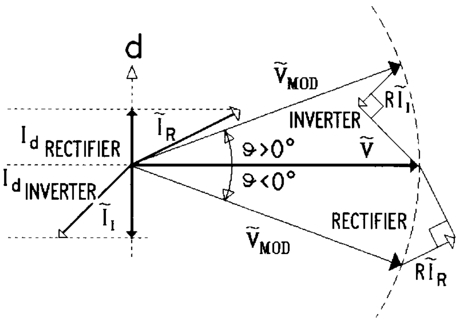

Fig. 9. Id magnitude under inverter and rectifier operation.

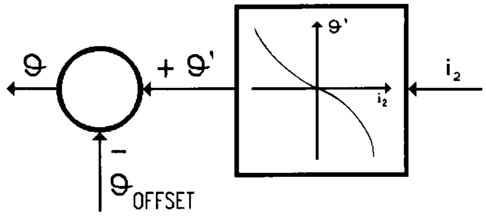

Fig. 10. Control block of the rectifier with Θ_{OFFSET}.

V. Leading Power Factor Operation

One important characteristic of the PWM rectifiers is that they can operate at leading power factor. In other words, they can generate reactive power. The amount of reactive power is given by $Q = 3 \cdot V \cdot I \cdot \sin \phi$. This equation, transformed to the d-q frame, can be written as

$$Q = \sqrt{3} \cdot V \cdot Id. \tag{11}$$

When $Id < 0$, the converter absorbs reactive power. To avoid that, it would be required to have $|V \bmod|$ greater than $|V|$; otherwise, the converter will work at lagging power factor under inverter operation. This is because when i_2 becomes negative, the $\Theta - i_2$ relation (given in Fig. 7) makes Θ positive and, then, if $|V \bmod|$ remains equal to $|V|$ because of (9), Id becomes negative. This is shown in the phasor diagram of Fig. 9.

A solution for this problem is to increase the magnitude of V mod . This is reached by adding a negative value of Θ in the control block, defined as Θ_{OFFSET}, which is shown in Fig. 10.

Θ_{OFFSET} shifts the power angle, allowing leading power factor operation also during power inversion. Let us first analyze the behavior of Θ_{OFFSET} when $i_2 = 0$. When Θ_{OFFSET} is modified, Vmod moves describing a circle, as shown in Fig. 11. Under these conditions, the rectifier works as a var compensator, which was described in detail in [10].

Now, adjusting Θ_{OFFSET} to a particular value and adding the required "zero regulation" linking curve shown in Fig. 7, a second circle diagram, which depends on i_2, is described. The radius of this circle is $|V \bmod|$, which is constant because the "zero regulation" control forces Vc to be constant. As Vmod and Vc are related through (6), it yields Vmod = constant. Fig. 12 shows this second circle diagram drawn with respect to the d-q axis. In this figure, the leading current limits for rectifier and inverter operation are clearly shown, and correspond to the dotted lines marked "cos $\phi = 1$" (unity power factor operation). From the geometry of the circles in Fig. 12, it can be seen that the power factor inside these limits is always leading but not constant.

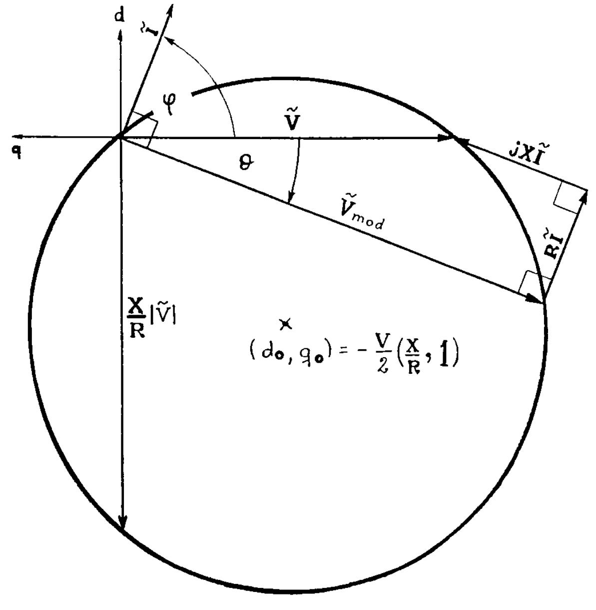

Fig. 11. The circle diagram for $i_2 = 0$.

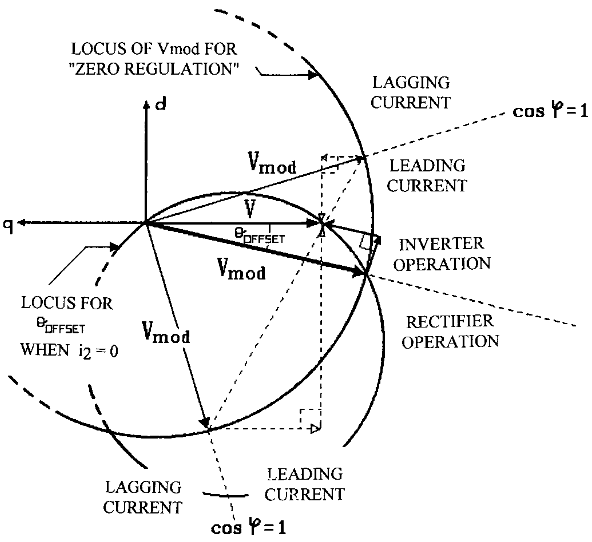

Fig. 12. "Zero regulation" circle diagram.

VI. Linear Control

Looking at Fig. 7 once again, it can be observed that the relation between Θ and i_2 is almost linear for normal currents ($i_2 < i_{2\mathrm{CRIT}}$). This behavior allows a simplification in the

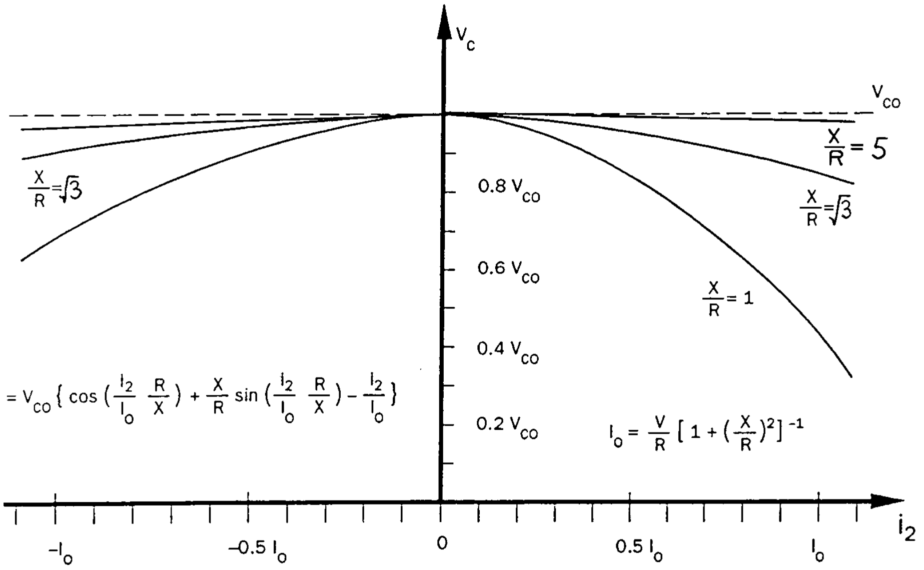

Fig. 13. $Vc - i_2$ characteristic using linear control.

control block by changing (10) for a very simple expression

$$\Theta = -Kc \cdot i_2. \tag{12}$$

Kc can be chosen by taking the tangent to the curve of Fig. 7 [cf. (10)] at the origin. This ensures adequate regulation near the origin for both rectifier and inverter operation. With this criterion,

$$Kc = (R^2 + X^2)/(3 \cdot Kv \cdot V \cdot X). \tag{13}$$

By replacing (12) and (13) into (7), we get

$$\begin{aligned} Vc = (V/Kv)[&\cos\{(R/X)\alpha\} \\ &+ (X/R)\sin\{(R/X)\alpha\} - \alpha] \end{aligned} \tag{14}$$

where

$$\alpha = i_2 \cdot R \cdot [1 + (X/R)^2]/(3Kv \cdot V). \tag{15}$$

Fig. 13 shows the regulation characteristic of the rectifier, obtained for the linear control through (14). It can be noted that the regulation may be good enough for some applications in order to justify the simplification of the circuits with respect to the zero regulation control. In the linear control, the ROM look-up table which relates i_2 with Θ is replaced by the simple proportional gain Kc given by (12).

VII. STABILITY

Assuming that the frequency of the PWM pattern is high enough, the harmonics can be neglected. Using the equivalent circuit given in Fig. 4 and analyzing the system through the d-q frame,

$$L \cdot di_d/dt + R \cdot i_d - X \cdot i_q = v_d - v\,\text{mod}_d \tag{16}$$

$$L \cdot di_q/dt + X \cdot i_d + R \cdot i_q = v_q - v\,\text{mod}_q \tag{17}$$

where

$$v\,\text{mod}_d = -\sqrt{3}|V\text{ mod }|\sin\Theta \tag{18}$$

and

$$V\,\text{mod}_q = -\sqrt{3}|V\text{ mod }|\cos\Theta. \tag{19}$$

These two differential equations, (16) and (17), represent the ac side of the rectifier. The differential equation for the dc side of the converter is

$$C \cdot dv_c/dt = i_1 - l_2 \tag{20}$$

where i_1 represents the output rectifier dc current, and i_2 is the forcing function. i_2 is also the load dc current. Input and output equations are related through the power balance equation given in (1). Replacing (18) and (19) into (1) and because of (6), i_1 can be evaluated in terms of i_d and i_q

$$i_1 = -\sqrt{3} \cdot Kv(i_d \cdot \sin\Theta + i_q \cdot \cos\Theta). \tag{21}$$

The Θ angle depends on the forcing function i_2 [cf. (10)] and then can be considered constant for the analysis. Replacing (4)–(6), (18), and (19) into (16) and (17),

$$L \cdot di_d/dt = -R \cdot i_d + w \cdot L \cdot i_q - K_d \cdot v_c \tag{22}$$

$$L \cdot di_q/dt = -w \cdot L \cdot i_d - R \cdot i_q - K_q \cdot v_c - \sqrt{3}V \tag{23}$$

where

$$K_d = -\sqrt{3} \cdot Kv \cdot \sin\Theta \tag{24}$$

and

$$K_q = -\sqrt{3} \cdot Kv \cdot \cos\Theta. \tag{25}$$

There are three unknown values in (22) and (23): i_d, i_q, and v_c. The third equation is obtained by replacing (21), (24), and

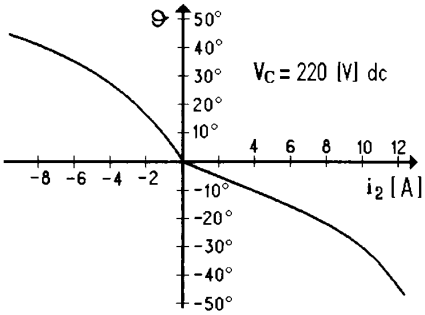

Fig. 14. $\Theta - i_2$ characteristic using linear control.

(25) into (20)

$$C \cdot dv_c/dt = K_d \cdot i_d + K_q \cdot i_q - i_2. \tag{26}$$

Equations (22), (23), and (26) can be written in the form:

$$\dot{\boldsymbol{x}} = [A] \cdot \boldsymbol{x} + \boldsymbol{B} \tag{27}$$

where

$$[A] = \begin{bmatrix} -R/L & w & -Kd/L \\ -w & -R/L & -Kq/L \\ Kd/C & Kq/C & 0 \end{bmatrix}. \tag{28}$$

The stability of the system can be found through the eigenvalues of the $[A]$ -matrix

$$\det\{S[I] - [A]\} = 0 \tag{29}$$

or

$$a_0 s^3 + a_1 s^2 + a_2 s + a_3 = 0. \tag{30}$$

Applying Routh's criterion ($a_j > 0$ for $j = 0, 1, 2, 3$ and $a_1 a_2 - a_0 a_3 > 0$), it is found that the system is stable if and only if $R > 0$ and $L > 0$. These two conditions are automatically satisfied because L is necessary for commutation and R is always positive. The analysis also shows, unlike other control methods, that the stability of this rectifier is independent of the size of the dc capacitor.

VIII. SIMULATIONS AND EXPERIMENTAL RESULTS

A 2-kW 120–250-V dc prototype was implemented and tested to verify the analyses. The PWM pattern has a carrier frequency of 15 times the fundamental with a modulation index $m = 1$. Some of the simulations and experimental results are displayed in the figures cited below.

Fig. 14 shows the $\Theta - i_2$ curve obtained experimentally to get "zero regulation" with the prototype implemented. It can be observed that this curve has a discontinuity in the origin due to the change of the value of "R" when the converter changes from inverter to rectifier operation and vice versa.

Fig. 15 shows the regulation characteristic of the prototype when linear control is used. Kc from (13) was chosen to take the value of "R" under rectifier operation. As "R" changes under inverter operation, the load dc voltage increases. This characteristic can be improved choosing a better value of Kc.

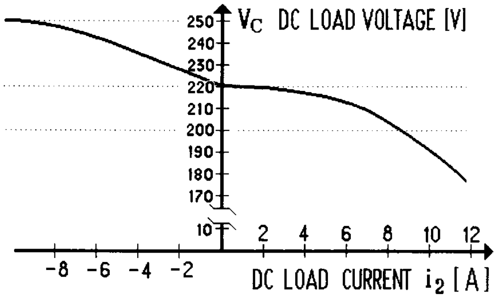

Fig. 15. Regulation for linear control.

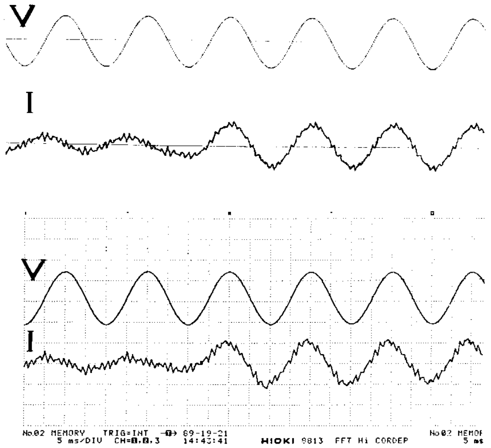

Fig. 16. Step response from 0 to 6 amps dc: (a) simulation and (b) experiment.

Fig. 16 shows (a) a simulation and (b) an experiment for a step response from 0 to 6 amp dc. Input voltages and currents are displayed for both cases. The dc voltage was adjusted to 220 V for $i_2 = 0$, and the ac voltage to 65 V rms (90 V peak).

Fig. 17 shows similar results for a power reversal from rectifier to inverter operation, with the same values of voltages. The dc current changes from 5 to −6 amps dc. It can be observed that the converter has a very fast dynamic response, reaching steady-state during the first cycle.

IX. 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 stability characteristics which are 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; and d) power angle 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

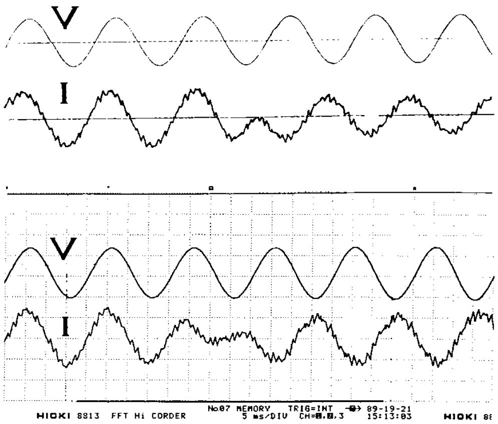

Fig. 17. Reversal of power from 5 to −6 amps: (a) simulation and (b) experiment.

for all load conditions, providing the adequate adjustment of the Θ_{OFFSET} angle.

Some of the drawbacks of this system are: i) the power factor is load dependent and, hence, despite the fact that it can be adjusted to be leading for all load conditions, is not constant; ii) under rectifier operation, there is a dc current value, $i_{2\mathrm{CRIT}}$, beyond which it is not possible to get "zero regulation control;" and iii) in practice, the resistance "R" is not constant and, hence, the curves $\Theta - i_2$ have to be obtained experimentally to get zero regulation.

A simpler circuit configuration was implemented for laboratory tests using "linear control." The linear control does not work with zero regulation but needs only a proportional gain instead of a ROM look-up table.

Finally, all the characteristics of the rectifier were also studied with the help of digital computer simulations.

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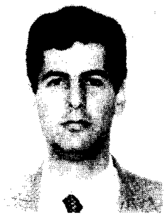

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