Compensated Carrier PWM Synchronization: A Novel Method to Achieve Self-Regulation and AC Unbalance Compensation in AC Fed Converters

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Abstract—**The compensated carrier PWM synchronization (CCPS) method for ac-fed PWM converters is presented. The method provides a solution to PWM converters fed by industrial power systems (IPS). Such environments usually present unbalances and magnitude fluctuations of ac voltages. Those circumstances impair standard PWM techniques because low-order harmonics (i.e., 2nd) are produced and dc-link regulation is poor. To reduce these undesirable effects produced by IPS, a method based on using independently compensated carriers per phase was conceived. In particular, CCPS prevents second harmonic generation and achieves converter self-regulation. The method can be used with any PWM technique and bidirectional power flow. The evaluation of CCPS is based on a complete performance comparison of a PWM rectifier with and without CCPS for various known PWM techniques.**

NOMENCLATURE

H = converter transfer matrix (3×1)
H_1 = first harmonic of the converter transfer matrix (H)
H_a, H_b, H_c = elements of H
H_{2w} = second harmonic amplitude of v_0
K_1 = constant that depends on the modulation technique.
M_0 = optimum modulating vector
M_{00} = ideal modulating vector
M_a, M_b, M_c = elements of M_0
P_f = input factor power
v_p = input phase voltage
v_{pa}, v_{pb}, v_{pc} = phase voltages
v_0 = output voltage
V_0 = average output voltage

I. INTRODUCTION

EXTENSIVE research has been conducted toward the development of fully controlled power semiconductors with impressive results [1]. Similarly, many contributions have been reported on the improvement of PWM techniques [2]. It is clear that the effectiveness and the full utilization of the advances in gated turn-off power semiconductors rely on the use of improved PWM techniques. This is because, when combined, they produce new converter structures and technological solutions with numerous advantages [3]–[7]. Among the wide variety of applications of the ever expanding use of PWM, the three-phase ac powered converter family requires particular attention. This is reasonable because the majority of industrial power systems (IPS's) are three-phase ac.

For medium- and large-power applications, the optimal use of the utility requires synchronization units capables of overcoming typical regulation and/or unbalanced conditions. Otherwise, nonregulated outputs and noncharacteristic low-frequency harmonics will be produced [3]. In SCR phase-controlled converters those undesirable effects are prevented with the widely used cosine-crossing synchronization method [8]. The above-mentioned method provides self-regulation and balances the three-phase input power of converters. Similarly, with the use of CCPS, PWM ac-fed converters will have many industrial applications. Specifically, CCPS is a synchronization method for PWM based on the use of compensated carriers per phase. Such solution is conceptually an extension of the cosine-crossing synchronization.

The main attributes of the method are to provide self-regulation and to prevent unnecessary waveform distortion (e.g., second harmonic generation in PWM rectifiers) while preserving the capability of bidirectional power flow. Those attributes are accomplished without compromising the characteristics of the particular PWM technique being used.

The implementation of CCPS requires signal processing of standard PWM carriers with logical and simple arithmetical operations. Moreover, a CCPS unit can be used

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as a modular synchronization unit that will work efficiently with any carrier PWM technique without any special requirement.

II. THE COMPENSATED CARRIER PWM SYNCHRONIZATION (CCPS) METHOD

A. Effects of AC Imbalances in PWM Rectifiers

In general, PWM provides power control with a power factor close to unity and shifts harmonic components to higher frequencies around a carrier. However, ac-fed PWM converters with unbalanced input voltages will produce low-order harmonic content. Specifically, the second harmonic is encountered at the dc output voltage of a PWM rectifier [3]. Therefore, unless compensation is performed an important property of PWM will be lost.

Typical carrier PWM techniques (e.g., SPWM [9], harmonic injection (HISPWM) [10] and trapezoidal (TSPWM) [11]) produce typical spectrum patterns. Fig. 1 shows the transfer matrix (TM) [12] and respective spectrum of the SPWM technique. The other two techniques produce similar patterns but with a 16.66% larger fundamental. Multiplying the TM with the input voltages (using trigonometric series) the second harmonic generated under unbalance becomes explicit. As expected, that magnitude depends only on the unbalances and the fundamental of the TM, which should be considered as a constant for a specified output voltage.

Table I shows the performance indexes required to perform an ac/dc evaluation of PWM under unbalanced input voltages, particularly the power factor at the ac input and the output average voltage at the dc output. Also, the magnitude of the second harmonic at the dc output is considered.

B. Description of the CCPS Rectifier

Fig. 2 shows a circuit scheme of a bridge rectifier implemented with gated turn-off semiconductors and a CCPS synchronization unit for PWM carrier compensation. It can be seen that the CCPS unit receives the input phase voltages and a voltage level and delivers compensated modulating carriers to be compared with the PWM technique normalized reference in the modulation unit. The normalized references can be stored in a memory to be read at synchronous speed. This scheme is specially suitable for PWM techniques with complicated references such as the HISPWM. The advantages of a digital implementation using the carrier amplitude to modulate have been shown in [13].

Fig. 3 show three modulating carriers and respective SPWM normalized references required by the modulation unit to produce the control signals of the rectifier. The method employed to compute the carrier amplitude is discussed next.

C. The CCPS Method

To cancel the negative effects caused by unbalanced inputs requires balancing the power per phase. Therefore, each phase must be compensated independently with "adjusted" modulation factors. In particular, the input voltage level (see Fig. 3) must be adjusted to define three modulation factors. Those are defined to be optimum if they produce maximum self-regulation and minimum second harmonic for given reference and input voltages. The optimum modulation factors or modulation vector M_0 can be implemented varying the relative magnitude between the technique's reference and the carrier. As shown in Figs. 2 and 3 the mechanism suggested here is to vary the carrier's amplitude.

Another important attribute that CCPS automatically adds to PWM converters is self-regulation. This property can be understood by considering that ac input voltage variations constitute a particular case of unbalance in which all phases are to be compensated. Therefore, the inner loop for voltage regulation becomes unnecessary.

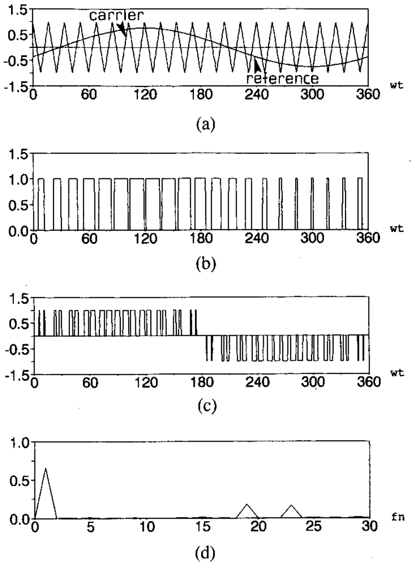

Fig. 1. The SPWM technique. (a) Reference and carrier. (b) SPWM phase variable. (c) IM of the SPWM [13]. (d) Spectrum of a SPWM-IM.

TABLE I
PERFORMANCE INDEXES FOR PWM RECTIFIER EVALUATION

Input Power Factor	Averge Output Voltge	Second Harmonic Amplitude
$P_f = \dfrac{\text{average power}}{\text{apparent power}}$	$V_0 = \dfrac{1}{T}\displaystyle\int_0^T v_0(t)\,dt$	$H_{2w} = (v_p^T \cdot H_1) - V_0$

D. The Optimum Modulating Vector M_0

To compute the algorithm required by the CCPS unit, the converter model presented in [13] is used. Thereby, the converter is characterized by its TM as follows:

$$H^T = [H_a \quad H_b \quad H_c] \tag{1}$$

where H_k are normalized line currents in this case (see

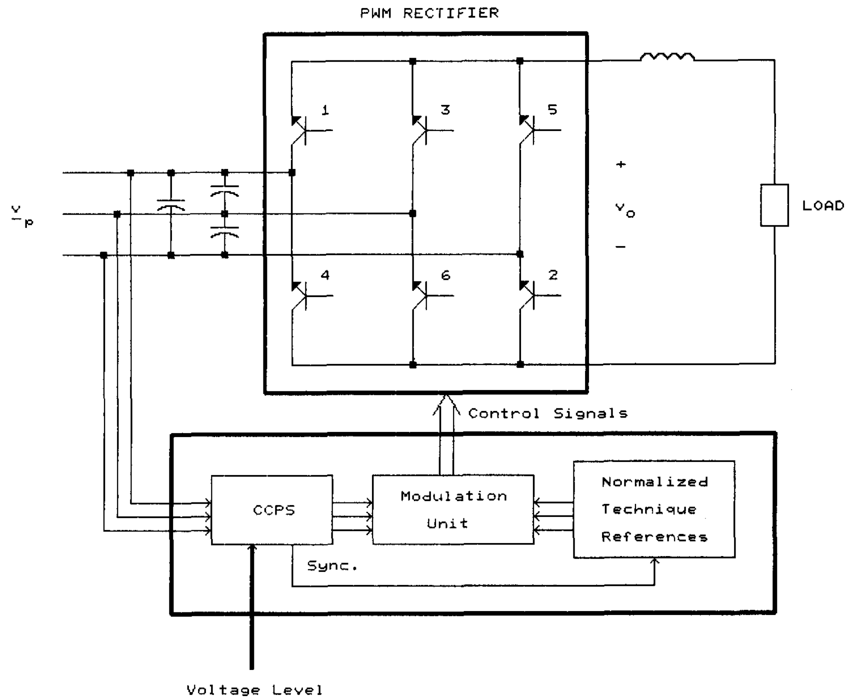

Fig. 2. CCPS bridge rectifier circuit schematic.

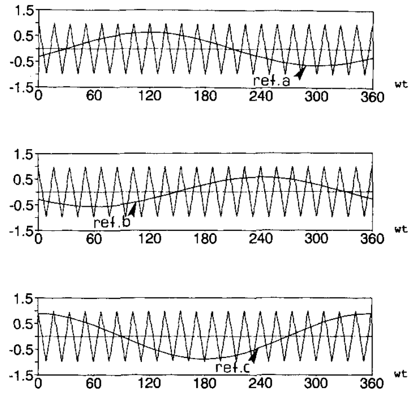

Fig. 3. Modulating carrier signals and SPWM normalized references.

Fig. 1(c)) and therefore

$$H_a + H_b + H_c = 0. \tag{2}$$

According to the CCPS method the elements of H must be a function of their respective modulation factors for a given PWM technique:

$$\boldsymbol{H}^T = [H_a(M_a) \quad H_b(M_b) \quad H_c(M_c)] \tag{3}$$

where

$$\boldsymbol{M}_0^T = [M_a \quad M_b \ M_c] \tag{4}$$

is the optimum modulating vector.

Using the model [13] the instantaneous output voltage is

$$v_0 = \boldsymbol{H}^T * \boldsymbol{v}_p \tag{5}$$

where v_p are the input phase voltages given by

$$v_0 = [H_a(M_a), H_b(M_b), H_c(M_c)] * [v_{pa}, v_{pb}, v_{pc}]^T. \tag{6}$$

Using (6) and considering V_a, V_b, V_c to be the input voltage amplitude, the output average voltage becomes

$$V_0 = K_1(M_a(V_c + V_a) + M_b(V_a + V_b) + M_c(V_b + V_c)) \tag{7}$$

and the second harmonic is

$$H_{2w} = K_1(3X^2 + Y^2)^{1/2} \tag{8}$$

where K_1 is a constant that depends on the modulation technique (given in Table II) and

$$X = -[M_aV_a + M_bV_b) + M_c(V_b + V_c) \tag{9}$$

$$Y = -M_a(V_a + 2V_c) + M_b(V_a + 2V_b) + M_c(V_b - V_c). \tag{10}$$

Expressions (7)–(10) are useful for evaluation purposes. To determine the optimum expression (8) must be minimized. However, there are physical restrictions for the maximum modulation factors; usually

$$-1 < M_k < 1 \qquad k = a, b, c. \tag{11}$$

Thus, depending on the degree of unbalance and the required voltage level, CCPS will not be able to fully eliminate the second harmonic (i.e., $H_{2w} = 0$). However,

TABLE II
CONSTANT K_1 FOR EXPRESSIONS (7) AND (8) WITH PROCESS REFERENCE EQUAL TO ONE

Technique PWM	k_1
SPWM	0.50
HISPWM	0.63
TSPWM	0.64

CCPS will always provide the maximum possible compensation if we minimize (8).

An ideal modulating vector M_{00} can be defined to obtain a fast minimization algorithm. This ideal modulating vector will achieve self-regulation and complete elimination of the second harmonic. Naturally, such vectors will not always be realizable according to (11). Therefore, using (8) with $H_{2w} = 0$,

$$M_{00} = [V_b, V_c, V_a]^T * \frac{3 * \text{Ref}}{V_aV_b + V_bV_c + V_cV_a}. \quad (12)$$

After the computation of M_{00} the modulating factors that exceed (11) are just truncated to obtain M_0 (optimum modulating vector). This can be explained from a practical point of view, because by doing so the CCPS unit will always try to balance the power to the PWM limit.

III. SIMULATED AND EXPERIMENTAL RESULTS

The theoretical analysis presented in Section II provides mathematical expressions to compute the average output voltage (7) and the second harmonic generation (8)-(10). The behavior of a PWM rectifier with normal/unbalanced input voltages and with/without CCPS becomes determined. In particular, normal input voltages implies ($V_a = V_b = V_c$ and $M_a = M_b = M_c$), unbalanced input voltages implies (($V_a \neq V_b \neq V_c$ and $M_a = M_b = M_c$), and unbalanced input voltages with CCPS means ($V_a \neq V_b \neq V_c$ and $M_0 = [M_a, M_b, M_c]$ as given by (11) and (12).

To verify the theoretical expressions a PWM rectifier, simulation using the transfer mtrix approach was performed. Therefore, every one of the input/output PWM converter waveforms is the result of signal processing, and respective spectrum results are obtained using FFT-tested subroutines. Moreover, to ensure the validity of the results a number of experimental tests were performed.

A. Computer Simulation

Fig. 4 shows the waveforms of the output voltage and respective spectra of a SPWM rectifier. In particular, Fig. 4(a) and (b) are obtained with the SPWM rectifier fed with unbalanced ($V_a = 1.4$ pu, $V_b = 1.0$ pu, $V_c = 0.9$ pu) voltages. The generation of the second harmonic becomes apparent in Fig. 4(d). Finally, Fig. 4(e) and (f) are obtained with a CCPS-SPWM rectifier fed with the same unbalance. As result of the CCPS, the generation of the second harmonic is replaced with harmless harmonics around the carrier.

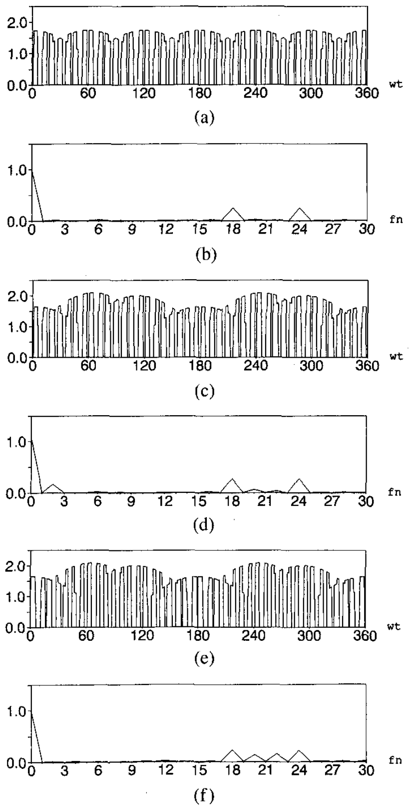

Fig. 4. SPWM rectifier output voltage, $f_{cn} = 21$. (a) Output voltage with balanced input. (b) Spectrum in (a). (c) Output voltage with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu. (d) Spectrum of (c). (e) Output voltage using CPS with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu. (f) Spectrum of (e).

Fig. 5 shows the waveforms of the input line currents and respective spectra of a SPWM rectifier. In particular, Fig. 5(a) and (b) are obtained with the SPWM rectifier fed with balanced voltages. Fig. 5(c) and (d) are obtained with the SPWM rectifier fed with unbalanced voltages. In Fig. 5(c) it can be seen as ''amplitude modulation'' the reflection of the second harmonic generated at the rectifier output. Fig. 5(e) and (f) are obtained with the CCPS-SPWM rectifier. Since the unbalance has been compensated the waveforms are similar to those shown in Fig. 5(a) and (b), respectively.

B. CCPS Evaluation

The CCPS method was evaluated computing the performance indexes summarized in Table I. The results are presented for a SPWM rectifier with and without CCPS for balanced and unbalanced input voltages. Fig. 6 shows the input power factor of an SPWM rectifier with unbalanced voltages. It can be seen that unbalances do not affect the input power factor. This means that this result is also valid for a CCPS-SPWM rectifier. Fig. 7 shows the effect of unbalances in the output average voltage. Fig. 7(a) shows the output average voltage variations with unbalanced input voltages. Fig. 7(b) shows the self-regulated output voltage of a CCPS-SPWM rectifier.

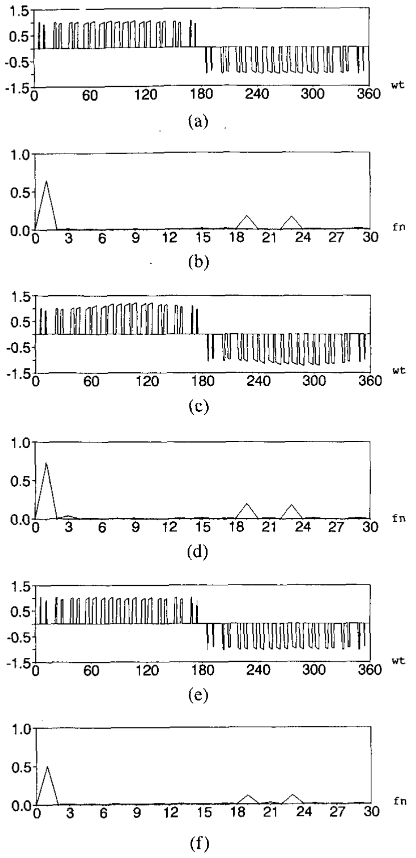

Fig. 5. SPWM rectifier inputs line currents with normalized carrier frequency $f_{cn} = 21$. (a) Input current with balanced input. (b) Spectrum (a). (c) Input current with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu. (d) Spectrum of (c). (e) Input current using CCPS with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu. (f) Spectrum of (e).

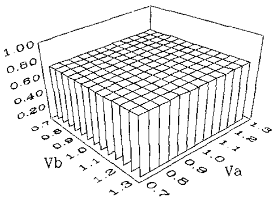

Fig. 6. Input power factor of a SPWM rectifier fed with unbalanced voltages.

Finally, Fig. 8 shows the second harmonic generation of a SPWM rectifier. In particular, Fig. 8(a) shows the second harmonic of a SPWM rectifier fed with unbalanced voltages and Fig. 8(b) shows the elimination of second harmonic of a CCPS-SPWM rectifier fed with unbalanced voltage.

It can be seen that for unbalances greater than (V_a = 0.8 pu, V_b = 0.8 pu, V_c = 1.0 pu and input voltage level = 0.75), it is only possible to reduce the second harmonic. Therefore, a gradual increase of the second harmonic is seen at the left corner of Fig. 8(b). To further compensate (for greater unbalances), the input voltage level range must be reduced.

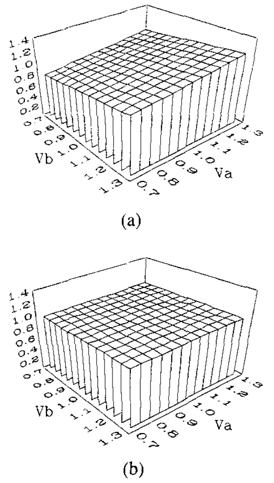

Fig. 7. Effects of unbalances in the output average voltage. (a) SPWM rectifier. (b) CCPS-SPWM rectifier.

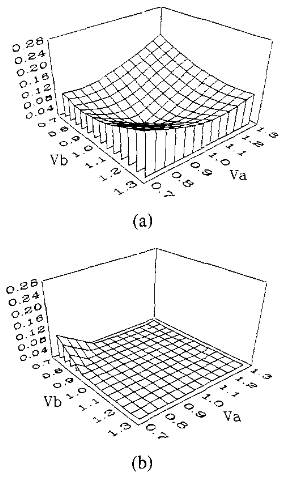

Fig. 8. Second harmonic generation under ac unbalance at the output dc voltage. (a) SPWM rectifier. (b) CCPS-SPWM rectifier.

C. Experimental Results

A 2-kVA breadboard unit of a SPWM rectifier was implemented to verify simulated results. Fig. 9(a) and (b) show the output voltage for the same unbalance used to obtain respective simulated output voltages (Fig. 4(c) and (d). Also, Fig. 9(c) and (d) show the compensated output voltage for such unbalance which should be compared with Fig. 4(e) and (f).

Finally, Fig. 10(a) and (b) show the input current under unbalance (simulated in Fig. 5(c) and (d)) and Fig. 10(c) and (d)) show the CCPS input current (simulated in Fig. 5(e) and (f)). Comparisons of predicted waveforms and experimental waveforms show an exact one-to-one correspondence.

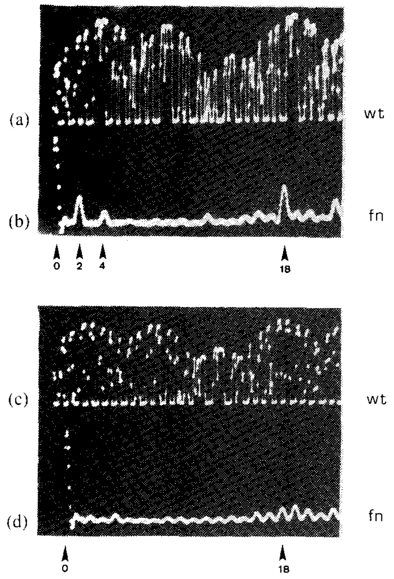

Fig. 9. SPWM rectifier experimental output voltage, $f_{cn} = 21$. (a) Uncompensated output voltage with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu (see also Fig. 4(c)). (b) Spectrum of (a) (see also Fig. 4(d)). (c) CCPS-compensated output voltage with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu (see also Fig. 4(e)). (d) Spectrum of (c) (see also Fig. 4(f)).

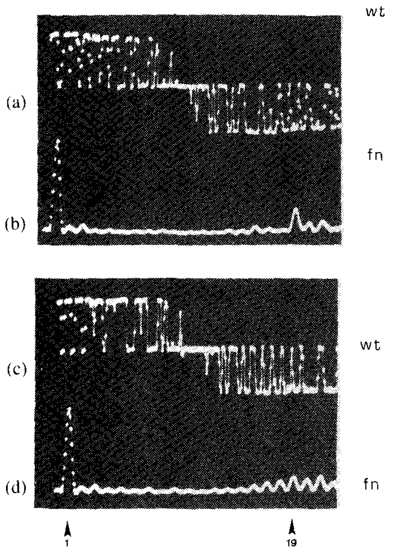

Fig. 10. SPWM rectifier experimental input currents, with normalized carrier frequency $f_{cn} = 21$. (a) Uncompensated input current I_a with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu (see also Fig. 5(d)). (b) Spectrum of (a) (see also Fig. 5(d)). (c) CCPS input current I_a with $V_a = 1.4$ pu, $V_b = 1.0$ pu, and $V_c = 0.9$ pu (see also Fig. 5(e)). (d) Spectrum of (c) (see also Fig. 5(f)).

It is interesting to mention that the CCPS compensation algorithm requires approximately 250 μs. This time ensures that CCPS can work with a normalized carrier of at least 21 for a 60-Hz input.

IV. Discussion

With the aim of producing distortion-free lightweight equipment the technological trend is to increase PWM carrier frequencies. This is reasonable because filtering requirements (weight and cost) decrease as the carrier frequency increase. Moreover, a number of improved power conversion schemes using ac-fed modulated converters have been proposed [3]–[6]. The elimination of second harmonics produce by the CCPS method will further improve the feasibility of those schemes.

V. Conclusion

A novel method to modulate and synchronize PWM ac-fed converters has been presented. The method should be used to compensate unbalances and voltage regulation of utility voltages regardless of the particular PWM technique being used. It has been demonstrated that the use of CCPS prevents low-order harmonic generation and provides self-regulation. Finally, using CCPS lightweight, self-regulated, high-performance PWM ac fed power conversion structures should be expected. Selected predicted results have been verified experimentally.

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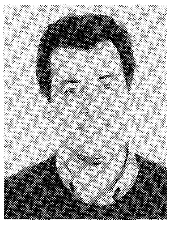

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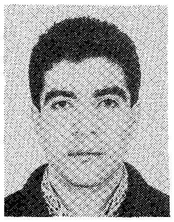

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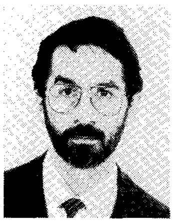

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