Unity Power Factor Control of a Three-pole PWM AC/DC Converter under Single-phase Input

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***Abstract*— This paper proposes a new control scheme for the three-pole pwm ac/dc converter under the extreme case of three-phase unbalanced input such as a two sinusoidal input with opposite phase and a center tapped neutral input. By nullifying the oscillating power inputs at the pole of the converter instead of the front-end, the positive and negative dq current references can be derived without a singular matrix problem. This control method allows the three-pole pwm ac/dc converter to generate a dc output without considerable even-order harmonics and to maintain unity power factor under the unbalanced input conditions of single-phase ac and the neutral point in the distribution transformer, which makes it possible to reduce the output dc-link capacitor and also to eliminate two inductors in two phases resulting in the reduced total cost. Simulation results confirm the feasibility of the new control method. A hardware implementation and experimental verification are in progress.**

I. INTRODUCTION

Single-phase ac input is the dominant type of utility power in the residential housings, office buildings, and small factories. The simple diode and thyristor full-bridge rectifier have been widely used to rectify single-phase ac source resulting in many disadvantages such as low power factor, dc output voltage of low quality, large dc-link reactors, and lack of bi-directional power flow. The pwm full-bridge rectifier can solve almost all of these problems [1]. If the mid or neutral point of the input voltage is accessible from the utility line or the popular distribution transformer in low voltage distribution line, then by adding another leg with a pole connected to this input mid-point the advantages of pwm rectifier can be greatly enhanced. This pwm full-bridge rectifier with an additional leg is equivalent to three-pole pwm rectifier having an unbalanced three-phase input source. Several modeling and control schemes covering the operation of the three-pole ac/dc pwm converter under the unbalanced input supply have been proposed to prevent the unbalanced input voltages from offsetting several advantages of the pwm ac/dc converter [1], [2], [3], [4]. However none of these approaches has addressed this particular type of unbalanced input; a center tapped single-phase input.

This paper proposes a new control scheme for the three-pole pwm ac/dc converter under the more general unbalanced input conditions including an extreme case of two sinusoidal input with opposite phase and a center tapped neutral input. The positive and negative sequence dq-components of the input voltages, pole voltages, and currents in the synchronous frame are employed to accurately describe the behavior of the ac/dc converter. On the basis of the newly proposed control criteria, the references of the input currents in the synchronous frame are obtained. The active and reactive power components each calculated at the front input, at the pole of the converter, and across the inductor demonstrate the fact that nullifying the oscillatory active power components at the pole of the converter can sufficiently achieve the dc output voltage of high quality.

II. MODEL OF THREE-POLE RECTIFIER UNDER GENERALIZED UNBALANCED OPERATING CONDITIONS

It is possible to represent an unbalanced three-phase input voltage without a zero sequence as the orthogonal sum of positive and negative sequence. E_{dq}^{p} and E_{dq}^{n} are transformed space vectors in the positive and negative synchronous rotating frame respectively.

$$E_{dqs} = e^{j\omega t} E_{dq}^{p} + e^{-j\omega t} E_{dq}^{n} = \frac{2}{3}(E_a + a\, E_b + a^2 E_c) \quad (1)$$

$$E_{dq}^{p} = \frac{2}{3}(E_a^{p} + a\, E_b^{p} + a^2 E_c^{p})\, e^{-j\omega t} = E_d^{p} + j\, E_q^{p} \quad (2)$$

$$E_{dq}^{n} = \frac{2}{3}(E_a^{n} + a\, E_b^{n} + a^2 E_c^{n})\, e^{j\omega t} = E_d^{n} + j\, E_q^{n} \quad (3)$$

where $a = e^{j(2\pi/3)}$.

I_{dq}^{p}, I_{dq}^{n}, V_{dq}^{p}, and V_{dq}^{n} can be defined in the same manner as in E_{dq}^{p} and E_{dq}^{n}. The conventional electrical equations on the ac side of the pwm ac/dc converter are shown in (4), (5).

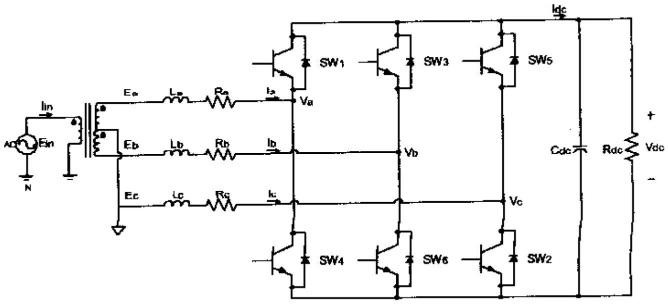

Fig. 1. Three-pole pwm ac/dc converter with input center tapped transformer.

$$E_{dq}^{p} = V_{dq}^{p} + L\frac{d}{dt}I_{dq}^{p} + j\omega L\, I_{dq}^{p} + R\, I_{dq}^{p} \tag{4}$$

$$E_{dq}^{n} = V_{dq}^{n} + L\frac{d}{dt}I_{dq}^{n} - j\omega L\, I_{dq}^{n} + R\, I_{dq}^{n} \tag{5}$$

The input complex power of the converter is given in (6). At most six real and imaginary terms are found in S_{in} considering only the first harmonics of the input voltage and current.

$$\begin{aligned} S_{in} &= E_{dqs}\, I_{dqs}^{*} \\ &= \frac{3}{2}\left(e^{j\omega t} E_{dq}^{p} + e^{-j\omega t} E_{dq}^{n} \right)\left(e^{j\omega t} I_{dq}^{p} + e^{-j\omega t} I_{dq}^{n} \right)^{*} \end{aligned} \tag{6}$$

$$\begin{aligned} S_{in} &= (P_{o}^{in} + P_{c2}^{in}\cos(2\omega t) + P_{s2}^{in}\sin(2\omega t)) \\ &+ j(Q_{o}^{in} + Q_{c2}^{in}\cos(2\omega t) + Q_{s2}^{in}\sin(2\omega t)) \end{aligned} \tag{7}$$

In order to cancel 120-Hz ripple in the dc output P_{s2}^{in} and P_{c2}^{in} are set to zero [2], [3]. The average reactive power exchanged between the utility source and the converter becomes zero by nullifying Q_{o}^{in} leading to unity power factor [2], [3]. These conditions are incorporated into the following matrix equation (8). The positive and negative dq-components of the currents in the synchronous frame are regulated to the reference values obtained from (9).

$$\frac{2}{3}\begin{bmatrix} P_{o}^{in} \\ Q_{o}^{in} \\ P_{s2}^{in} \\ P_{c2}^{in} \end{bmatrix} = \begin{bmatrix} \frac{2}{3}P_{o}^{in} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} E_{d}^{p} & E_{q}^{p} & E_{d}^{n} & E_{q}^{n} \\ E_{q}^{p} & -E_{d}^{p} & E_{q}^{n} & -E_{d}^{n} \\ E_{q}^{n} & -E_{d}^{n} & -E_{q}^{p} & E_{d}^{p} \\ E_{d}^{n} & E_{q}^{n} & E_{d}^{p} & E_{q}^{p} \end{bmatrix} \begin{bmatrix} I_{d}^{p} \\ I_{q}^{p} \\ I_{d}^{n} \\ I_{q}^{n} \end{bmatrix} \tag{8}$$

$$[\, I_{dq} \,] = [\, E_{dq} \,]^{-1} [\, S_{in} \,] \tag{9}$$

In the specific case of the unbalance condition introduced in this paper as shown in Fig. 1, this approach cannot be applied because the matrix of $[\, E_{dq} \,]$ is singular.

$$\begin{aligned} & E_{d}^{p} = -E_{d}^{n},\ E_{q}^{p} = -E_{q}^{n} \\ & \Rightarrow \mathrm{Det}\,[\, E_{dq} \,] = (E_{d}^{p})^{2} + (E_{q}^{p})^{2} - (E_{d}^{n})^{2} - (E_{q}^{n})^{2} = 0 \end{aligned} \tag{10}$$

III. PROPOSED CONTROL STRATEGY

The complex power in the dq reference frame is conserved not only in the whole but also in each term by term as expected from the orthogonality among average, cosine, and sine terms in real and imaginary part of the complex power; P_{o}^{in}, P_{c2}^{in}, P_{s2}^{in}, Q_{o}^{in}, Q_{c2}^{in}, Q_{s2}^{in}. Therefore if the terms of P_{s2}^{in} and P_{c2}^{in} are compensated in the inductors then P_{s2}^{out} and P_{c2}^{out} calculated at the three poles of the converter become vanished resulting in the dc output without 120-Hz ripple. This can also be achieved by regulating P_{s2}^{out} and P_{c2}^{out} to zero directly. Because the even-order harmonic contents in the dc output voltage are due to the oscillatory active power components applied through the three-pole ac/dc converter. The output complex power, S_{out} and the new version of matrix equations (8) and (9) are described as the followings.

$$\begin{aligned} S_{out} &= V_{dqs}\, I_{dqs}^{*} \\ &= \frac{3}{2}\left(e^{j\omega t} V_{dq}^{p} + e^{-j\omega t} V_{dq}^{n} \right)\left(e^{j\omega t} I_{dq}^{p} + e^{-j\omega t} I_{dq}^{n} \right)^{*} \end{aligned} \tag{11}$$

$$\frac{2}{3}\begin{bmatrix} P_{o}^{in} \\ Q_{o}^{in} \\ P_{s2}^{out} \\ P_{c2}^{out} \end{bmatrix} = \begin{bmatrix} \frac{2}{3}P_{o}^{in} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} E_{d}^{p} & E_{q}^{p} & E_{d}^{n} & E_{q}^{n} \\ E_{q}^{p} & -E_{d}^{p} & E_{q}^{n} & -E_{d}^{n} \\ V_{q}^{n} & -V_{d}^{n} & -V_{q}^{p} & V_{d}^{p} \\ V_{d}^{n} & V_{q}^{n} & V_{d}^{p} & V_{q}^{p} \end{bmatrix} \begin{bmatrix} I_{d}^{p} \\ I_{q}^{p} \\ I_{d}^{n} \\ I_{q}^{n} \end{bmatrix} \tag{12}$$

$$[\, I_{dq} \,] = [\, V_{dq} \,]^{-1} [\, S_{in} \,] \tag{13}$$

The determinant of the matrix $[\, V_{dq} \,]$ is not zero in this case, which makes it possible to obtain the four reference values of the currents in the positive and negative synchronous frame since the matrix of $[\, V_{dq} \,]$ is not singular any more.

The system block diagram is shown in Fig. 2. It is noted that there are newly added feedback path of V_{d}^{p}, V_{q}^{p}, V_{d}^{n}, and V_{q}^{n} from the space vector pwm block to current reference calculating block representing the matrix equation (13) as compared to the approach proposed in [3]. These feedback paths are realized inside the DSP controller as the program codes so that no additional hardware components are needed to complete these control schemes.

In this paper, the new algorithm of calculating the positive and negative dq-components of the input voltages in the synchronous frame(E_{d}^{p}, E_{d}^{n}, E_{q}^{p}, E_{q}^{n}) from the measured abc input voltages($E_{a}(t)$, $E_{b}(t)$, $E_{c}(t)$) is proposed. The control block that performs this function is named as "Extractor of positive & negative sequence dq components in synchronous frame". The detailed block diagram of this control algorithm is described in Fig. 4.

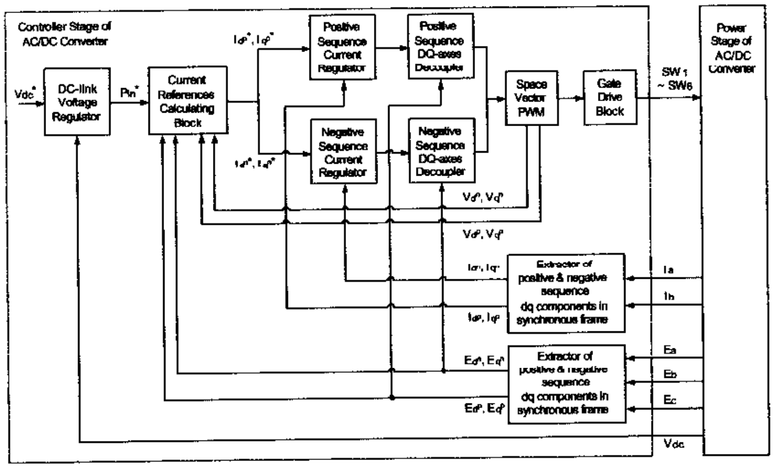

Fig. 2. System block diagram.

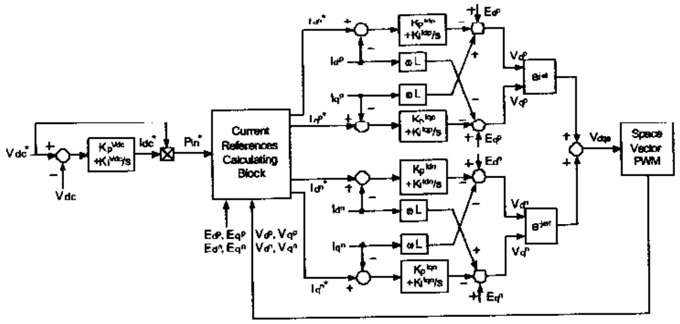

Fig. 3. Detailed control block diagram.

The previous works found in [2], [3] utilized the low pass filter to obtain the positive and negative dq-components. However, the use of a filter typically introduces measurement delay or phase delay of several cycles leading to the inefficient transient characteristics. The newly proposed control block in Fig. 4 generates the outputs within at most 2/3 of the input period under any type of unbalanced inputs.

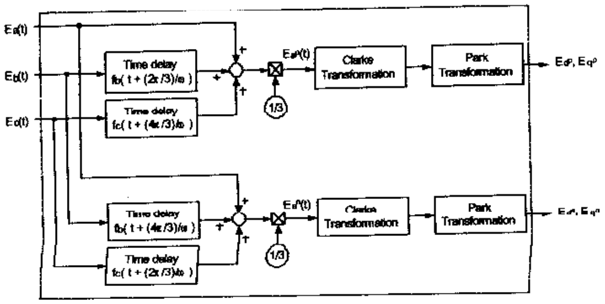

Fig. 4. Extractor of positive & negative sequence dq components in synchronous frame.

IV. SIMULATION RESULTS

The simulation was performed on the basis of two different control schemes, respectively. One is the control scheme introduced in [3](*Simulation-A*), and the other is the control scheme proposed in this paper(*Simulation-B*). The simulation conditions for each control scheme are summarized in Table I and II. In *Simulation-B*, L_a and L_b of 50 uH were chosen to model the internal leakage inductance in the distribution transformer as well as the utility line inductance, which eventually makes it possible to need only single external inductor in phase c, L_c.

The active and reactive power components at the front input of the converter, across the inductors, and at the poles of the converter are calculated using SIMULINK®. As for the case of *Simulation-A*, the calculation results are shown in Fig. 5-7. It is noted from Fig. 5-7 that the complex power in the dq reference frame is conserved not only in the whole but also in each term by term as expected from the orthogonality among average, cosine, and sine terms in real and imaginary part of the complex power. The input active power($P^{in}(t)$) in Fig. 5 is almost flat. This confirms the fact that P^{in}_{s2} and P^{in}_{c2} are to be zero in consistent with (8).

TABLE I

PARAMETERS USED IN THE SIMULATION-A [3]

Parameter	Value	Parameter	Value
La, Lb, Lc	2 mH	f	60 Hz
Vdc*	150 V	Ea	44cos(ωt) V
Rdc	120 Ω	Eb	28cos(ωt-95°) V
Cdc	2200 uF	Ec	50cos(ωt-214°) V

TABLE II

PARAMETERS USED IN THE SIMULATION-B

Parameter	Value	Parameter	Value
La, Lb	50 uH	Vdc*	300 V
Lc	10 mH	Cdc	100 uF
R	1 mΩ	Rdc	100 Ω
f	60 Hz	Ein	100sin(ωt) V

In *Simulation-B*, the three-pole pwm ac/dc converter is simulated under the extreme case of three-phase unbalanced input; a two sinusoidal input with opposite phase and a center tapped neutral input. The control scheme employed in *Simulation-A* cannot be applied in this case due to the problem of singular matrix as explained earlier in (10).

The waveforms in Fig. 8-10 are the active and reactive power components calculated at the same points as those of Fig. 5-7. The output active power($P^{out}(t)$) in Fig. 10 is almost flat as compared to the $P^{in}(t)$ in Fig. 5 of *Simulation-A*. This also confirms the fact that P^{out}_{s2} and P^{out}_{c2} are to be zero in consistent with (12).

The simulation waveforms in Fig. 12, 13 are obtained using SABER®. It is noted that V_{dc} is regulated within ±5 V around the nominal output voltage using C_{dc} of 100 uF. E_{in} and I_{in} are in-phase leading to almost unity power factor. These preferred results are accomplished by regulating the positive and negative dq-components of the input currents to the references of the currents calculated in (13).

The positive and negative dq-components of the input voltages in the synchronous frame(E^p_d, E^n_d, E^p_q E^n_q) obtained from the measured abc input voltages($E_a(t)$, $E_b(t)$, $E_c(t)$) through Extractor of positive & negative sequence dq components in synchronous frame are shown in Fig. 11. The abc input voltages($E_a(t)$, $E_b(t)$, $E_c(t)$) correspond to the unbalanced input condition in *Simulation-B*. The fluctuation of the output values in Fig. 11 for 2/3 of input period is due to the intrinsic characteristic of the algorithm that needs atmost 2/3 of input period(16.67 ms × 2/3 = 11.11 ms) to generate E^p_d, E^n_d, E^p_q, E^n_q.

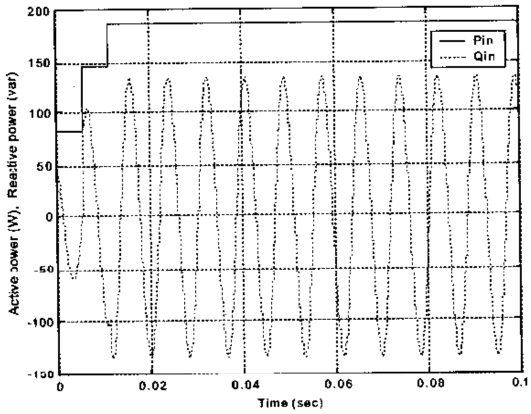

Fig. 5. Input active and reactive power in the dq synchronous reference frame of the simulation-A.

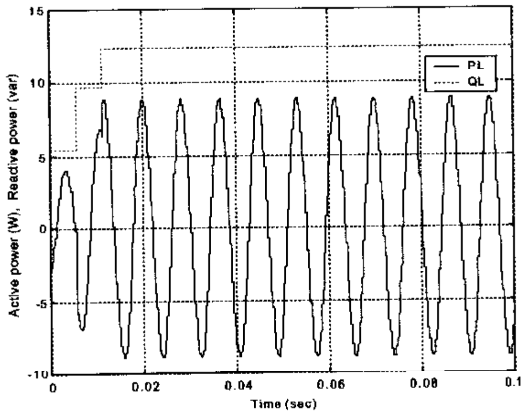

Fig. 6. Active and reactive power dissipated across the inductors in the dq synchronous reference frame of the simulation-A.

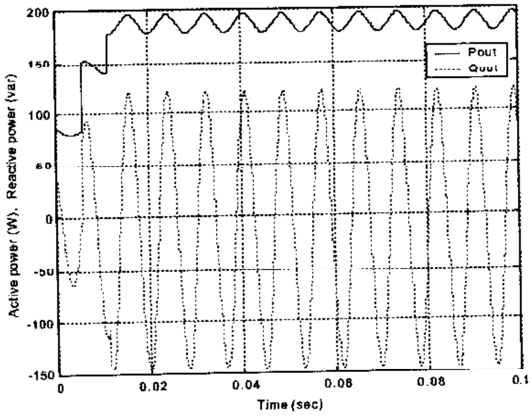

Fig. 7. Output active and reactive power in the dq synchronous reference frame of the simulation-A.

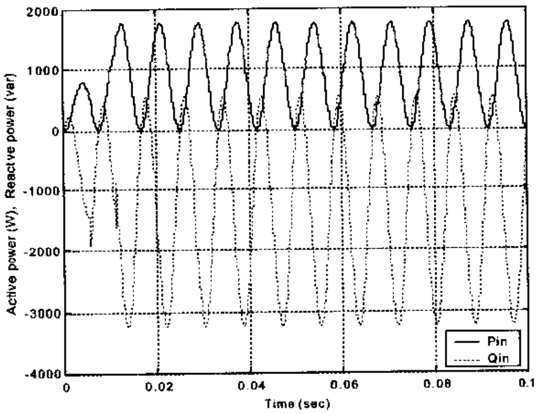

Fig. 8. Input active and reactive power in the dq synchronous reference frame of the simulation-B.

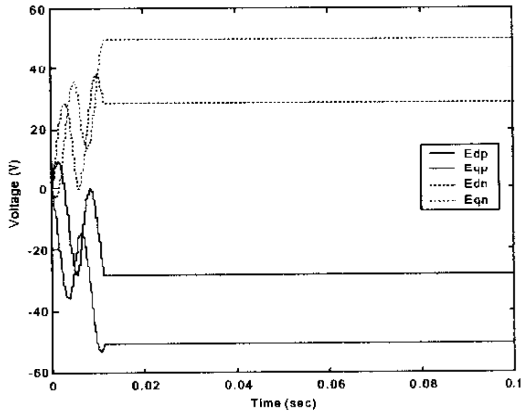

Fig. 11. Positive & negative sequence dq components of the input voltages derived from the Extractor Block in the simulation-B.

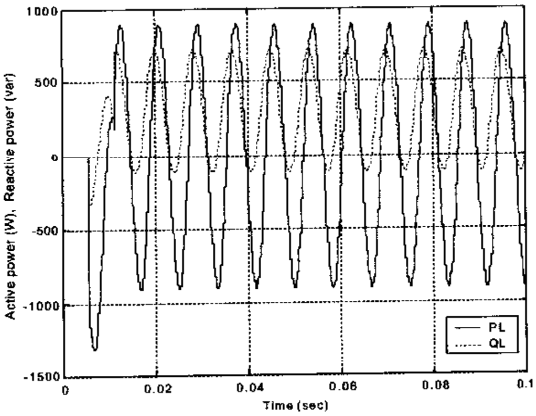

Fig. 9. Active and reactive power dissipated across the inductors in the dq synchronous reference frame of the simulation-B.

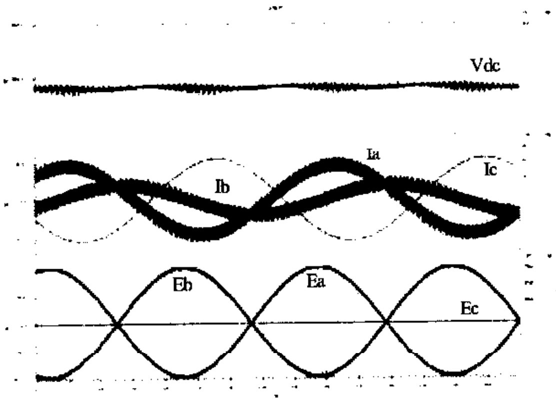

Fig. 12. Waveforms of the simulation-B.

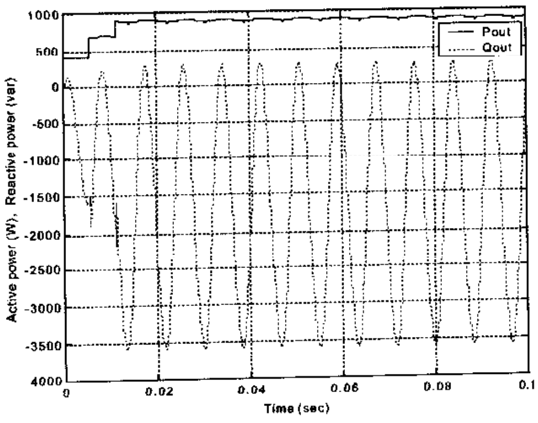

Fig. 10. Output active and reactive power in the dq synchronous reference frame of the simulation-B.

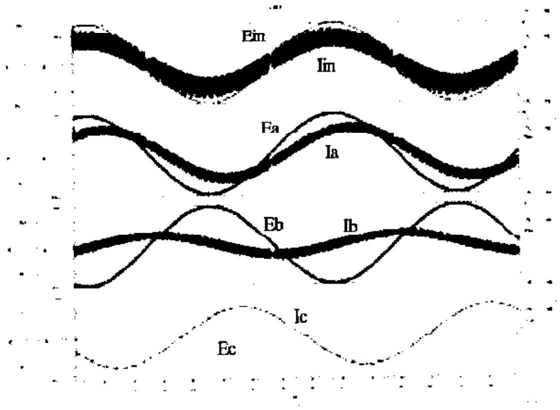

Fig. 13. Waveforms of the simulation-B.

V. CONCLUSION

This paper has proposed a new control method for the three-pole pwm ac/dc converter under the extreme case of three-phase unbalanced input such as a two sinusoidal input with opposite phase and a center tapped neutral input. By nullifying P_{s2}^{out} and P_{c2}^{out} instead of P_{s2}^{in} and P_{c2}^{in}, I_d^{p*}, I_q^{p*}, I_d^{n*}, and I_q^{n*} can be derived without a singular matrix problem. A proposed control scheme needs the new feedback path of V_d^p, V_q^p, V_d^n, and V_q^n from the space vector pwm block to current reference calculating block in no additional cost compared to the scheme proposed in [3].

The simulation results were presented to verify the proposed control scheme. The dc output without considerable even-order harmonics and unity power factor in the ac side of the rectifier under the unbalanced input conditions of a two sinusoidal input with opposite phase and a center tapped neutral input make it possible to reduce the output dc-link capacitor dramatically and also to eliminate two ac side inductors leading to the reduced total system cost. A hardware implementation and experimental verification are in progress.

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