Investigation of The impact of Unbalanced and Non-sinusoidal Supply Voltages on Converters

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***Abstract*—In this paper two input current modulation strategies for matrix converters are experimentally analyzed under two different supply conditions: sinusoidal unbalanced voltages and non-sinusoidal balanced voltages. Both strategies use the Space Vector Modulation (SVM) technique in order to control the matrix converter accordingly to the input and output constraints. Strategy A modulates the input currents keeping the corresponding space vector in phase with the input voltage vector. Strategy B operates in order to keep the input current vector in phase with the positive sequence fundamental component of the input voltage vector. A comparison between the two strategies is made in terms of the reduction of the input current disturbances due to the unbalanced and non sinusoidal voltage on the grid. It is found that a dynamic current modulation strategy, independent of the voltage disturbances such as Strategy B, is more effective for the reduction of the RMS value of input current disturbances. The validity of the theoretical investigation i.e. the effectiveness of the current modulation strategy conforms to experimental tests result carried out on a matrix converter prototype.**

***Index Term*—Converters, disturbance, non-sinusoidal, unbalanced load.**

I. INTRODUCTION

THE performance of the matrix converter topology has been widely discussed and different approaches have been proposed to determine the proper control strategy [1-3], [10-12], [14]. The relatively small reactive component in the DC link is one of the significant advantages of the matrix converters. However, due to the lack of internal energy storage, the matrix converter is sensitive to disturbances in the input voltages. In general, the modulation strategies for matrix converters are developed under the assumption that input voltages are sinusoidal and balanced, but in reality to some extents, the supply is very often unbalanced and distorted as the result of non-linear loads connected to the grid. Under this distortion condition, low-order harmonics in the output voltages but also harmonics in the input currents will be apparent [9]. In order to overcome these problems and then to improve the input power quality, it is of practical interest to investigate the performance of matrix converters under non ideal supply voltages.

Previous researches have shown the possibility to obtain balanced and sinusoidal output voltages even if the input voltages are unbalanced [4]-[7]. It has also been shown that the power disturbance of this kind will disturb the critical services such is in a healthcare facility and/or hospital [10-11]. By using proper modulation strategies, it is possible to reduce or to eliminate up to the significant level the input current harmonics under unbalanced supply voltages. Another paper explains a general approach to predict the behavior of matrix converters using the SVM technique under normal as well as unbalanced and non-sinusoidal supply voltages [8]. The input current harmonics are determined by linearization of the input/output equations. Using this method, the investigation of converter performance under any condition determined by input disturbances is now possible to be conducted.

This paper investigates a new current modulation strategy, which by keeping the input current vector in phase with the positive sequence component of the fundamental frequency of the input voltage vector, it enable us to reduce the harmonic of the input current of the matrix converter operating under unbalanced and/or non-sinusoidal supply voltages. Similarly, this paper also proves the validity of linearization approach techniques (from which the analytical results presented in this paper are derived) explained in the previous paper [13]. [15-16].

Two input current modulation strategies have been considered and experimentally tested. The performance in terms of the quality of the input current is emphasized as well as highlighting agreement and discrepancy with the theory. A prototype of a three-phase to three-phase matrix converter has been used. Experimental results are presented for both input current modulation strategies under two different non ideal supply voltage conditions.

II. INPUT CURRENT ANALYSIS UNDER UNBALANCED NON-SINUSOIDAL SUPPLY

Assuming that the matrix converter uses ideal switches, the input power flow equals the output power flow at any instant, then

$$\frac{3}{2} e_i \, . \, i_i = P_0 \tag{1}$$

where P_0 represents the output power, i, is the input line current vector and e, is the input line to neutral voltage vector, henceforth called input voltage vector. Assuming that the input current is modulated along the direction of an arbitrary space vector ψ, which is called a modulation vector, yields

$$\psi . j i_i = 0 \tag{2}$$

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Solving Eqs. 1 and 2 with respect to i_i leads to

$$i_i = \frac{\frac{4}{3}P_0}{\overset{*}{e_i}\psi + e_i\psi^*}\psi \tag{3}$$

Under balanced output conditions and neglecting the high order and switching harmonics P_o is constant. Eq. (3) is a general expression for the input current vector in matrix converters as a function of the output power, the input voltage vector and modulation vector. It can be further developed once the modulation law for the input current is chosen. In this paper two modulation strategies are compared. Strategy A is based on keeping the input current vector in phase with the input voltage vector. Strategy B is based on keeping the input current vector in phase with the positive sequence fundamental component of the input voltage vector.

In general, the input/output equation (3) cannot be used to obtain the harmonic content of the input currents. However, for practical values of voltage disturbances, an approximate solution can be obtained using a general approach based on the linearization of Eq. (3). The analysis is carried out by assuming the input voltage vector given by two terms: the first vector represents a system of balanced and sinusoidal supply voltages and the second vector represents a small input voltage vector disturbance. With these assumptions the input voltage and current vectors can now be written as

$$e_i = E_{i_1} e^{j\omega_i t} + \Delta e_i \tag{4}$$

$$i_i = \frac{2P_0}{3E^*_{i_1}} e^{j\omega_i\ t} + \Delta i_i \tag{5}$$

Where: *eEi*1 represents the positive sequence OF fundamental component of the input voltage vector. The modulation space vector ψ, along which the input current is modulated, can be similarly expressed as

$$\psi = E_{i_1} e^{j\omega_t t} + \Delta\psi \tag{6}$$

A representation of the main space vectors is shown in Fig. 1. Strategy A is obtained with $\Delta\psi = \Delta e_1$ and Strategy B with $\Delta\psi = 0$

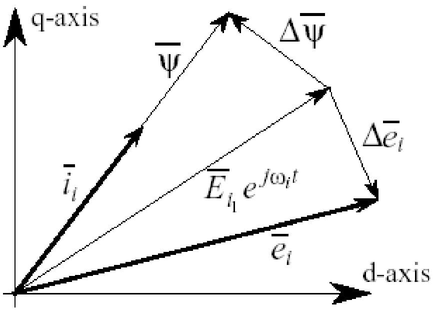

Fig. 1. Representation of the main Space Vector.

The input voltage vector disturbance can be decomposed in complex Fourier series as

$$\Delta e_i = \sum_{-\infty}^{+\infty}{}_{k\neq 1} \Delta E_{i_k} e^{jk\omega_t t} \tag{7}$$

Substituting (4)-(7) in (3) and neglecting second-order effects, leads to:

Strategy A

$$i_i = \frac{2P_0}{3E^*_{i_1}} e^{k\omega_t t} - \frac{2P_0}{3E^{*2}_{i_1}} \sum_{-\infty}^{\infty}{}_{k\neq 1} \Delta E_{ik} e^{j(2-k)\omega_i t} \tag{8}$$

Strategy B

$$\begin{aligned} i_i = {} & \frac{2P_0}{3E^*_{i_1}} e^{k\omega_t t} - \frac{P_0}{3\left|E_{i1}\right|^2} \sum_{-\infty}^{\infty}{}_{k\neq 1} \Delta E_{ik} e^{jk\omega_1 t} \\ & - \frac{P_0}{3E^{*2}_{i_1}} \sum_{-\infty}^{\infty}{}_{k\neq 1} \Delta E^*_{i_k} e^{j(2-k)\omega_i t} \end{aligned} \tag{9}$$

Using Strategy A, a harmonic component of order *k* in the input voltage disturbance produces a harmonic component of the input current disturbance of order 2-*k*. Using Strategy B, a harmonic component of order *k* of the input voltage vector disturbance produces two input current harmonic components of orders *k* and 2-*k* with amplitude one half of that in (8). It is possible to demonstrate analytically that Strategy A will produce the lowest total RMS value of the input current, whereas Strategy B represents the optimal modulation strategy which determines the lowest total RMS value of the input current turbulence.

III. EXPERIMENTAL DESIGN: DESCRIPTION

The two modulation strategies were tested on a 7 kVA matrix converter prototype, feeding a three-phase star connected R-L load (R = 12.5 Ω and L = 0,027 H). The diagram of the test system is presented in Fig. 2.

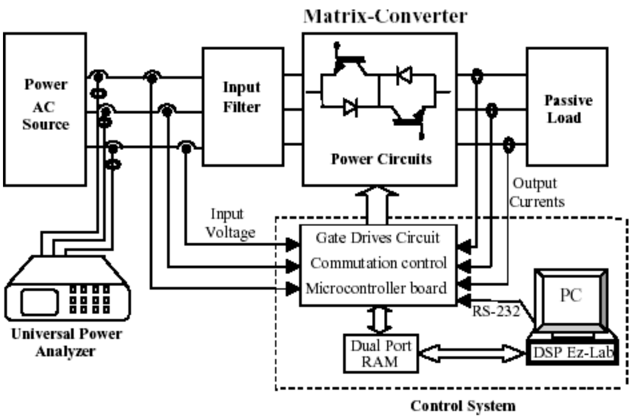

Fig. 2. Block Diagram of Experimental Design.

An AC Power Source (15003 iX California Instruments) was used to generate the operating supply conditions. A second-order LC filter was used at the input side of the matrix converter to reduce the input line current ripple. It comprised of three inductors connected in series (1.2 mH) and three shunt capacitors (6 μF).

The frequency of the input voltages is 50Hz The power stage of the matrix converter was based upon three specially designed power modules and made with 1200V, 25A IGBT's and fast recovery diodes. Each module contained three AC switches and each AC switch comprised of two anti-parallel IGBT's in common collector configuration with a series diode. A single common clamp circuit protected the converter on the input and on the output side. The control system of the matrix converter comprised of a dual processor: a floating-point 32/40 bit digital signal processor (DSP) SHARC 21602 and a fixed-point 16-bit microcontroller (μC) SAB80C167. The DSP provides fast calculations, while the μC is used to generate the SVM pulses pattern. A standard PC computer provides the user with an interface to the DSP and the μC.

IV. IMPLEMENTATION OF THE TWO STRATEGIES

In Strategy A, the reference angle of the input current vector is continuously synchronized to the input voltage vector angle which can be easily determined through the acquisition of the Instantaneous values of the input voltages. In Strategy B, the reference angle of the input current modulation vector is synchronized with the phase angle of the positive sequence fundamental component. This synchronization has been achieved by means of a digital filtering action applied to the input voltage vector. A first order low pass filter is used on a d-q reference frame rotating at the fundamental positive angular speed ω_i. The state equation of the digital filter, truncated at the second order, in the stationary reference frame is then

$$\begin{aligned}\tilde{e}_i(k+1) = {} & \left[1+(D+j\omega_1)T_c^2\right]\tilde{e}_i(k) \\ & +\left[-\frac{1}{2}DT_c-\frac{1}{2}D\left(D+j\omega_1\right)T_c^2\right]e_1(k) \\ & +\left[-\frac{1}{2}DT_c\right]e_1(k+1)\end{aligned} \tag{10}$$

Where $\tilde{e}_i$ is the filtered input voltage vector, D is a filter parameter, T_c is the cycle period (250 μS), k is the sampling instant.

V. EXPERIMENTAL RESULTS

The matrix converter was controlled in order to generate a three-phase system of balanced sinusoidal, line to neutral, voltages with a maximum amplitude of 132.5 V -0.43 transfer ratio- and a frequency of 25 Hz. The matrix converter used an optimized SVM pulse pattern for control. [13] A four-step commutation strategy provides a semi-soft switching for the bi-directional AC switches. The switching frequency is 4 kHz in all measurements. The harmonic components of the three input currents were measured using a PM 3000 A Universal Power Analyzer (Voltech), a TDS 3014 Oscilloscope (Tektronix), and an AM 503 Current Probe Amplifier (Tektronix). Both modulation strategies (A & B) were tested in two cases with different supply voltage conditions.

Case 1: The input voltages are sinusoidal and unbalanced (see Fig. 3) and defined as follows:

$$E_{i_1} = 300\angle 0^0 V \quad E_{i_{-1}} = 30\angle 0^0 V \quad u = \frac{\left|E_{i_{-1}}\right|}{\left|E_{i_1}\right|} = 0.1$$

Where u represents the degree of input unbalance. In this case, the disturbance is

$$\Delta e_i = E_{i\_k} e^{-j\omega_i t} \tag{11}$$

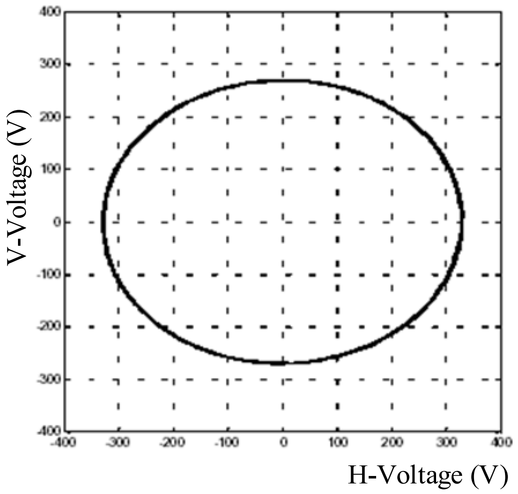

Fig. 3. Locus of the input voltage Vector in Case 1.

Fig. 4 shows the waveform of line current input using Strategy B.

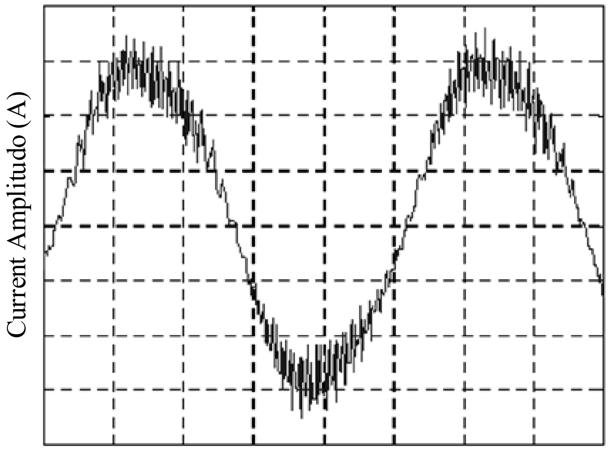

Fig. 4. Input line current. Strategy B 1 Amp/div.

The corresponding input current harmonic spectrum is shown in Figure 4 and compared to the one obtained using Strategy A. For display purposes, in all the following figures representing harmonic spectra, the scale of the y-axis is linear and limited to 20% of the fundamental component amplitude. In Fig. 5, it is evident that the 3rd harmonic component will be reduced if strategy B is used. The effect on the line current harmonic distortion factor (THD$_i$) can be clearly seen in Table I.

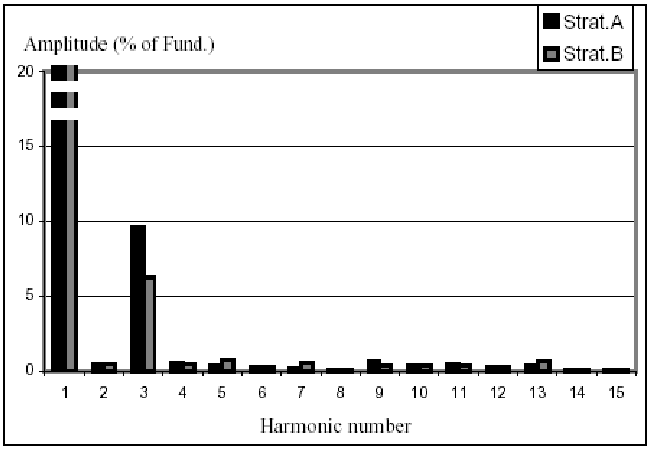

Fig. 5. Comparison of Input Line Current Spectrum

TABLE I
CURRENT HARMONIC DISTORTION FACTOR (CASE-1)

Strategy	Case 1 – THD$_i$ (% of the fundamental)		
	Line a	Line b	Line c
Strategy A	9.7	9.7	9.1
Strategy B	6.4	6.4	5.9

The results shown in Table I and in consecutive tables are calculated using Eq. (12) to show further evidence of the strategies effectiveness (only the first 15 harmonic components are taken into account). The difference in the line values is due to a slight physical asymmetry of the input side of the system setup that is observed during the tests.

$$THD_i = \frac{\sqrt{\sum_{K=2}^{15} I_{K_{\max}}}}{I_{1_{\max}}} \tag{12}$$

With regard to Strategy A, it can be observed that the amplitude of the 3rd and 5th harmonic components is *u* and u^2 respectively, as predicted by the theory [6].

Case 2: The input voltages are balanced but non-sinusoidal (see Fig. 6) and defined as follows [8].

$$E_{i_1} = 300\angle 0^0 V \quad E_{i_{+7}} = 15\angle 0^0 V \quad E_{i_{-11}} = 9\angle 0^0 V$$

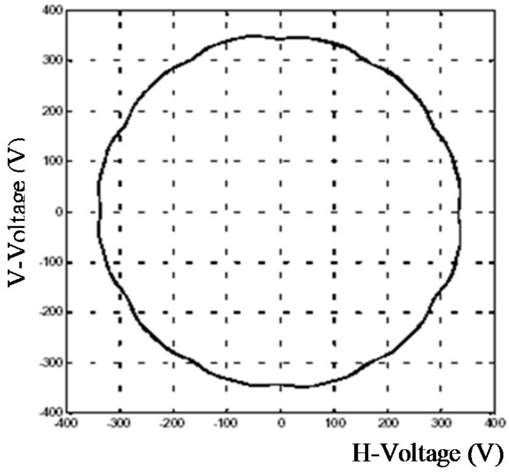

Fig. 6. Locus of the input voltage Vector in Case 2.

In this case, the disturbance is given by:

$$\Delta e_i = \Delta E_{i_{+7}} e^{j7\omega_t t} + \Delta E_{i_{-11}} e^{j-11\omega_t t} \tag{13}$$

Fig. 7 shows a comparison of the input line current harmonic spectra for Strategy A and Strategy B.

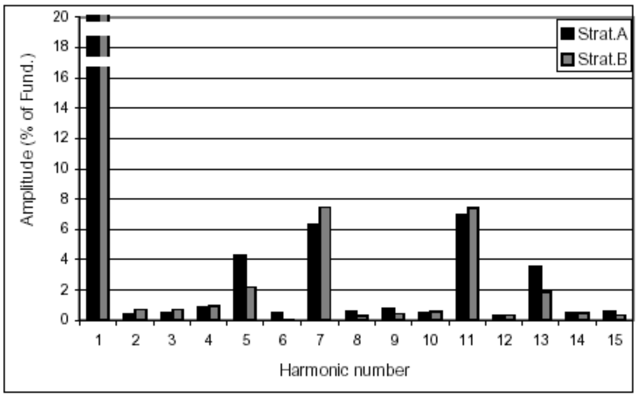

Fig. 7. Comparison of Input Line Current Spectrum.

In Table II the corresponding THD$_i$ values are given. It can be noted that there is no improvement when Strategy B is used instead of Strategy A. Actually; the improvement is offset by the current drawn by filter capacitors.

TABLE II
CURRENT HARMONIC DISTORTION FACTOR (CASE-2)

Strategy	Case 2 – THD$_i$ (% of the fundamental)		
	Line a	Line b	Line c
Strategy A	11.1	11.5	11.3
Strategy B	11.1	11.4	11.5

Two remarks have to be made here. The first is that the two modulations aim to control just the load current, the matrix converter input current. The second is that a voltage harmonic component which is present on the grid produces an equal order current harmonic component to be drawn by the filter capacitors. The percentage of such harmonic component in the line current spectrum decreases when the converter input current increases e.g. the power flow to the load increases. On the contrary, the current harmonic components introduced by the modulation strategies maintain approximately constant amplitude.

In order to exclude the effect of the filter capacitor currents from the line current harmonic spectrum and bring evidence of the better performance of Strategy B compared to Strategy A, we proceed the following three steps:

i) The input line current waveform was firstly acquired, by an oscilloscope, with matrix converter not operating;
ii) The input line current waveform was secondly acquired with the matrix converter operating to a certain load;
iii) The first waveform was subtracted to the second one and a Fourier analysis was performed to get waveform as shown in Fig. 7. The waveform acquisitions at point i) and ii) were synchronized to the same input line to neutral voltage.

Fig. 7 shows spectrum comparison in which the contribution of the filter capacitors current at no load has been subtracted.

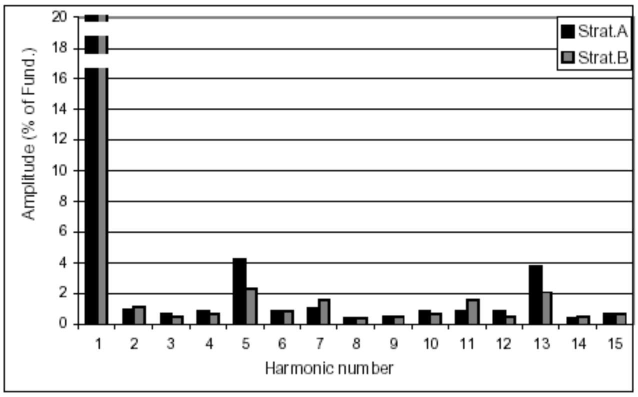

Fig. 7. Converter Input Current harmonic Spectrum Comparison.

Table II clearly shows that Strategy B, if compared to Strategy A, brings about a significant reduction of the input current disturbance. The THD$_i$ values shown in Table 3 are calculated on the basis of the harmonic component values reported in Fig. 7.

TABLE III
COMPARISON BETWEEN THD OF STRATEGY A AND B

Strategy	Case 2 – THD$_i$ (% of the fundamental)		
	Line a	Line b	Line c
Strategy A	6.2	6.0	5.7
Strategy B	4.6	4.4	4.0

Referring to Figure 6 it can also be spotted that the amplitude of the harmonic components is nearly halved if strategy B is used instead of using strategy A and thus two new harmonic components appear. Such results are in a good fit with the theoretical results obtained by the linearization [14] (see also Eq. (8) and Eq. (9)). Both Case 1 (unbalanced and sinusoidal supply conditions) and Case 2 (balanced and non-sinusoidal supply conditions) indicates that the experimental results conform with the analytical solutions, which in turn show to the validity of the linearised analysis approach in estimating the effects of any given input voltage disturbance. Fig. 8 demonstrates the comparison of harmonic of converter input line current as captured by an oscilloscope in the experiment. Fig. 9 represents an output line current using modulation Strategy B (for Strategy A the waveform is actually the same).

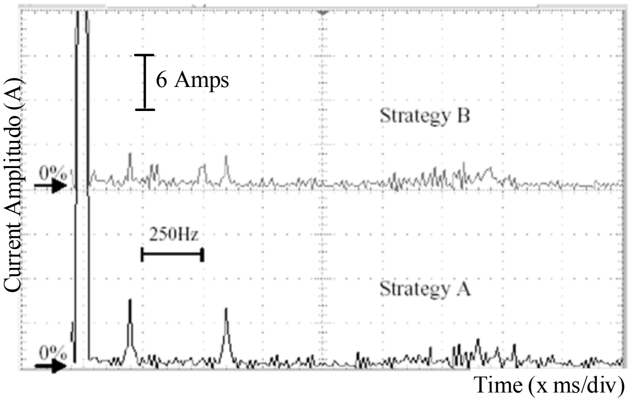

Fig. 8. Converter Input Current harmonic Spectrum Result from Oscilloscope (2.6% per Div).

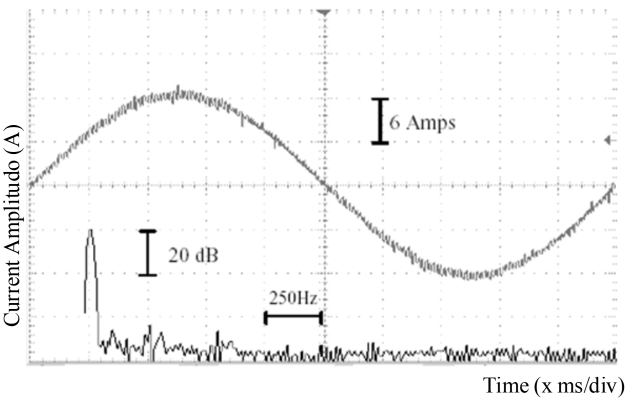

Fig. 9. Output Line Current and harmonic Spectrum for strategy B. Case-2.

It shows that as far as the compensation of the input supply voltages disturbances is concerned, both strategies perform very well since distortion is not significant.

IV. CONCLUSION

Two input current modulation strategies for space vector controlled matrix converter are presented and experimentally tested on a 7kVA laboratory prototype in Laboratory. To some extents, it has been proved that based on the test, theoretical investigations and experimental results demonstrates approximately the same result in both modulation strategies. Therefore, the linearised analysis approach should be considered as a suitable tool in predicting the effects of a certain input voltage disturbance on the grid. Strategy B, if compared to Strategy A has been proven to reduce the input current disturbances either with sinusoidal and unbalanced supply voltages or balanced and non-sinusoidal supply voltages. It is also concluded that from an input power quality viewpoint, Strategy B is preferable to Strategy A.

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