

# A Duple Quasi-Sinusoidal Waveform Elicitation from Matrix Converter Based on Orthogonal Strategy

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This paper has scrutinized an effective approach regarding to how to elicit double quasi-sinusoidal waveform with orthogonal angles that can be applicable for two-phase induction motors. Hither, to be more precisely declared, a switching strategy is proposed so that the provided voltages by Matrix Converter (MC) i.e., A and B phases have  $90^{\circ}$  difference with each other. This switching strategy assists two-phase induction motors aimed at operating in appropriate state. As the created frequency is an important item for this motor, matrix converter can also undertake this function. It is worth mentioning that, the switching is somehow performed until bio-directional switches couldn't be simultaneously triggered and withal taken place in the accurate switching order. Its related circuit in order to producing appropriate current and voltage has been tested considering MATLAB Simulink and experiment. The simulation result is extracted with respect to inductive and resistive load. Meantime, PWM method is carried out to extract experimental results that clearly show its effectual performance.

**Index Terms:** Two-phase induction motor, matrix converter, orthogonal phase, AC/AC converter, switching strategy.

## 1. Introduction

Providing voltage with an appropriate frequency is regarded as one of prominent issues in power electronic field [1, 2]. This issue will be appeared whereas multi-phase machines to be fed with this voltage [3].

The most prominent features of multi-phase machine with respect to three-phase machine can be here introduced: great torque density, good efficiency, low torque pulsations, good fault tolerance, and decreased rating per inverter leg [4, 5]. Furthermore, noise efficiency of the drive is appropriately enhanced. The multi-phase machine limitations lead to engage power electronic converter aimed to phase conversion owing to three-phase supply [6, 7].

Two-phase Induction motors have been widely utilized in many different industrial applications. The rotor's synchronous speed has been controlled using the number of poles as well as the frequency

of voltage. Two-phase induction motor efficiency driven via the inverter is referred in [8, 9]. It can acquire the different ranges of speed for controlling these kinds of motors, which is based on operating by fixed-frequency square wave, and also is fed using a DC power supply. To obtain wide range control of the frequency, the phase difference angle approaches along with the selected harmonic elimination PWM method are reported in [10, 11] so that an appropriate output voltage with wide range frequency is obtained. Ref. [12] presents an inverter to drive two-phase asymmetrical induction motors, whereas encompasses six transistors [13].

For such applications, a direct PWM AC/AC can play an important role and acquire more advantages namely: one converting process, simple structure, small size and lower cost price. In past decades, several converter structures have been introduced [14].

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Apart from that, AC to AC converters have been widely applied for induction motor drives. Such converters have been diurnally attracting so many attentions by scholars and industrial applications owing to the presence of the best switching devices [15]. At the present time, these devices engage IGBT's or CBT's switches in a complex formation [16], [17]. In recent years, the performed research in this regard of progress of modulation approach for voltage source inverter (VSI) as well as current source inverter (CSI) to acquire several harmonic elimination and optimization strategies that employ a SVM method optimized for a special target and decrease the low order harmonics.

In several implementations the frequency and amplitude of voltage are connected via a permanent relationship, e.g., providing an output voltage with a permanent magnetizing current in drive system of induction motor.

Matrix Converters (MC), AC to AC converter, can directly turn an AC voltage into an AC voltage with variable amplitude and frequency without any encompassing great energy storage capacitors. Also, it can easily decrease the low order harmonics at the expense of increased high order components and create proper input power factor operation. Even so, employing the real time of PWM switching could be complex. It is presented that how Matrix Converter [18, 19] can employ a SVM with minimum low order harmonics alongside of no grow of switch number.

Matrix converter is firstly suggested by Venturini and Alesina in 1979 that currently is the most famous AC to AC direct converter families [18, 19]. The small input filter is required to propagate the high-frequency order of switching.

Matrix converters solve the issue of turning AC voltage from one frequency to different frequency. They have several advantages as compared to converters based on the DC-link [20]. Appropriate characteristics of matrix converters are generally sinusoidal input and output waveforms that bidirectional energy flow and minimum energy storage and controllable power factor (PF) [20]. The MC removes the engagement of DC voltage link that supply average power [21, 22], and it is also able altering both the magnitude and frequency of voltage. It can acquire the maximum outputs voltage provided it should be utilized line to line voltages or space vector modulation. Anyhow, this paper suggests an approach to use AC to AC theory to obtain a standard control level without need to any supplementary switching devices. This converter kinds are simply constructed with several attractive characteristics; its prominent feature is adjustable PF [23, 24].

It is worth mentioning that matrix converters are optimum alternative of the minimum switch number and filtering elements viewpoint. The output voltage of matrix converter is an optimal criterion based on the limitation of constant modulation frequency, minimum harmonic distortion and determined fundamental power factor at the inputs.

In this paper an effective approach based on double quasi-sinusoidal waveform with orthogonal angles is proposed so that two-phase induction motors can be applicable. In this regard, Matrix Converter (MC) provides A and B phases with  $90^\circ$  difference with each other. The relevant switching strategy applicable for two-phase induction motors has been well performed. Furthermore, the related circuit in order to producing appropriate current and voltage has been tested considering Matlab Simulink and experiment. The results elicited by both the simulation and experiment have been done considering inductive and resistive loads. Finally, the experimental results confirm the effectual performance of proposed approach.

## 2. Analayse

In this part of study, the operation of  $m \times n$  matrix converter hither considering  $m = 3$ ,  $n = 2$  which  $m$  and  $n$  are respectively the number of input phase and output phases [25] is considered. In fact, this structure encompasses  $3 \times 2$  bidirectional switches. Fig. 1, presents the input power supply including three-phases with  $120^\circ$  phase shift. Likewise, this simulation has been carried out using MATLAB/SIMULINK. Two-phase with difference of  $90^\circ$  has been created for the load. Each switch in the MC encompasses two diodes and two MOSFETs as well as snubber circuit to keep them from voltage spikes at turning off times. Surely, by soft switching system protection of circuit will be effectively done. Aiding input filter leads to discard the switching effects in the input voltage and current. By means of this switching system which is based on semiconductors receive more attention aimed to avoid overvoltage. The overvoltage leads to destructive events in the semiconductors' structure. One of the effective and standard approaches to avoid overvoltage is application of clamp circuit, which is given in Fig. 1. It must be mentioned that soft-switching system makes power consumption trivial in clamp circuit.

All input three phases currents and voltages i.e.,  $i_A, i_B, i_C$  and  $v_A, v_B, v_C$  and also output voltages are  $v_a, v_b$  which have orthogonal state.

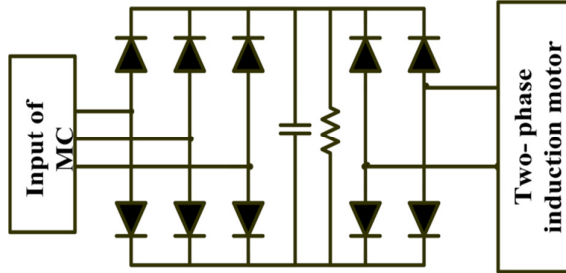


Fig. (1): Single line diagram of the clamp circuit

$$i_o(t) = \begin{bmatrix} i_A(t) \\ i_B(t) \end{bmatrix} = \begin{bmatrix} I_i \cos(\omega_i t) \\ I_i \cos(\omega_i t + \pi/2) \end{bmatrix} \quad (1)$$

$$v_i(t) = \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = \begin{bmatrix} v_i \cos(\omega_i t) \\ v_i \cos(\omega_i t + 2\pi/3) \\ v_i \cos(\omega_i t + 4\pi/3) \end{bmatrix} \quad (2)$$

$$v_o = \begin{bmatrix} v_a(t) \\ v_b(t) \end{bmatrix} = q \cdot \begin{bmatrix} V_i \cos(\omega_o t) \\ V_i \cos(\omega_o t + \pi/2) \end{bmatrix} \quad (3)$$

The output voltages gain i.e.,  $q$  in each modulation system might have dissimilar value that is defined by employed modulation strategy or either the line-line or phase-neutral.

### 3. Equation

Any switch in the matrix converter can be connected or disconnected with an appropriate combination of the conduction states. Venturini presents [26] this output voltage for phases (4):

$$[V_{out}] = [S] \times [V_{in}] \quad (4)$$

$S$  is determinative matrix in order to conditioning of each switch in an instant. Of course, in matrix converter just one closed switch in a column for each time instance is possible. That (5) is revealed:

$$\sum_{i=A,B,C} S_{ij} = 1 ; j = \{a, b\} \quad (5)$$

And also the output voltages are:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \end{bmatrix} \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \quad (6)$$

It can be presented that modulations are determined as follows:

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} \\ S_{Ba} & S_{Bb} \\ S_{Ca} & S_{Cb} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (7)$$

It is worth mentioning that 86.6% voltage ratio is upper value for any modulation method whereas the output voltage refrence is the same as the mean output voltage in time of each switching sequence. Venturini has proofed the presented declaration in

[18, 19]. Thus, the output voltage can be represented by (8):

$$[v_o(t)] = [M(t)] \times [v_i(t)] \quad (8)$$

$M(t)$  indicates the matrix that presents an accurate time period that the input voltages must be connected to the two-phases induction motor. Yet, three-phases to two-phase induction motor can be obtained by:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \end{bmatrix} = \begin{bmatrix} m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t) \end{bmatrix} \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \quad (9)$$

Furthermore, the output and input currents can be given as follows:

$$[i_i(t)] = [M(t)]^T \times [i_o(t)] \quad (10)$$

Venturini confirms matrix  $M$  has two parts that expressed in [18, 19]. As explained, aimed to obtain the maximum gain in both induction motor inputs, in whole  $T$  (sample time) and  $t_{ij}$  is the duty cycle, matrix  $M$  can be represent by:

$$m_{ij} = \frac{t_{ij}}{T} = \frac{1}{3} \left[ 1 + \frac{2v_k v_i}{v_i^2} \right] ; i = \{A, B, C\} ; j = \{a, b\} \quad (11)$$

Using optimal approach of venturini in [18, 19], the duty cycle for each switch can be computed of the following relationship, switch of matrix converter must be closed in an accurate time that given in (12) for each switch:

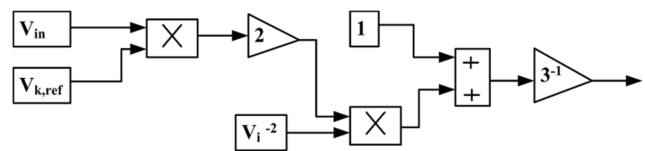
$$t_{ij} = m_{ij} \times T ; i = \{A, B, C\} ; j = \{a, b\} \quad (12)$$

The output voltage for each phase cosidering low frequency component can be expressed by:

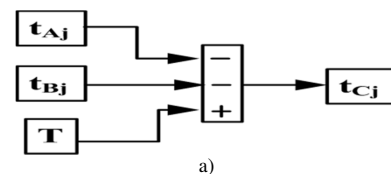
$$v_{jn} = \frac{t_{Aj} v_A(t) + t_{Bj} v_B(t) + t_{Cj} v_C(t)}{T} ; j = \{a, b\} \quad (13)$$

### 4. Simulation

Fig. 2 presents a block diagram to simulate Eq. (1) in order to figure out matrix  $m$ :


 Fig. (2): Block diagram for matrix  $M(t)$  production

The most prominent requirement that must be considered is producing the matrix  $S$ . Fig. 3 presents the switching functions of  $j$ th output phase. This block determines that how matrix  $m$  should be produced:



a)

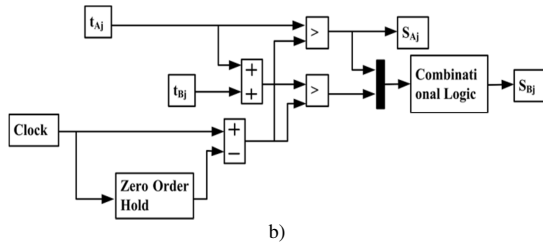


Fig. (3): a) Achieving activation time from  $t_{Aj}$  and  $t_{Bj}$  in order to reach  $t_{Cj}$ . b) generation of switching function.

Source voltage magnitude is taken to be 200v and frequency 50 Hz as well as load resistance 100Ω and load inductance 30mH. The output voltage is essential to be 140v magnitude with 30Hz frequency whereas the switching frequency is 1 kHz, also the sampling time is 1ms.

To perform the relevant simulation a variable-step solver included in MATLAB/SIMULINK (ODE45, Dormand-prince), is utilized.

Fig. 4 clearly portrays that using the voltage produced by switching, will result in an appropriate quasi-sinusoidal behavior that can utilized for all frequency domains.

Based on Fig. 4, the most prominent requirement is the switching order in the whole period. It must be noted that switching open time is T and must never be activated at the same time. This switching order leads to apply accurate one input voltage in an instant of time.

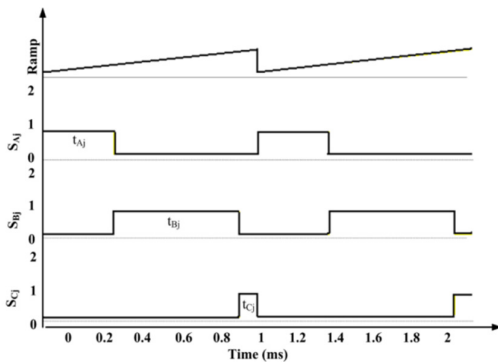


Fig. (4): Switching function of jth output phase

The main part of this simulation is providing a switching function to obtain an accurate time that each switch must be activated or not. Applying Venturini's equations, matrix  $M(t)$  can be represented. So by entrance matrix  $M(t)$  into the (12) the duty cycle for any switch could be extracted:

$$t_{Aj} = T.m_{Aj}, t_{Bj} = T.m_{Bj}, t_{Cj} = T.m_{Cj}, j = \{a, b\} \quad (14)$$

### 5. Experimental analysis

It is obvious that all three inputs require acquiring the low frequency. Collection of these parts of

voltage together causes an appropriate voltage with frequency and amplitude in the output voltage (max  $0.86 V_{in}$ ) [26]. Fig. 5 presents the output voltages of matrix converter that encompasses all three input voltages and also it leads to two orthogonal input voltages for induction motor. It withal portrays matrix converter's input connected to a three-phases source with 50 Hz frequency, will generate 30Hz the output voltage.

Table (1): Switching strategy

Step	$I_i > 0$				$I_i < 0$			
	$S_{Aa}$	$S_{Ab}$	$S_{Ba}$	$S_{Bb}$	$S_{Aa}$	$S_{Ab}$	$S_{Ba}$	$S_{Bb}$
Initial	on	on	Off	off	on	on	off	Off
1	on	off	Off	off	off	on	off	Off
2	on	off	On	off	off	on	off	On
3	off	off	on	off	off	off	off	On
Final	off	off	on	on	off	off	on	On

In accordance with Fig. 5, the output voltage in a moment couldn't be more than the maximum input voltage for that moment.

The reliable current commutation between switches in matrix converter is more complex to obtain. It has to be actively controlled at all times considering two basic rules.

- Avoid short circuit in the input.
- Avoid open circuit in the input.

Both the conditions may lead to overcurrent and overvoltage owing to saved inductive energy in the induction motor. More reliable approach of commutation aimed at overcoming these problems is utilizing a multi-step commutation strategy in which current direction of current flow can be sensed and controlled. A structure with capability of changeable switching order to extract a desirable deriving of switches is shown in Table 1.

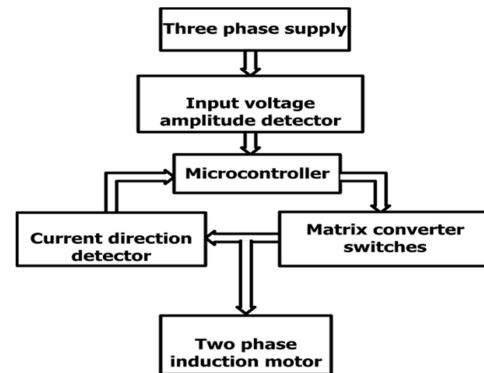


Fig. (5): Block diagram of driving system

As can be seen in Fig. 5, a block must be available to sense direction of the current to select an

appropriate switching as well as sensing the input voltage in order to put in Venturini's equations to obtain switching duty cycle. The state among the micro and matrix converter must be appropriately designed so that the maximum speed and safe switching process be acquired.

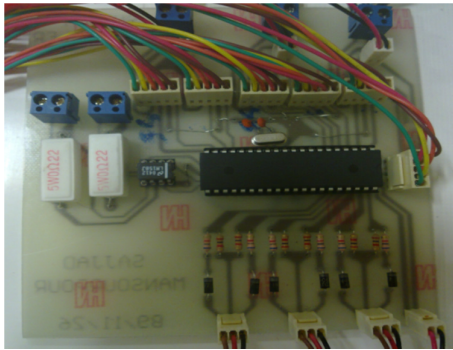


Fig. (6): Main board related to switching control

The main board related to detection of the current direction in every switch aimed at turning on or off any switch in appropriate way is presented Fig. 6. Surely, this board can easily measure the input voltage for utilizing in (11).

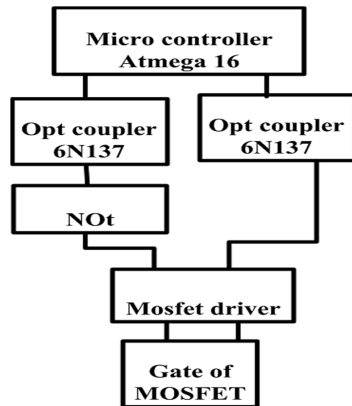


Fig. (7): The utilized scheme among the micro and every switch

To drive matrix converter's switches, the proposed scheme in Fig.7 is applied.



Fig. (8): The structure of every switch

Here, to construct a high speed switch applicable for driving the induction motors, a switch structure

which is shown in Fig. 8 is applied.  $T_i$  is one switch form the utilized six switches in matrix converter, which all diodes (DSEP30) and MOSFETs (2SK2879) utilized in the switching part of this structure are high speed and they are utilized in power electronic devices.

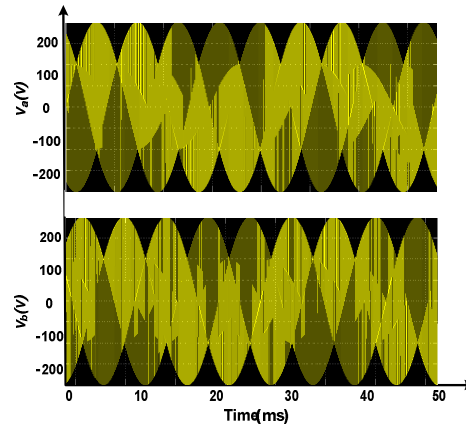


Fig. (9): Output voltage of matrix converter as induction motor input

Fig. 9 presents the output orthogonal voltage  $V_{a,b}$  which is previously mentioned. Note that, the output frequency can't be restricted to input frequency. Whenever this wave form is used for inductive load similar to induction motor, it leads to remove the undesirable harmonics and also provide two orthogonal quasi-sinusoidal voltages with the required frequency to have an appropriate switching periods.

## 6. Experimental results

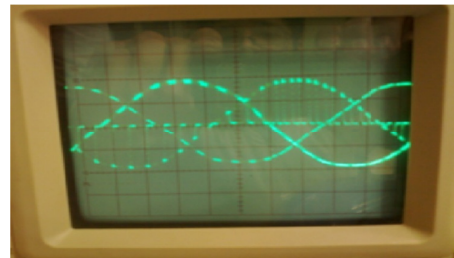


Fig. (10): The output voltage ( $v_a$ ) waveform after switching

Three input voltages that have triggered in the appropriate instant are shown in Fig. 10. As can be conceived the switching time is variable in each  $T_i$ , and accordingly this is the most prominent reason which lead to have the required amplitude with variable frequency.

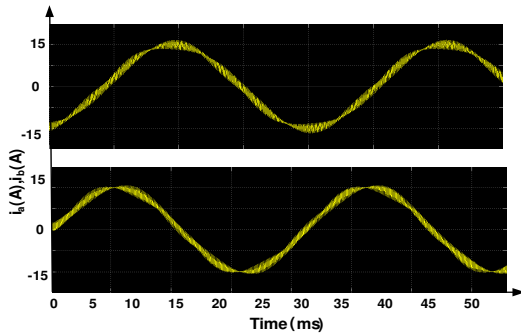


Fig. (11): Output current of matrix converter as input current of induction motor in phase a,b

Based on Fig.11, the maximum point in the waveform of  $i_b$  is approximately in the zero point of  $i_a$ . Thus, it is clear that two-phase induction motor have approximately an orthogonal state.

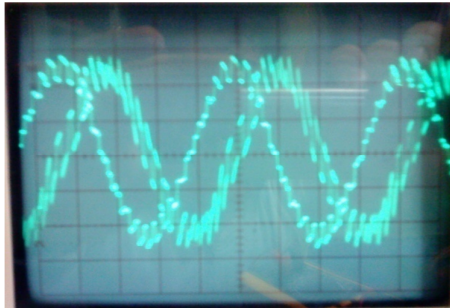


Fig. (12): Comparison of phase difference between two output currents

The experimental case presented in Fig. 12 is performed considering  $R=100\Omega$  and  $L=30mH$ . That is transparently approved the simulation results. Furthermore, the harmonic spectrum is presented in Fig. 13 to highlight our reason for approving this approach. This figure shows the orthogonal status of two input phases of induction motor.

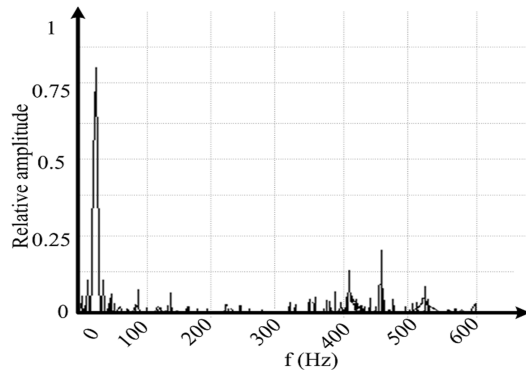


Fig. (13): Harmonic spectrum of output matrix converter,  $v_a$

Similar to the prior figure, Fig.14 also presents the output harmonic spectrum of matrix converter. It is obvious that the fundamental harmonic is occurred

close to the required frequency that is here considered to be 30Hz.

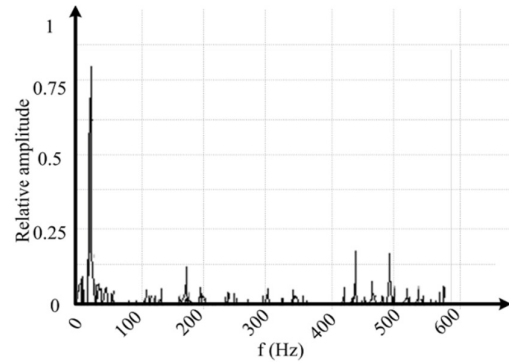


Fig. (14): Harmonic spectrum of output matrix converter,  $v_b$

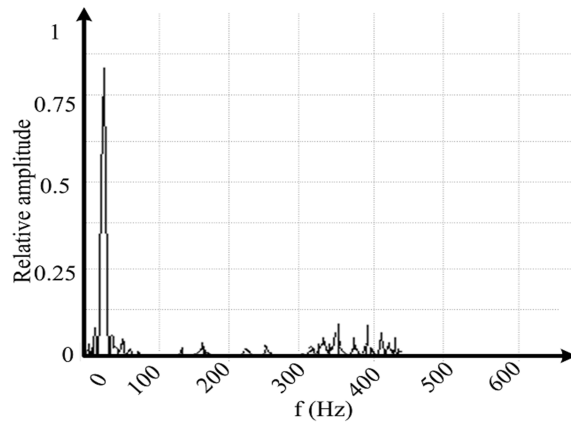


Fig. (15): Harmonic spectrum of output matrix converter,  $i_a$

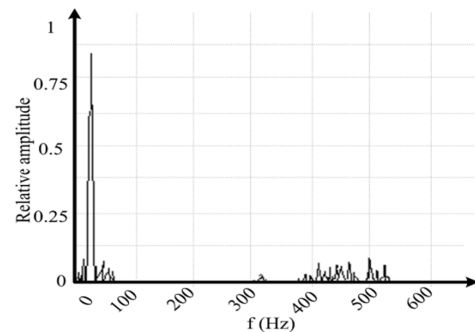


Fig. (16): Harmonic spectrum of output matrix converter,  $i_b$

The presented harmonic spectrums in Fig.13-16 have confirmed that the fundamental harmonic occurs close to the output frequency. What is here prominent is that the harmonic distortion is reduced that means an appropriate speed control of induction motor is performed and also the ripple is minimized.

## 7. Conclusion

This paper has scrutinized an effective approach regarding to how to elicit double quasi-sinusoidal waveform with orthogonal angles can be applicable for two-phase induction motors. Hither, to be more

precisely declared, a switching strategy is proposed so that the provided voltages by matrix converter i.e., A and B phases have  $90^\circ$  difference with each other. This switching strategy assists two-phase induction motors aimed at operating in appropriate state. As the created frequency in an important item for this motor, matrix converter can also undertake this function. It is worth mentioning that, the switching is somehow performed until bi-directional switches couldn't be simultaneously triggered and withal taken place in the accurate switching order. Its related circuit in order to producing appropriate current and voltage has been tested considering Matlab Simulink and experiment. The simulation result is extracted with respect to inductive and resistive load. Meantime, PWM method is carried out to extract experimental results that clearly show its effectual performance.

In this paper  $3 \times 2$  matrix converter has been constructed in both the Matlab/Simulink and experiment. This matrix converter provides two orthogonal phases of the voltages which can be

applicable for two-phase induction motor. Furthermore, by means of this matrix converter unwanted harmonics are reduced. The result clearly suggests that two-phase matrix converter render the better quality at low frequency at output and low-order magnitude harmonics in output. This model confirms that the switching order applied in matrix converter is an appropriate approach to control a two-phase induction motor with variable frequency to obtain the maximum gain with desirable frequency. The presented structure for matrix converter for induction motor decreases the harmonics distortion of both current and voltage. Meantime, the switching approach presents an appropriate performance in the high frequency applications that lead to elimination of any overvoltage and overcurrent.

### 8. Acknowledgment

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