A low cost single-phase to three-phase power converter for low-power motor drive applications

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***Abstract*- This paper presents an economic single-phase to three-phase converter which provides variable output voltage and soft starting capability by using four high frequency switches (IGBT, MOSFET), four diodes, and a triac. This converter can run a three-phase Induction motor which is much more efficient compared to a single phase motor. In order to have a balanced output voltage in all modes of operation (start-up, speed control, and steady state) two closed loop controllers has been utilized: one for dc link voltage and the other one for inverter output. The proposed scheme with variable output voltage and fixed frequency provides a limited-range speed control of the induction motor. As a result, the new single-phase to three-phase converter brings the controllable output voltage as in a six-switches standard three-phase inverter. The front-end rectifier has the capability of active input current shaping. Analysis and simulation results are presented in the result section to demonstrate these new features.**

Keywords: Induction motor; Three-phase motor; Single-phase motor; High frequency switches; Triac

I. Introduction

In the power distribution systems, the single-phase grid has been considered as an alternative for rural or remote areas [1]. On the other hand three-phase motors are more efficient, cheaper, and smaller and have less output torque ripple. This converter is a good bridge between single-phase grid and three-phase appliances. Generally, three-phase induction machines have been introduced a long time ago but since in many areas three-phase power system does not exist, single-phase motors were invented but their performance and their efficiency is not satisfactory [1].

By using a converter with four IGBT switches, 4 diodes and a Triac one can create a variable three-phase output voltage to for limited-range speed control(with fixed output frequency), the speed control resulted from this method is suitable for fan-type loads, in which load torque follows speed reduction. The two left side switches (front end rectifier consisting of two IGBTs and Two diodes) and the inductance will produce a high quality input current due to active input current shaping feature.

A. *Advantages of Three Phase Motors over Single Phase Motors*

1) *Lower Cost*

It is usually cheaper to purchase a three phase electric motor for power requirements. For example a 10hp three-phase motor might cost about $300 meanwhile an equivalent single-phase motor might cost more than $700. Price differences become more pronounced as the horsepower of the electric motor increases [4].

2) *Simpler motor construction*

Three phase electric motors are generally simpler in construction than their single-phase counterparts. Three-phase motors do not require a starting system as they have inherent self-starting capability. A single-phase electric motor starting system, the integral centrifugal switch and starting winding, significantly increases the initial and maintenance costs of single-phase motors [4].

3) *Smaller physical size*

A three-phase electric motor is usually physically smaller than single-phase electric motor, all other factors being equal. Fig. 1 shows a good comparison in which a 5hp three-phase motor is much smaller than a 3hp single phase motor [4].

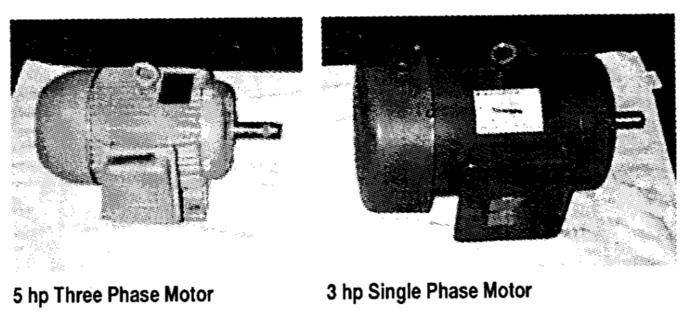


Fig. 1: Physical size comparison between a single and a three phase electric motor.

4) *Higher operating efficiency*

Generally, three-phase induction motors are considerably more efficient than single-phase induction motors at converting electrical energy to mechanical energy [4]. Single-phase induction motor efficiency is usually less than 60 percent, while this number for three-phase induction motors is usually more than 80 percent. Yet, three-phase line start permanent magnet synchronous motors are even better options for many applications such as fan-type (pumps, fans, etc.) loads. They typically offer about 90 percent efficiency and almost unity power factor [5-10]

5) Lower starting current requirement

Electric motors require motor current to bring the motor and load up to operating speed (during start up) than is required to drive the motor at full load. The starting current is usually between 6 to 8 times the running current for a typical single-phase motor while it is about 3 to 5 times the full load current for a typical three-phase motor. The large starting currents can produce power quality problems in power distribution systems, such as voltage sags. Power quality problems are less when three-phase motors are used compared to equally rated single-phase motors, if all other factors are equal[4].

B. Conventional single-phase to three-phase converter

Before early 1960's the single-phase to three-phase electrical system conversion were done by connecting some passive elements such as capacitors, reactors, and autotransformer converters [11]. Those systems demonstrate several clear disadvantages and limitations. Power electronics devices such as silicon-controlled rectifiers and transistors emerged in the market from the early 1960s. By looking at the power electronics devices used in the primitive controlled rectifiers and comparing them with new products, it is possible to figure out the dramatic development. After the improvement made to power devices, a great activity in the circuit topology innovation in the field of single-phase to three-phase conversion systems was also identified [12].

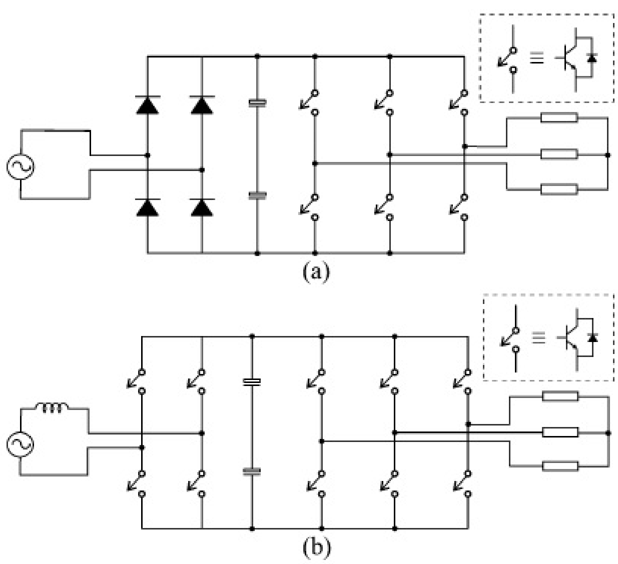


Fig. 2: Conventional single-phase to three-phase configuration

Among the single-phase to three-phase power conversion, two main tendencies can be observed: 1) configuration with a reduced number of components; 2) configuration with an increased number of components. The conventional single-phase to three-phase ac-ac direct conversion is shown in fig. 2. [12].

C. Economic single-phase to three-phase converter

Variable speed drives employing a three-phase induction motor and a PWM voltage source inverter, are being used for various purposes in many different industrial and non-industrial applications. Although their technical advantages are generally known, engineers are becoming aware of their high cost and are continuously exploring the possibility of cost reduction [13]. The cost reduction of motor drives is generally accomplished by the two following approaches:

1) Topological approach
2) Control approach

In the first one, minimum number of switches is used to make the power conversion circuit. In control approach, many different algorithms and methods are invented and implemented in conjunction with the reduced parts converter to produce the desired dynamic and static motor performance characteristics. Consequently, many topologies have been developed and various control methods have been presented to enhance the performance of the drive system. So far, the reduced parts converters have been applied to the motor drives [13-18]. A well-known family of reduced parts single-phase to three-phase converters are used when the output frequency is fixed as we can see in Fig. 3 [13-18]. Although these converters have reduced the cost but they has some disadvantages such as:

1) The switches are subjected to twice the peak voltage of the single-phase mains;
2) The VA rating of the capacitors in the DC link is higher especially due to the low frequency current [612].

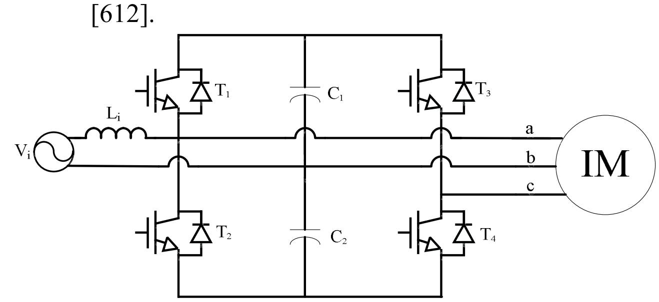


Fig. 3: Economic single-phase to three-phase configuration

The simplified equivalent circuit is shown in Fig. 4. From this diagram it can be seen that the input line current I_{in} is essentially equal to the motor current I_a , and the inverter current I_{inv} is equal to I_b. If we can ignore switching harmonics and unbalance conditions, the circuit can be analyzed using fundamental components [14].

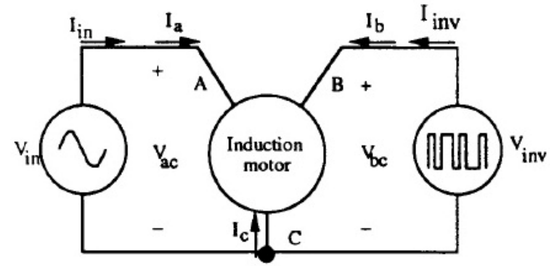
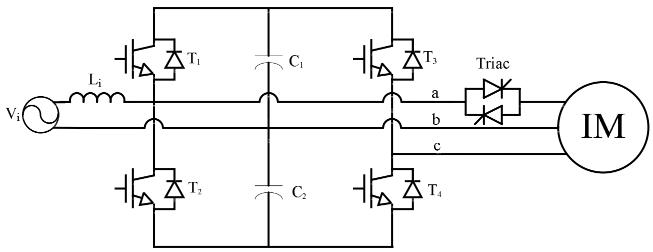


Fig. 4: Simplified circuit diagram of the converter

II. PROPOSED CONVERTER

A configuration with a reduced number of semiconductor switches considered in this paper uses four high frequency switches (IGBT, MOSFET), four diodes and a triac. with DC link (Fig. 5) In this proposed scheme the inductor Li helps in filtering current harmonics, two left switches T1 and T2 adjust the DC-link voltage, the switches on the right leg T3 and T4 adjust the output voltage, and giving firing pulses the triac, causes variable output voltage which is suitable for limited-range speed control of fan-type loads (such as fans and pumps). Moreover, it provides soft-starting capability for the system.



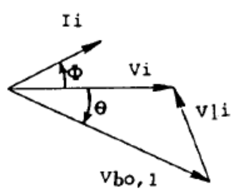


Fig. 5: Proposed economic single-phase to three-phase configuration and its phasor diagram

Since the dc link voltage various by changing the load current, especially when the load torque varies from zero to full load, it is necessary to have a regulating circuit in order to maintain the DC link voltage constant. This feature has been obtained using a feedback control system.

The input current phasor I_i is given by:

$$I_i \measuredangle \phi = \frac{V_i \measuredangle 0 - V_{oc,1} \measuredangle \theta}{jX_i}$$

Where $V_i \measuredangle 0$ is the input voltage and $V_{oc,1} \measuredangle \theta$ is the reflected voltage, and θ is the phase shift angle between the voltages and $V_{oc,1}$ in the phasor diagram [15].

The power factor angle is given by:

$$\phi = \tan^{-1}\left(\frac{V_i - V_{oc,1}\cos\theta}{V_{oc,1}\sin\theta}\right)$$

And the input power factor (pf) is:

$$pf = \cos\phi = \frac{V_{oc,1}\sin\theta}{\sqrt{V_i^2 + V_{oc,1}{}^2 - 2V_iV_{oc,1}\cos\theta}}$$

A. Converter Design:

The following design determines the required inverter power rating and the VA rating of capacitors. The design will be performed in per unit. Total three phase inverter output VA will be 1 pu. Line to line output voltage (rms) will be 1 pu. As a result, line current of the three-phase load is o.58 pu. Since the full load power factor is unity (because of the current shaping capability)

$$P_{inv} = 0.866 V_{bc} I_c$$

Substituting the line current value defined earlier will yield:

$$P_{inv} = (0.866)(0.58) = 0.5\,pu$$

Meaning that the inverter side is responsible for processing of 50 percent of the motor demand [15].

$$\Delta V_{c,ripple} = \frac{I_{c,ripple}}{\omega C}$$

$$C = \frac{I_{c,ripple}}{\omega \Delta V_{c,ripple}}$$

For a 220-v ac 1.4- kVA output and 3 percent voltage ripple the required C will be 943 uF, and the total capacitor VA is:

$$VA_{Cap} = 2V_0(0.707)I_C$$

$$VA_{Cap} = 2V_0(0.707)(0.577)$$

$$VA_{Cap} = 1.155\,pu$$

Table I. Per unit Design values

pu value	Amount
1 pu voltage	220 V
1 pu kVA	2.7 kVA
1 pu current	14 A
1 pu impedance	21.6 ohms
1 pu frequency	60Hz

III. SIMULATION RESULTS

Schematics of the Induction motor drives have been shown in Fig. 6a and 6b. The Induction motor's power which is used in these simulations is 3 HP, and its speed at full load is 1760 (rpm). Simulation results show comparison between the input current of Four-switch (diode) converter and the input current of the two-switch two-diode converter induction motor drive. As we can see, the current of the four-diode rectifier has a peak value of about 20 amps which is only flowing for about 30 percent of the period. Furthermore, the current waveform is lagging behind the reference voltage, which means the power factor is clearly less than unity. This type of current waveform can cause power quality issues for the utility. By considering the Fig.6b, we can see that the current in the four-switch converter (in which the front end rectifier has two IGBTs and two diodes) has a better shape with a good power factor of unity. The peak current is about 12 amps which is flowing for the whole period. It should be mentioned that the front-end rectifier in this case is working in its critical discontinuous conduction mode.

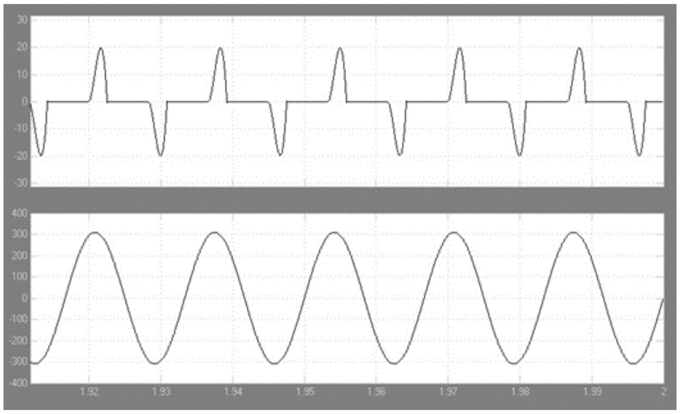


Fig. 6.a: Input current and voltage of the convertor with four-diodes as its front end rectifier

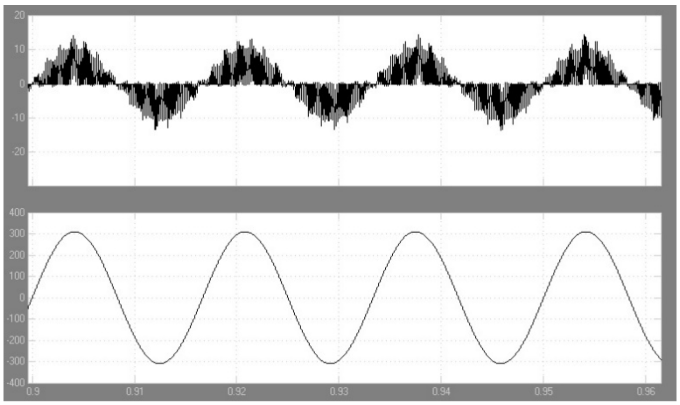


Fig. 6.b: Input current and voltage of the convertor with two switches and two diodes as its front end rectifier (it is in critical discontinuous conduction mode)

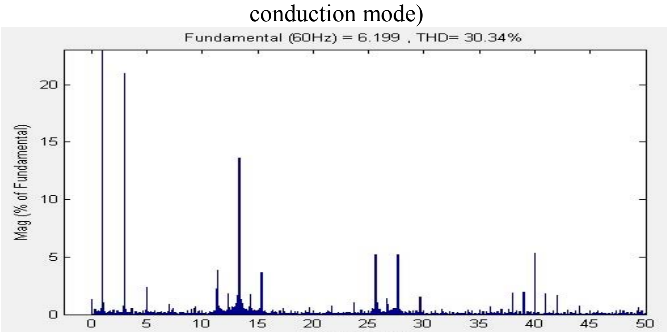


Fig. 7.a: FFT input current of four-diodes as the front end rectifier

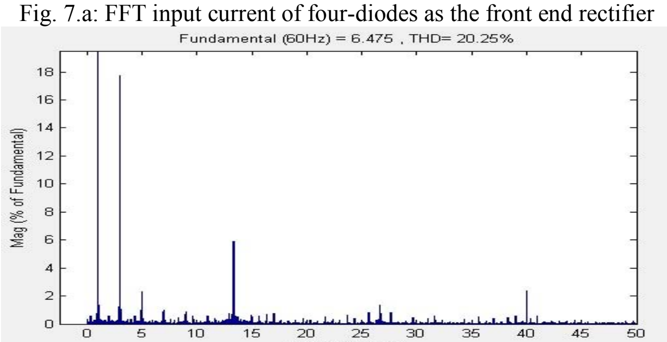


Fig. 7.b: FFT input current of two switches (IGBT) and two diodes as the front end rectifier

By comparing THD in these two schemes (Fig. 7), it is clear that the THD in IGBT-diode is 20.25% and for the diode scheme THD is 30.34%, which shows that a better current shaping in four-switch inverter has been accomplished.

In order to control the output voltage for motor speed control (or soft starting), firing pulses are given to the triac, which is connected directly to the input voltage source. Then the RMS value of the first component of the triac's output voltage is normalized (it is divided by 220) and is compared with the carrier signal to adjust the modulation index (M) (Fig. 8).

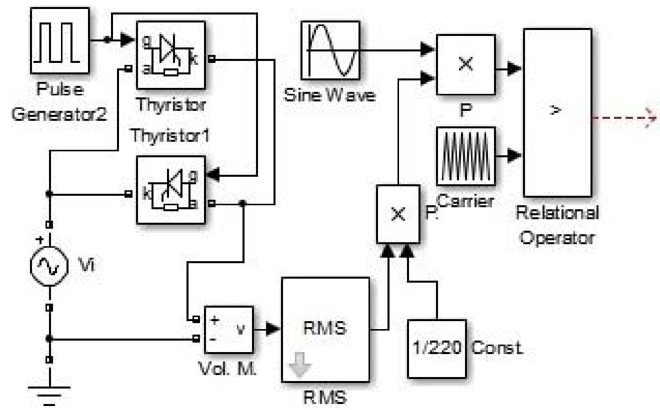


Fig. 8: Modulation index (M) control

We use the M value to derive the inverter switches to maintain a balanced voltage at three-phase that has been shown in Fig. 9. The Fig. 10.a to 10.c show the simulation results of the four-switch inverter (Proposed converter) output voltages.

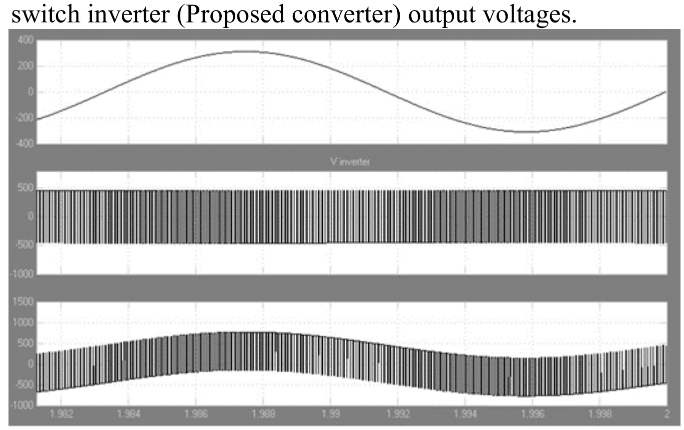


Fig. 9: the inverter output voltage (V_{AC}, V_{BC},V_{AB} as defined in Fig.5)

Modulation index of this converter at full load is 0.7 (since the DC link voltage is about 450 V)

- Current ripple through inductors <5%
- Voltage ripple across capacitors <3%

The values of two capacitors are the same. By this consideration capacitor value is achieved 1 mF and inductor value is achieved 1 mH. The input AC voltage is 220 volt with the frequency of 60 Hz.

A three-phase 3hp Induction motor with the specifications listed in the appendix section has been used in this simulation. The equivalent circuit of the induction motor is shown in Fig. 10.

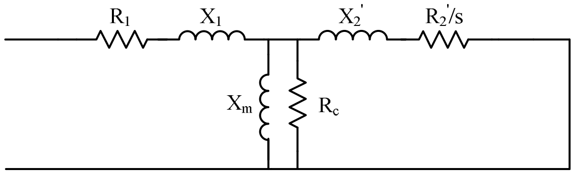


Fig. 10: Equivalent circuit of induction motor

The load torque has been set at 12 N-m. The Fig. 11.a to 11.d show the simulation results of the Induction motor drive fed by four switches inverter without output voltage control, and the Fig. 12.a to 12.d show the simulation results with output voltage control (in which triac firing pulses control the output voltage). The Fig. 11.a and 12.a show the inverter output RMS voltage, The Fig. 11.b and 12.b show the motor input current, which is 7.34 at full load. The motor speed curve, when reference speed is 1760 (rpm) shown in Fig. 11.c and 12.c which is the same as the motor nominal speed. The Fig. 11.d and 12.d show the motor output torque which is 12 (N.m). As it shown the converter with triac is limited the current and reduced the oscillation of motor speed and motor torque. Fig.13 shows the Induction motor phase currents.

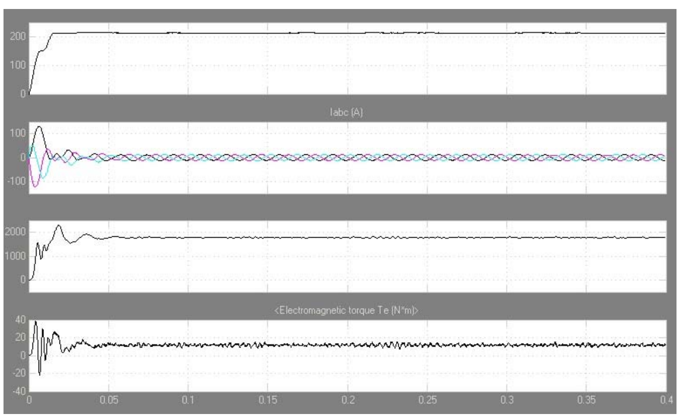


Fig. 11(a-d) motor start up without soft-starter

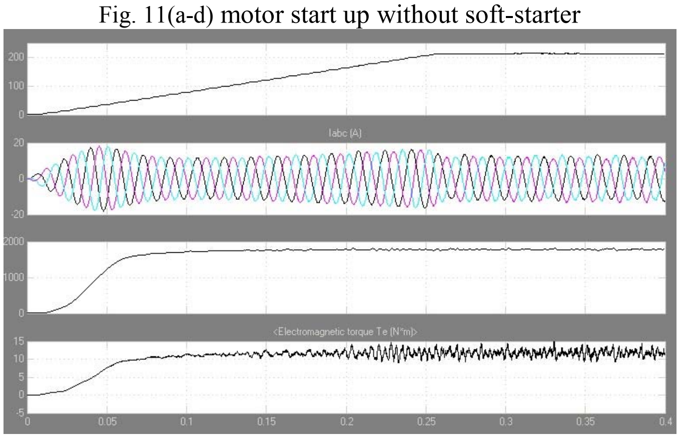


Fig. 12(a-d) motor start up with soft-starter

a: Output voltage of the inverter with respect to the ground

b: Motor input current, Irms (7.34 A)

c: Motor speed (1760 rpm)

d: Motor torque (12 N.m)

IV. CONCLUSION

This paper presents a single-phase to three-phase converter for controlling the speed of an induction motor. This converter controls the output voltage with fixed frequency. It also reduces the current demand of the motor during the start up. The minimum components are used in this scheme, which effectively decreases cost. This converter also provides voltage boost capability and active current shaping, which cannot be achieved with two-diode scheme as front end rectifier. As a

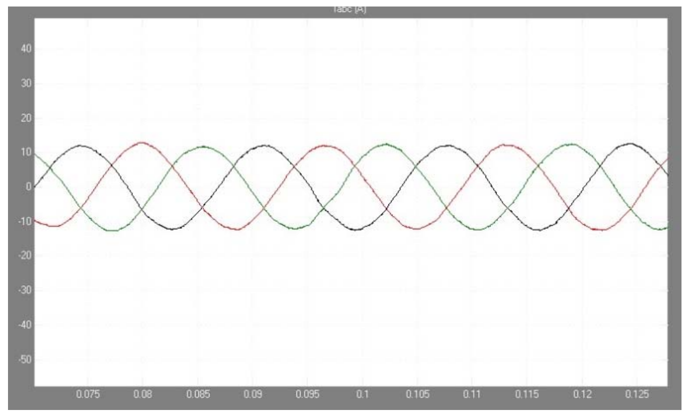


Fig. 13: Induction motor input currents

result, the new economic converter reduces line (utility) harmonics, and regulates DC-link voltage in a high value. Implementing single-phase to three-phase converter has many advantages that have been described in this paper such as:

1) It can generate and regulate required DC link voltage

2) It provides greater operation speed range for Induction motors compared to fixed-voltage fixed frequency schemes

3) This converter can start the motor with reasonable starting torque and low input current

5) It has low cost

6) It can control the output voltage to maintain a balanced 3 phase system during the speed control

Appendix

TABLE II
INDUCTION MOTOR PARAMETER REFERRED TO STATOR

R_s (Ω)	0.7
R_r (Ω)	0.7
X_{ls} (Ω)	1
X_{lr} (Ω)	1
X_m (Ω)	24
$V_{Grid\ (rms)}$ (v)	230
Base frequency (Hz)	60
Number of pole pairs	2
Inertia (kg.m^2)	0.152
Friction (Nm.s/rad)	0.001
Rated power (hp)	3

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