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An Economic Single Phase to Three Phase Power Converter with Active Input Current Shaping

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***Abstract* - This paper presents a converter topology for driving a three-phase motor load from a single-phase supply. It consists of a rectifier and an inverter circuit. The front-end rectifier is to provide a DC link voltage through a split capacitor. The two-leg inverter converts this Dc link voltage into 3 phase supply. This converter can run a three-phase Induction motor which is much more efficient compared to a single-phase motor. In this paper, two closed-loop controllers are employed to achieve balanced output voltage. Among those two closed-loop controllers, one is for maintaining the DC link voltage constant and, the other is for inverter output. Therefore, the single-phase to three-phase converter brings the controllable output voltage as in a six-switch standard three-phase inverter. The front-end rectifier has the capability of active input current shaping. The designed converter model is simulated by using MATLAB Simulink software. The Performance of the designed converter employing various controllers like PI and Fuzzy Logic is assessed.**

***Index Terms* - Front-end rectifier, Split-Capacitor, DC-Link voltage, Two-leg Inverter, Three-phase motor**

1.INTRODUCTION

Access to energy is a cornerstone for development and essential for a better quality of life. When this access does not exist or is very poor, it has negative impacts on everything from education, health, employment, and irrigation – touching all aspects of life and livelihood. The single-phase power has been alternative for rural areas or remote areas. Most of the remote areas have access to single phase power. On the other hand, three-phase electric motors have several advantages compared to single-phase electric motors. The performance of three-phase motor drive systems is superior when compared with single-phase motor drives. The three-phase motors are more efficient, low cost, and less output torque ripples [8]. Therefore, a bridge capable of connecting single-phase power to three-phase appliances is required. In the past, single-phase to three-phase conversion systems were made possible by the connection of passive elements (capacitors and reactors) with autotransformer converters [4]. Such kind of system presents well-known disadvantages and limitations. The power electronics with silicon-controlled rectifiers began emerging in the market from the early 1960s. A breakthrough in the field of power electronics came up with the invention of MOSFET and IGBT. There also been the great innovations in circuit topology in the field of power conversion systems was also identified [2].

2. CONVENTIONAL SINGLE PHASE TO THREE PHASE CONVERTERS

The conventional topology includes the converter, which can either be full bridge type, or half bridge type, with a DC link capacitor in cascade with a three-phase inverter [9]. In the conventional converters the AC-to-DC conversion is independent from the DC-to-AC conversion. The converter connected to the supply is called the lineside converter and the one connected to the load is the load-side converter. Therefore, in the conventional topologies the control of the line and the load side converters are independent.

A. Conventional full bridge topology

The conventional topology for single-phase to three-phase power converter employs a diode bridge rectifier and a regular six switch PWM inverter. The full bridge topology has four switches for the AC to DC conversion.

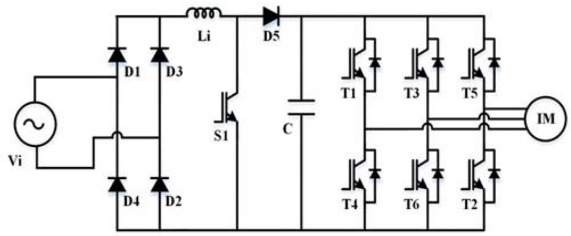

Fig. 1 Conventional single-phase to three-phase converter for ac motor drives.

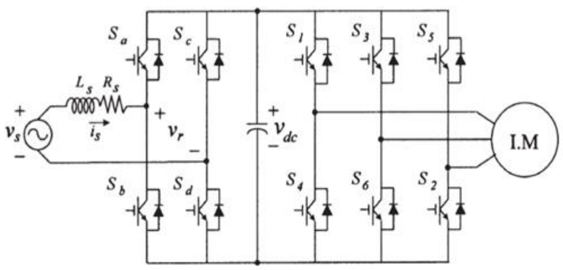

Fig. 2 Conventional single-phase to three-phase converters for AC motor drives with input current shaping.

B. Conventional half-bridge topology

The half bridge topology is like a full bridge topology except that a capacitor leg with neutral accessible replaces one of the converter legs of the line side converter, but the load side converter remains the same.

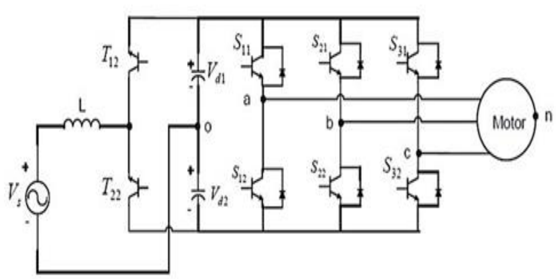

Fig. 3 Conventional Half bridge rectifier circuit single-phase to three-phase converter.

The irregular power distribution among the switches of the converter is shown in the figure 4. It means that 63% of the total losses measured in the single-phase to three-phase converter is concentrated in the rectifier circuit, while the rest 37% is observed in inverter circuit. With those numbers, it is possible to measure the stress by switch, which means that each rectifier switch is responsible for 15.7% of the total converter losses, while each inverter switch is responsible for only 6.1% [2]. The stress by each switch gives an important parameter regarding the possibilities of failures in the power converter. Therefore, the reduction in components leads to more efficiency of the converter.

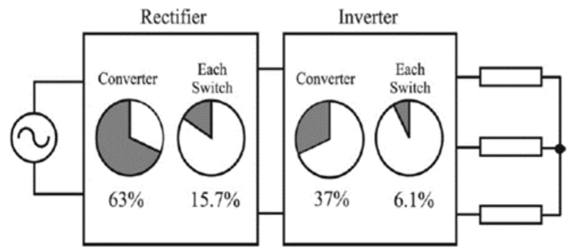

Fig. 4 Converter power losses distribution in both rectifier and inverter units.

3. PROPOSED SINGLE PHASE TO THREE PHASE CONVERTER

The proposed single-phase to three-phase converter which employs only six transistor or IGBT type switches. The proposed configuration incorporates a front-end half bridge active rectifier structure which provides the DC-link with active input current shaping feature. Further, the front-end rectifier allows bi-directional power flow between the DC-link and the AC mains. A four-switch inverter configuration with split capacitors in the DC-link provides a balanced three phase output to the AC motor load.

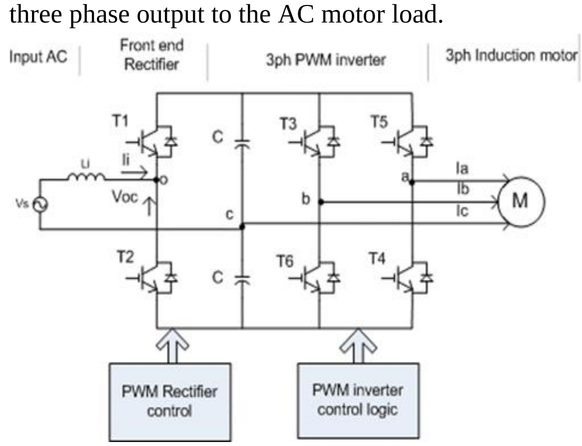

Fig. 5 Proposed single-phase to three-phase converter.

A. Converter design

The minimum inductance L that limits the ripple current Is

$$L_{min} = \frac{V_{in}*(V_o - V_{in})}{\Delta i_l * f_s * V_o}$$

L_{min}= 5 mH

Where f_s is the switching frequency and V_{in} is the rms voltage.

The capacitor size is determined by the percentage of desirable ripple in each half of the DC-link voltage.

$$C=\frac{V_{dc}}{f_s R_L V_r}$$

C =2.331 mF

Where C is the capacitance across half the DC bus and R_L is the equivalent load resistance for rated power transfer. V_{dc} is the DC bus voltage and V_r is the percentage of ripple voltage.

B. Front-end rectifier

The single-phase AC input which is of fixed frequency is rectified by the front-end rectifier switches T_1 and T_2. The split capacitor bank in the DC-link is charged through the diodes present in T_1 and T_6. The switches T_1 and T_2 are operated on a PWM pattern synchronized to the AC mains to shape the input current to be sinusoidal. The filter inductor L, aids in filtering higher order current harmonics. The fundamental component of the voltage at points 'O' and C' is $V_{oc,1}$ which is essentially the reflected voltage due to the PWM operation of T_1 and T_2. Fig. 6 shows the phasor diagram of the input voltage $V_{in}\angle 0$ and $V_{oc,1}\angle\theta$.

Where θ is the phase shift angle between the voltages V_{in}, and $V_{oc,1}$.

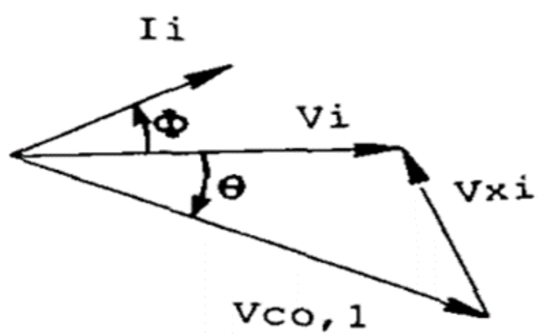

Fig. 6 Phasor diagram

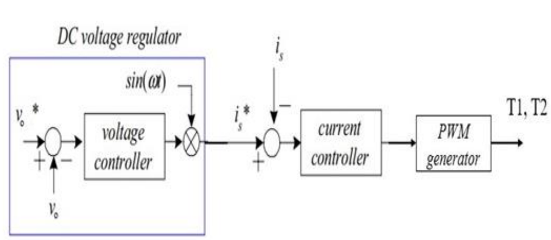

Fig. 7 Control strategy of Front-end rectifier

The input current I_i, is given by

$$I_i\angle\phi=\frac{V_{in}\angle 0-V_{oc,1}\angle\theta}{jX_i} \qquad (1)$$

The real power flowing from AC mains to the DC-link can be expressed as

$$Pi=\frac{V_{in}.V_{oc,1}\sin\theta}{X_i} \qquad (2)$$

The power factor angle is given by

$$\phi=\tan^{-1}\left(\frac{V_{in}-V_{oc,1}\cos\theta}{V_{oc,1}\sin\theta}\right) \qquad (3)$$

The input power factor pf is given by

$$\cos\phi=\frac{V_{oc,1}*\sin\theta}{\sqrt{V_{in}{}^2+V_{oc,1}{}^2-2.V_{in}.V_{oc,1}.\cos\theta}} \qquad (4)$$

A constant value of k implies that the DC-link voltage is regulated to maintain a constant value V_o, as given by

$$k=\frac{\sqrt{2}V_{oc,1}}{\sqrt{2}V_{in}}=\frac{V_o}{2\sqrt{2}.V_{in}} \qquad (5)$$

To obtain close to unity input power factor and a regulated DC-link voltage V_o, it is proposed that we maintain k = 1 with the help of a voltage control loop. Maintaining k = 1 also implies that the DC-link voltage

$$V_o=2\sqrt{2}V_{in} \qquad (6)$$

A. Control strategy of front-end rectifier

The DC bus voltage controller is used to control the DC-link voltage and to obtain the amplitude of the line current command. Because the system input power factor is controlled to be unity, the output signal obtained from the proportional-integral based voltage controller is multiplied by a sinusoidal wave in phase with mains voltage. The line current command is used in the inner current control loop to achieve line current tracking [5].

The Front-end rectifier can be operated in two modes.

1. Charging mode
2. Discharging mode

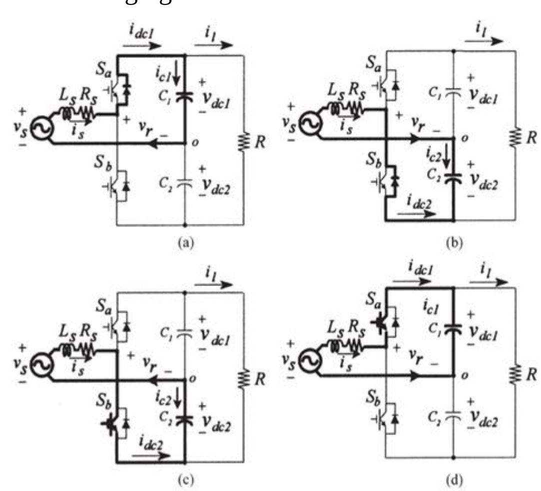

Fig. 8 Operating modes of the circuit. (a) and (b) Charging. (c) and (d) Discharging.

The Positive line current flows through boost inductor L, body diode of T_1, diode D_1 and capacitor C_1 such that, capacitor C_1 is charged by the line current. Because the half DC-link voltage is greater than the amplitude of mains voltage, the line current is decreasing linearly. During i_s>0, the switch T_2 is turned ON the capacitor C_2 is discharged.

When i_s>0, for the upper part of the rectifier, the current and voltage are given by

$$i_{c1} = i_{dc1} - i_l \quad (7)$$

$$i_{dc1} = S_a * i_s \quad (8)$$

$$V_{dc1} = \frac{1}{C}\int i_{c1}dt = \frac{1}{C}\int (i_{dc1} - i_1)dt \quad (9)$$

Where S_a is a switching state, i.e., 1 or 0. For discharging part, the similar equations are obtained as follows:

$$i_{c2} = -i_{dc2} - i_l \quad (10)$$

$$i_{dc2} = S_b * i_s = (1 - S_a) * i_s \quad (11)$$

$$V_{dc2} = \frac{1}{C}\int i_{c2}\, dt = \frac{1}{C}\int(-i_{dc2} - i_l)dt \quad (12)$$

For i_s < 0, the same equations can be applied to the relation of current and voltage.

By combining all the equations (7)-(12)

$$V_r = S_a * V_{dc1} - S_b * V_{dc2}$$

(13)

$$V_o = V_{dc1} + V_{dc2} \quad (14)$$

C. FOUR SWITCH THREE PHASE INVERTER

The output side of the proposed single-phase to three-phase converter consists of a four switch (T_3 to T_6) inverter. The centre point of the capacitors forms the third phase 'c'.

By controlling the switches T_5 and T_4 in a PWM fashion the output voltage V_{ca} can be defined. Further, switches T_3 and T_6 determine the V_{bc} voltage. To generate balanced three-phase output voltages, the voltage V_{bc} is phase shifted by -60° from V_{ca}. Thus, the control of switches T_3 to T_6 to have 60° phase shift between V_{ca} and V_{bc}, voltages ensure the third voltage V_{ab} to have the same magnitude (fundamental) and proper phase in accordance with the three-phase laws

It is noted that voltage V_{ab} is a two level PWM swinging between V_o and $-V_o$. On the other hand, the voltages V_{ca} and V_{ca} are two level type swinging between $+V_{o/2}$ and $-V_{o/2}$. Further, the fundamental content is the same in the three-phase output voltages.

D. Control strategy of four switch three phase inverter topology

In a DTC drive, flux linkage and electromagnetic torque are controlled directly independently by the selection of optimum inverter switching modes. The choice is made to restrict the flux linkages and electromagnetic torque errors within the respective flux and torque hysteresis bands [7].

This results in fast torque response, low inverter switching frequency and low harmonic losses. The required optimal switching vectors can be selected by using optimum switching-voltage vector look-up table. This can be obtained by simple physical considerations involving the position of the stator-flux linkage space vector, the available switching vectors and required torque flux linkage.

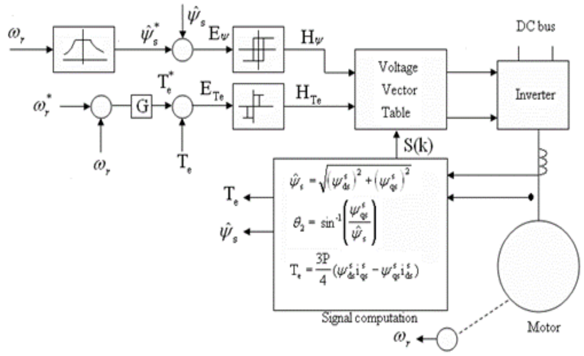

Fig. 9 Direct torque and flux control block diagram.

The magnitude torque is

$$\bar{T}_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s'}\left|\bar{\psi}_r\right|\left|\bar{\psi}_s\right| \sin\gamma \quad (15)$$

The command stator flux $\hat{\psi}_s^*$ and torque T_e^* magnitudes are compared with the respective estimated values and the errors are processed through hysteresis-band controllers.

The flux loop controller has two levels of digital output according to the following relations:

$$H_\psi = \quad 1 \quad \text{for} \quad E_\psi > +HB_\psi$$

$$H_\psi = -1 \quad \text{for} \quad E_\psi < -HB_\psi$$

The torque control loop has three levels of digital output, which have the following relations:

$H_{Te} = \quad 1 \quad$ for $\quad E_{Te} > +HB_{Te} \qquad H_{Te} = -1 \quad$ for $\quad E_{Te} < -HB_{Te}$

$$H_{Te} = \quad 0 \quad \text{for} \quad -HB_{Te} < E_{Te} < +HB_{Te}$$

The voltage vector table block in receives the input signals H_ψ, H_{Te}, and *S(k)* generates the appropriate control voltage vector (switching states) for the inverter by lookup table.

$$\Delta\bar{\psi}_s = \bar{V}_s.\Delta t \quad (16)$$

Which means that $\bar{\psi}_s$ can be changed incrementally by applying stator voltage $\bar{V}_s$ for time increment Δt.

For the proposed inverter switching requirements can be stated as follows. Given a desired set of three-phase voltages and a set of three-phase currents for the output inverter:

$$v_{01} = V_0 \sin \omega t$$
$$v_{02} = V_0 \sin\left(\omega t - \frac{2\pi}{3}\right)$$
$$v_{03} = V_0 \sin\left(\omega t + \frac{2\pi}{3}\right)$$
$$I_{01} = I_0 \sin(\omega t - \theta)$$
$$I_{02} = I_0 \sin\left(\omega t - \theta - \frac{2\pi}{3}\right)$$
$$I_{03} = I_0 \sin(\omega t - \theta + \frac{2\pi}{3})$$

where V, and I, are the magnitudes of the output voltages and currents, respectively.

$$v_{01n} = v_{01} - v_{03} = \sqrt{3}V_0 \sin(\omega t - \frac{\pi}{6})$$
$$v_{02n} = v_{02} - v_{03} = \sqrt{3}\, V_0 \sin(\omega t - \frac{\pi}{2})$$

where n is the DC bus centre point assumed to be ground.

4. FUZZY LOGIC CONTROL

In Fuzzy logic control (FLC), basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since, the numerical variables are converted into linguistic variables, mathematical modelling of the system is not required in FLC [3]. The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FLC is characterized as,

1. Seven fuzzy sets for each input and output.
2. Triangular membership functions for simplicity.
3. Fuzzification using continuous universe of discourse.
4. Implication using Mamdani's min operator.
5. Defuzzification using the "height" method.

To convert the numerical variables into linguistic variables, the fuzzy levels chosen are NB (negative small), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big). The value of input error E(K) and change in error CE(K) are normalized by an input scaling factor. In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any input there is only one dominant fuzzy subset.

$$C(K) = E(K) - E(K-1) \qquad (17)$$

In the present work, for fuzzification, non-uniform fuzzifier has been used. If the exact values of error and change in error are small, they are divided conversely and if the values are large, they are divided coarsely.

Table.1. Fuzzy rules

CE \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

$$U = -[\alpha E + (1 - \alpha) * C] \qquad (18)$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system; C is the change in error and U is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error E indicates that the system is near to balanced state. Overshoot plays an important role in the system stability. Less over-shoot is required for system stability and in restraining oscillations. C plays an important role, while the role of E is diminished. The optimization is done by α.

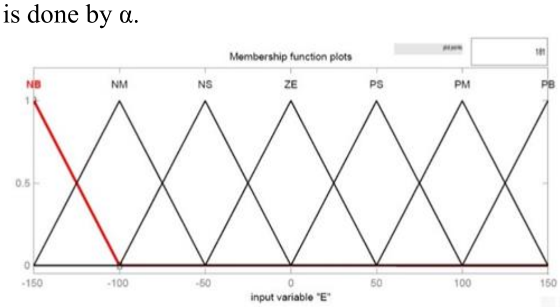

Fig.10Triangular wave form for fuzzy input variable E

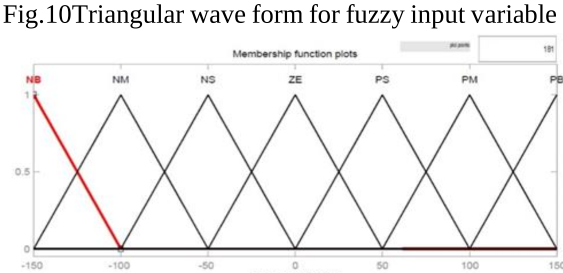

Fig. 11 Triangular waveform for fuzzy input variable CE

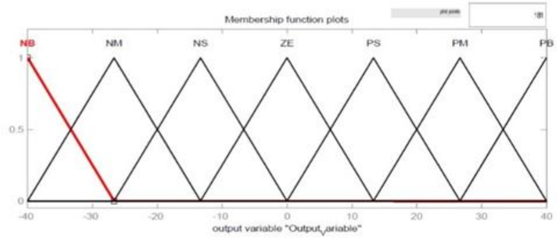

Fig. 12 Triangular waveform for Fuzzy output variable

5. SIMULATION RESULTS

A three-phase 5hp Induction motor with the specifications listed in the appendix section has been used in this simulation. The MATLAB model of the single-phase to three-phase converter is simulated and the results is shown in the below figures for the given three-phase induction motor. The output line voltages, three-phase output currents, speed (ωm), Electromagnetic torque (Nm) and THD for the input current.

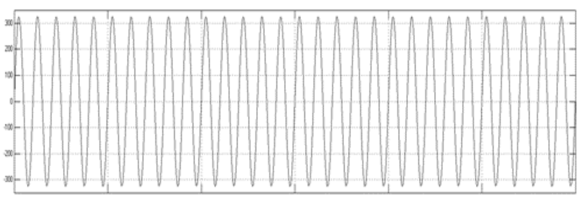

Fig. 13 Input source voltage

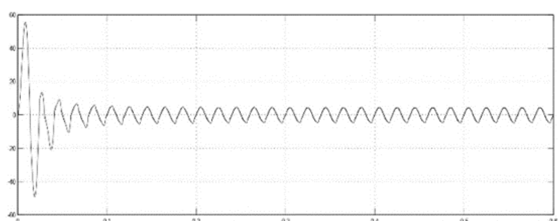

Fig. 14 Source current

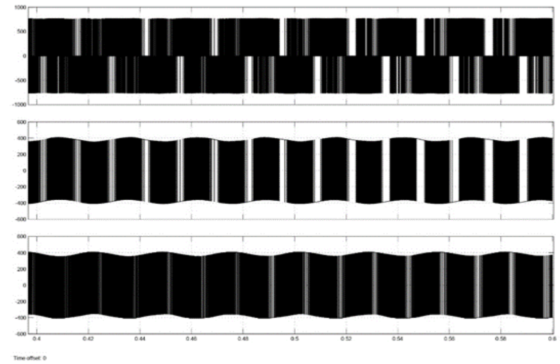

Fig. 15 Three-phase Inverter output voltages

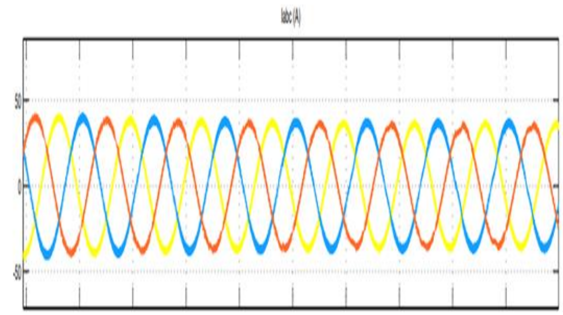

Fig. 16 Induction motor input currents

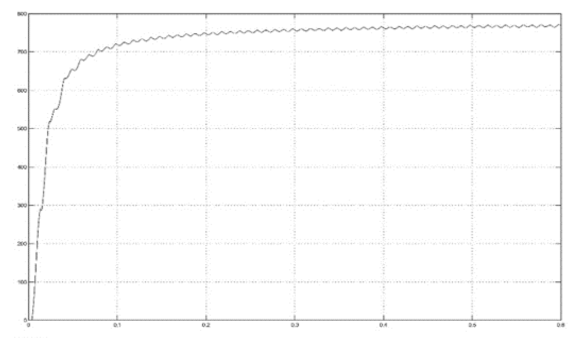

Fig. 17 DC-Link voltage with PI controller

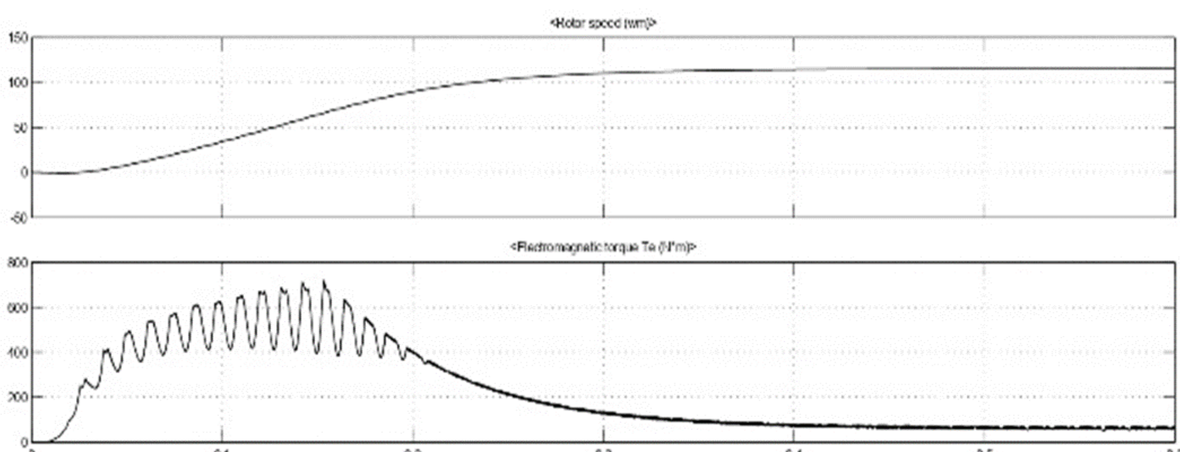

Fig. 18 Motor speed and Electromagnetic torque

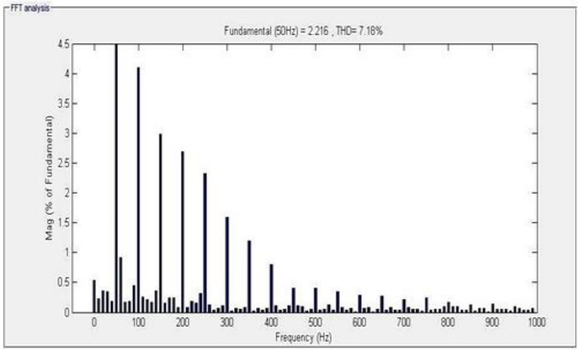

Fig. 19 FFT input current of the front-end rectifier using pi controller.

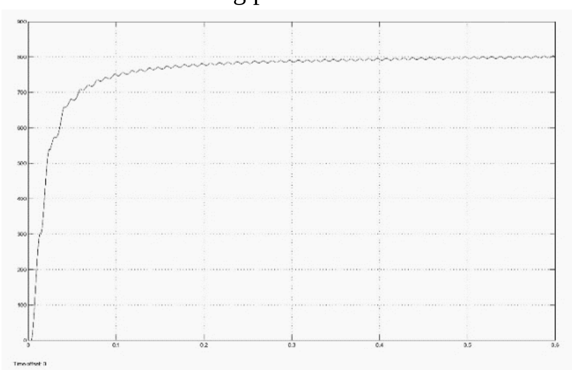

Fig. 20 DC-Link voltage with FLC controller

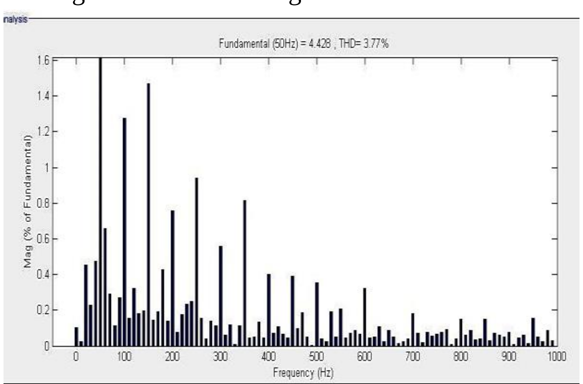

Fig. 21 FFT input current of front-end rectifier using fuzzy logic control strategy.

The load torque has been set at 50 N-m. The Fig. 18 shows the simulation results of the induction motor drive fed by four switch inverter with voltage control. The angular speed of the motor is 120 rad/sec. The output of four switch inverter is a three-phase balanced voltage. The Fig. 16 shows induction motor input current 40 Amperes. The DC-Link voltage 800 Volts is maintained constant.

The DC-link voltage response has been shown in figure 17 and 20. Comparatively the Fuzzy logic controller shows the good response. The parameters like rise time, settling time and steady state error has been calculated and shown in below tabular column.

Table. 2 Comparison of Parameters between PI controller and Fuzzy controller

Parameter	PI controller	Fuzzy controller
Rise time (Sec)	0.0983	0.06995
Settling time (Sec)	0.5	0.46
Steady state error (%)	3.75	1.25

The Total harmonic distortion for the input source current of the converter controlled by PI controller and Fuzzy controller is given in below tabular column.

Table. 3 THD Comparison of input source current

Parameter	PI controller	Fuzzy controller
THD (%)	7.18	3.77

The FFT analysis of the proposed converter operated with PI controller is 7.18 % and when operated by Fuzzy logic controller is 3.77 %.

6. CONCLUSION

This work 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. The minimum components are used in this scheme, which effectively decreases cost. This converter also provides voltage boost capability and active current shaping. This converter reduces line (utility) harmonics and regulates DC-link voltage in a high value. The control strategies for front end rectifier using PI control technique and Fuzzy logic control strategy is compared. Comparatively front-end rectifier operated with fuzzy logic control has shown better results in FFT analysis.

Appendix

Table. 4 Induction motor parameters referred to stator.

R_s (Ω)	0.087
R_r (Ω)	0.228
X_{ls}(Ω)	0.251
X_{lr}(Ω)	0.251
X_m(Ω)	10.916
$V_{(rms)}$ (volts)	400
Base frequency(Hz)	50
Number of pole pairs	2
Inertia(Kg.m^2)	0.831
Friction(Nm.s)	0.1
Rated power(hp)	5

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