Power Quality Improvement of a VSI-fed High Power Induction Motor Drive by Three Level Front-End Converter and Passive Filter

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Abstract :- A large capacity volage source inverter fed induction motor drive with a front-end three phase, three level ac to dc converter of neutral point clamping topology and parallel passive filter to the reactive power requirement is investigated. Ac supply current harmonics is reduced in this investigated topology. A control scheme is designed for the ac-dc front-end rectifier to vary the dc link voltage and regulate at any desired value. Total harmonic distortion of the ac supply current is evaluated and minimized. Input power factor is also made close to unity. The input power quality and drive system control performance both are improved. The simulation result confirms the improvement in input power quality and control performance of proposed drive scheme.

Keywords: Three level neutral point clamped converter, passive filter, induction motor drive, total harmonic distortion, input power factor, power quality, pulse width modulation, voltage source inverter

INTRODUCTION

In the distributed power generation systems, microgrids, isolated generation in remote locations and industries harmonics regulation is an important issue from power quality point of view. Wherever, power electronic equipment is used, associated quality of power should not be allowed to deteriorate for that device or equipment. So, it is pertinent to improve the quality of power using passive filter or active filter or hybrid filter. The same power electronic equipment with advanced control techniques and filters has improved the power quality in many reported articles. A high power three phase induction motor drive draws correspondingly large amount of reactive power. The power electronic converters are often used for variable speed induction motor drive. Pulse width modulated (PWM) three phase voltage source inverter (VSI) gives precise speed and torque control of induction motor. An ac to do converter at the front end accompanies the pulse width modulated voltage source inverter to make the drive compatible with ac supply. Power quality issues are addressed in this system.

Nonlinear control theory is described in detail in many books [1], [2]. Induction motor (IM) drive has poor transient performance due to coupled state dynamics. Unlike dc motor drive IM drive has poor flux and torque response because airgap flux and rotor current are dependent on each other. Increase in rotor current decreases the resultant magneto-motive-force (MMF) in the airgap and hence the airgap flux. Decrease in airgap MMF and flux leads to decrease in rotor induced electro-motive-force (RMF) and hence the rotor current. As the electromagnetic torque is produced due to interaction of current in rotor with the magnetic field in the airgap, the torque depends on both rotor current and airgap flux. As airgap flux and rotor current are mutually dependent, the flux and torque response during transient period are sluggish in IM drive. This is well known as coupled dynamics of IM drive. This creates a major drawback for induction motor in high performance drive applications. For improving the control performance of IM drive several techniques are implemented [3]-[10]. or In vector control [3]-[4], the stator current is controlled as a vector with both magnitude and phase varied independent of each other. It is also called field oriented control as the unit vector that is crucial for independent control of stator current's magnitude and phase is generated from field (or flux) components in an orthogonal reference frame rotating at synchronous speed or in some other speed [5]-[6]. Nonlinear control of induction motor through feedback linearization [7], [10] and input-output linearizing control through input-output linearization [8] provide good alternative to vector control. Decoupling of induction motor through sliding mode control technique is also reported [9].

Most of the variable frequency and speed IM drive use ac-dc-ac converters. These power electronic converters generate ac source current harmonics and hence poor input power factor. Distortion of the waveform of supply voltage at the point of common connection (PCC) is another consequence. For minimum cost, diode rectifier with passive and/or active filter can be used to reduce the harmonics and improve the power factor. Multi-level converters and inverters are often used to meet the augmented power rating requirement of high-power IM drive [11], [12], [13]. Three phase, three level, neutral point clamped (NPC) PWM converter has advantages [14] over two level converters. Switching device rating and switching loss are lower. Power quality and efficiency are also better in comparison to two level converters. The voltage step magnitude is lower in three level converters than those in two level converter. So, they are preferred in high power IM drives. The current waveform is also better in three level converter and harmonic content is lower. The dc link voltage is divided in two equal parts, which limit the voltage across all the switches. For the same current rating, lower voltage rating can be used. Conduction loss and switching loss are reduced. However, in the three level NPC converter, balancing of neutral point voltage and voltage control pose challenges. Due to this different topologies of three level converter are reported [11]-[14].

In this article a three phase, three level ac to dc NPC converter circuit is proposed for supplying induction motor drive through PWM voltage source inverter. For reactive power compensation and supply current harmonics reduction a passive filter is connected across the three level converter. Simulation results without passive filter and with are compared. These results are also compared with some previously reported results.

THREE LEVEL NPC CONVERTER WITH DC VOLTAGE REGULATOR

The block diagram of the proposed system is shown in Fig.1. The circuit topology of a three phase, three level NPC converter is shown in Fig.2. For the unidirectional power flow to the dc link, no current flows through upper three switches ($Q1_1$, $Q1_2$, $Q1_3$) and bottom three switches ($Q4_1$, $Q4_2$, $Q4_3$) as shown. So, these six switches are practically not present in the circuit. Switching states of switches in arm-1 are given in Table I. Operation of the NPC converter can be understood from Fig. 3 and Table I.

TABLE I. SWITCHING STATES FOR ARM-1 OF NPC CONVERTER

i_1	$Q2_1$	$Q3_1$	v_{1N}	i_N
> 0	−	0	$+V_{dc1}$	0
	−	1	0	i_1 (> 0)
< 0	0	−	$-V_{dc2}$	0
	1	−	0	i_1 (< 0)

When $i_{d1} > 0$, the converter charges the dc link capacitor (Fig. 3). The current and voltage in the upper part of the converter can be written as:

$$i_{c1} = i_{d1} - i_{dc} \quad (1)$$

$$i_{d1} = s_a * i_1 \quad (2)$$

$$V_{dc1} = \frac{1}{C1}\int i_{c1}dt = \frac{1}{C1}\int (i_{d1} - i_{dc})dt \quad (3)$$

Where s_a is a switching state which can be 1 for ‘on’ or 0 for ‘off’. For the lower part of converter, similar equations are written as follows.

$$i_{c2} = -i_{d2} - i_{dc} \quad (4)$$

$$i_{d2} = s_b * i_1 \quad (5)$$

$$V_{dc2} = \frac{1}{C2}\int i_{c2}dt = \frac{1}{C2}\int (-i_{d2} - i_{dc})dt \quad (6)$$

where, s_a = 1 when $Q3_1$ is ‘off’ and 0 when $Q3_1$ is ‘on’.

s_b = 1 when $Q2_1$ is ‘off’ and 0 when $Q2_1$ is ‘on’.

The output voltage of the converter being the dc link voltage is:

$$V_{dc} = V_{dc1} + V_{dc2} \quad (7)$$

The phase voltage is

$$V_{1n} = s_a V_{dc1} - s_b V_{dc2} \quad (8)$$

The equation including the three arms of converter is derived for voltage and current relationship.

$$C\frac{dV_{dc}}{dt} = \sum_{k}^{3} i_k s_k - i_{dc} \quad (9)$$

$$L\frac{di_k}{dt} + Ri_k = e_k - V_{dc}(s_k - \frac{1}{3}\sum s_n) \quad (10)$$

$$\sum_{k=1}^{3} e_k = \sum_{k=1}^{3} i_k = 0 \quad (11)$$

where, k = index for the three-phases, i.e., {1, 2, 3};

s_k = phase switching function; i_k = line currents; e_k = phase voltages; i_{dc} = dc bus current;

Using the transformation of eqns. (9) and (10) from three phase to synchronously rotating d-q reference frame:

$$C\frac{dV_{dc}}{dt} = \frac{3}{2}(i_q s_q + i_d s_d) - i_{dc} \quad (12)$$

$$L\frac{di_q}{dt} + \omega L i_d + Ri_q = V_q - V_{dc} s_q \quad (13)$$

$$L\frac{di_d}{dt} - \omega L i_q + Ri_d = V_d - V_{dc} s_d \quad (14)$$

Where, ω represents synchronous speed. Design of P-I controllers for dc link voltage control is done based on eqns. (12)-(14).

PASSIVE FILTER DESIGN

The passive filter is designed by calculating total reactive power requirement under full load condition. According to the proportional presence of the *h*-th order harmonic, the parameters of the filter [15] are given in eqns. (15) to (17).

$$C_h = \frac{VAR_h}{V_{ph}^2 \omega_h} \quad (15)$$

$$L_h = \frac{1}{\omega_h^2 C} \quad (16)$$

$$R_h = \frac{\omega L_h}{Q} \quad (17)$$

Where, VAR_h, V_{ph}, $\omega_{h,}$ are particular harmonic per phase reactive power, phase voltage and fundamental frequency. C_h, L_h and R_h are the corresponding harmonic filter. The design parameters of passive filter to eliminate 5th and 7th harmonics are given in Table II.

Table II. PARAMETERS OF SHUNT PASSIVE VAR COMPENSATOR

5th	C_5=25e-6	L_5=16e-3	R=0.83
7th	C_7=20e-6	L_7=15e-3	R=0.71

SIMULATION RESULTS AND DISCUSSION

The proposed scheme is simulated in SIMULINK using the induction motor whose specifications and parameters are as follows. Three phase induction motor: 5 HP (3.7 kW), 4 pole, Δ-connected, 415 V, 1445 rpm, R_s = 7.34 Ω, L_{ls} =0.021 H, L_m = 0.5 H, R_r = 5.64 Ω, L_{lr} = 0.021 H, J=0.16 kg-m^2, B=0.035 kg-m^2/s.

For step changes of speed and load torque simulation is done. Reference speed is increased from 0 to 500 rpm at t = 0 s. Load torque of 20 N.m is applied at t = 0.3 s. Transient responses of speed, developed torque and current are shown in Fig. 6. The harmonics in source current and voltage are analyzed. The input power factor, and reactive power are also determined. The reactive power is estimated as 5 kVAR. Accordingly passive filter is designed and P-I controller for dc link voltage regulator is tuned. Initially, voltage regulator is tuned for regulating the dc link at 500V. A passive shunt filter comprising of inductor, capacitor and resistance is designed and connected across supply terminal. Two sets of responses are compared: without passive filter and with passive filter when the load is variable. Without the filter, simulation responses of dc link voltage, ac source current, active power and reactive power are shown in Fig.7. THD in source current and voltage without filter are also shown in Fig.7. Corresponding results with filter are shown in Fig.9. Transient responses of speed, developed torque and current with the passive filter are shown in Fig. 8. Power quality performance is shown in the Table III. Without shunt passive filter power factor is 0.832 and with filter the power factor is 0.993. Total harmonic distortion (THD) in the supply current is 6.24 without filter and 1.63 with filter. THD in supply voltage is 0.02% without filter and 0.01% with filter. A hybrid filter reported in [15] for this purpose, has corresponding values as tabulated in Table III. All the results are better in the present scheme. Results for a three level NPC converter reported in [11] are also shown in Table III.

TABLE III. PERFORMANCE COMPARISON

Power Quality Parameters	**THD (%)**		**PF**	**P (kW)**	**Q (kvar)**
	V_s	I_s			
Proposed scheme without filter	0.02	6.24	0.832	7.5	5
Proposed scheme with filter	0.01	1.63	0.993	8.5	1
As per ref. [15]	9	3.83	0.974	2	0.468
As per ref. [11]	----	3	0.998	----	----

CONCLUSIONS

A three level ac to dc converter is used at the front-end of a PWM VSI supplying three phase induction motor for input power conditioning. For reactive power compensation and supply current harmonics reduction, passive shunt filter is designed and simulated. Simulation study is done without passive filter and with the designed filter. Without passive filter significantly large reactive power is drawn from supply lines. The overall performance is compared in terms of total harmonic distortion (THD) of source current, supply power factor and DC voltage regulation. The simulation results show that three level ac to dc converter with the designed passive filter gives less harmonics and almost unity power factor. For a large power drive, this reduction in harmonics and reactive power requirement makes the proposed scheme highly useful and economical.

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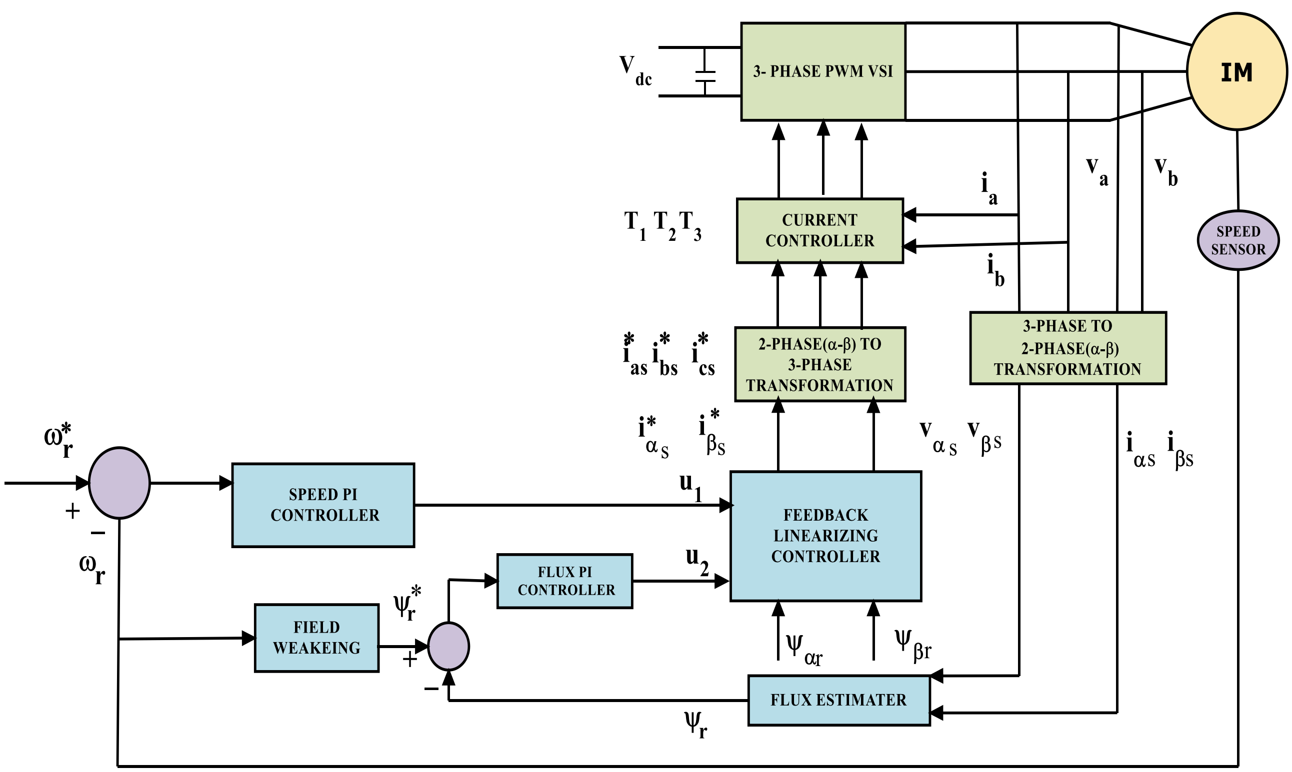


Fig.1 Schematic diagram of a linearized induction motor drive with PI speed flux controller

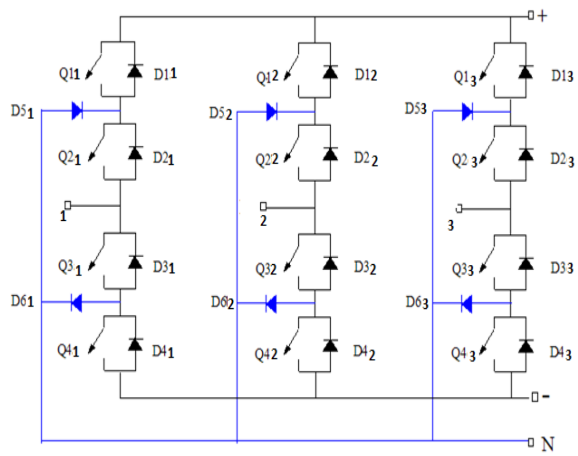


Fig.2 Configuration of 3-phase 3- level NPC converter

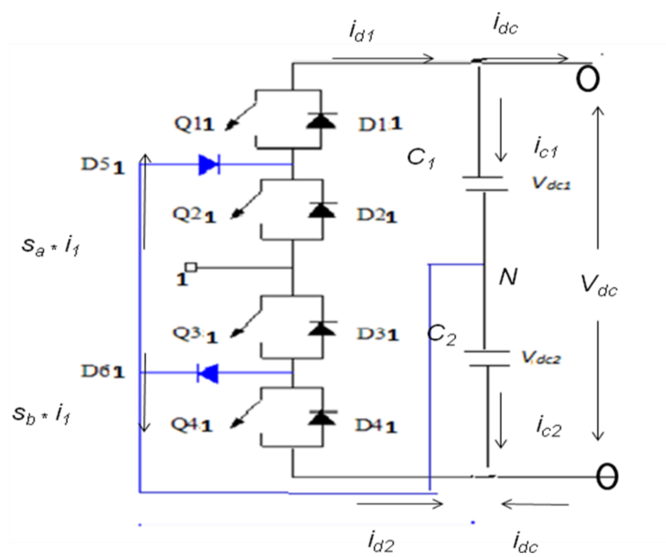


Fig. 3 Operation of one phase in 3-level NPC Converter

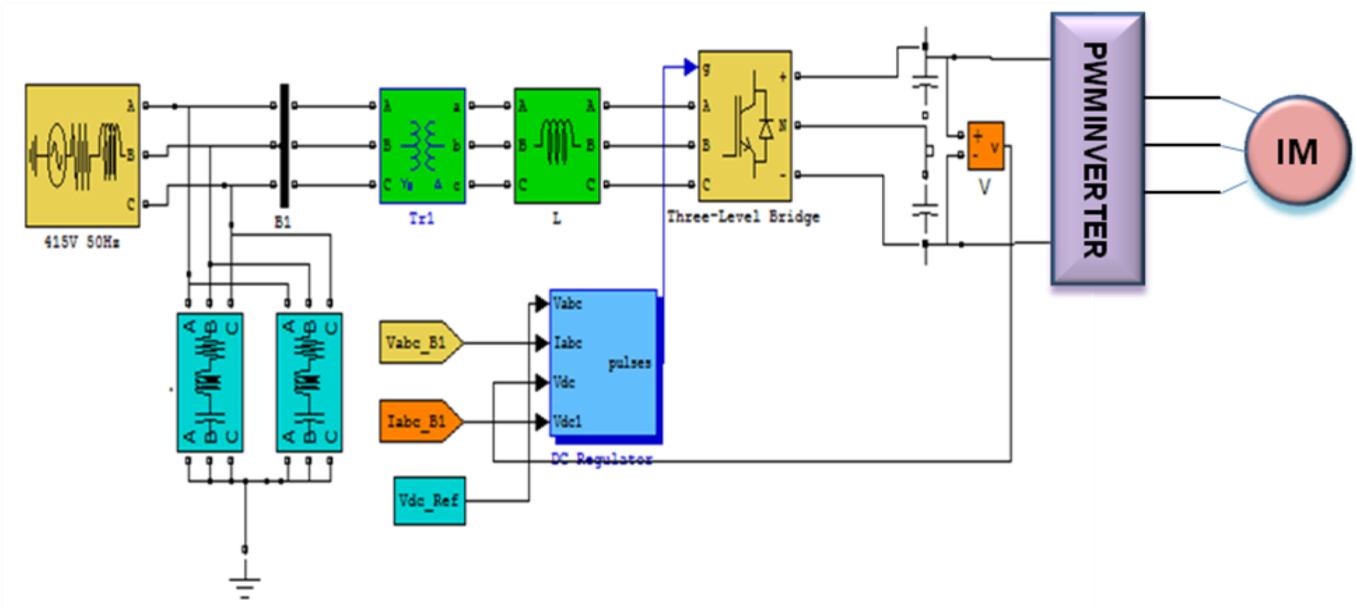


Fig. 4 Simulink block diagram of three level ac-dc converter with passive filters for linearized induction motor drive

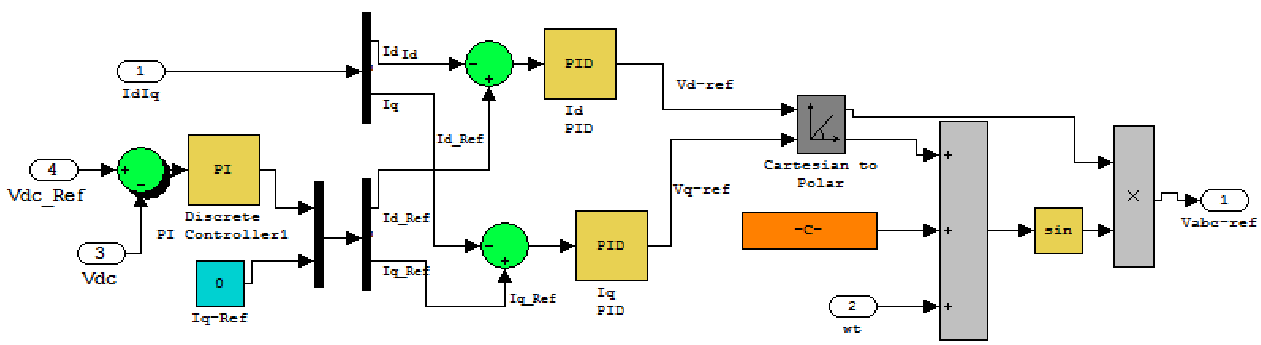
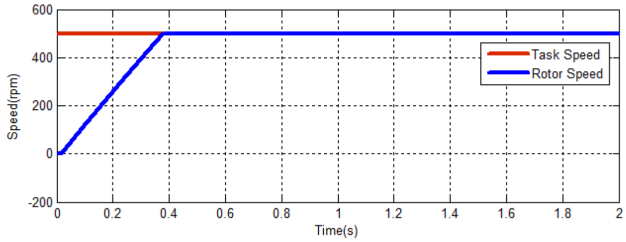
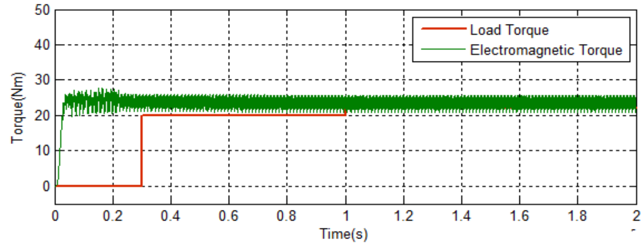


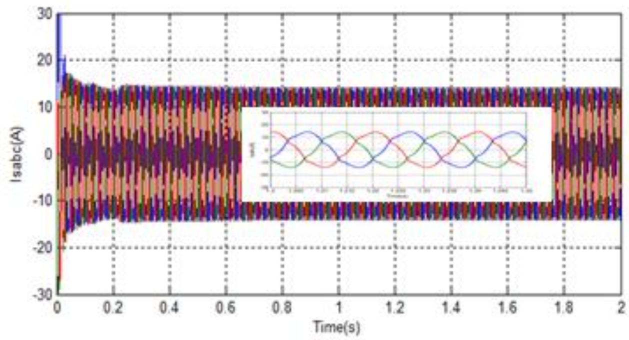
Fig. 5 Simulink block diagram of dc-bus voltage regulator



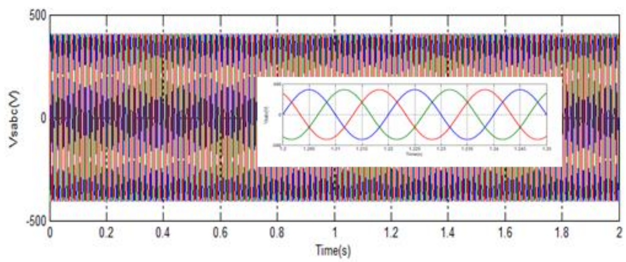
(a) Reference and actual speed response



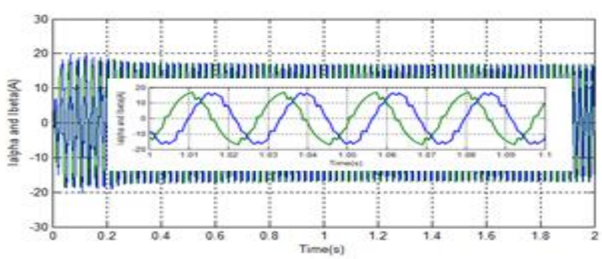
(b) Load torque and developed torque responses



(c) Three phase stator currents

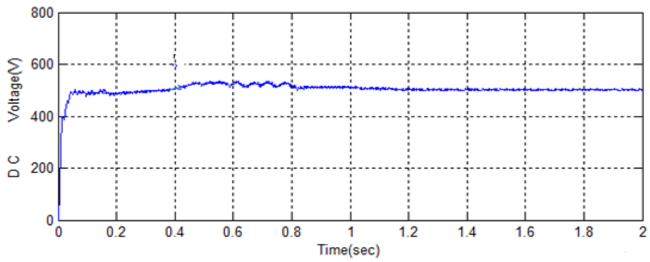


(d) Three phase stator voltages

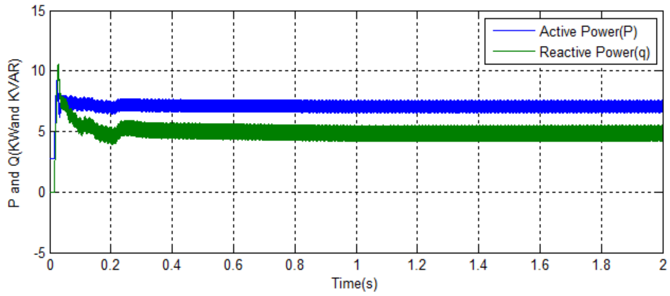


(e) Alpha-Beta components of stator current

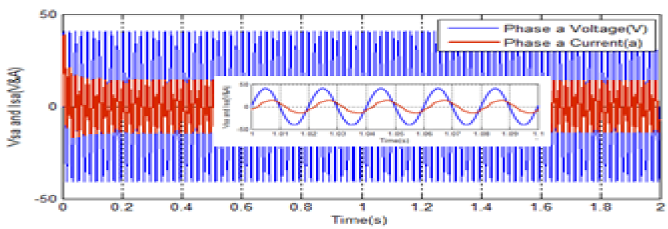
Fig. 6 Dynamic response of proposed ac-dc converter fed linearized induction motor with load perturbation without passive filter



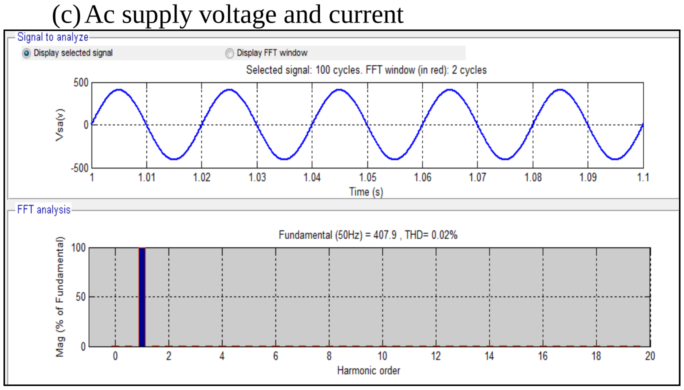
(a) DC link voltage response



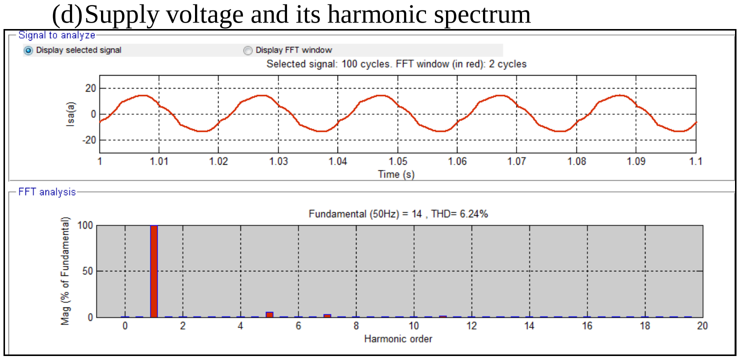
(b) Active and reactive power responses



(c) Ac supply voltage and current

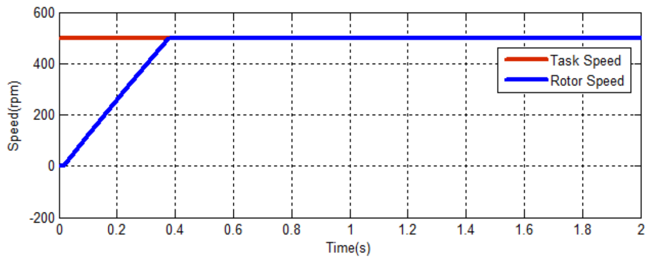


(d) Supply voltage and its harmonic spectrum

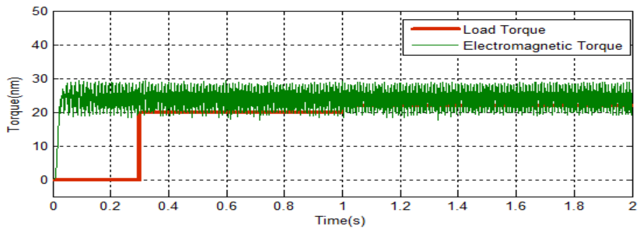


(e) Supply current and its harmonic spectrum

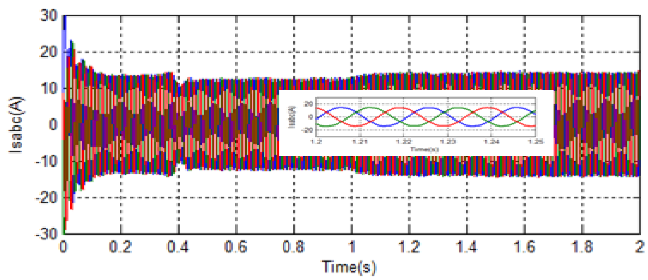
Fig. 7 Input performance characteristics without passive filter



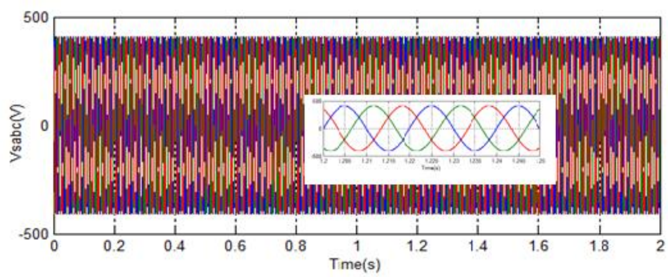
(a) Reference and actual speed response



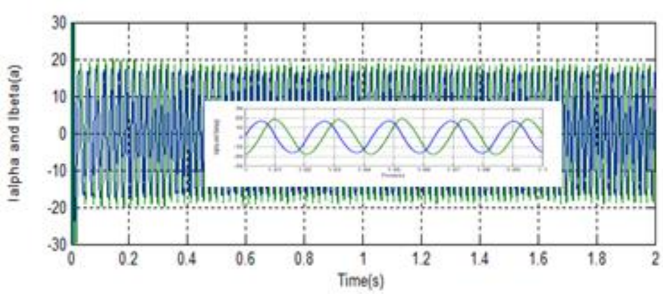
(b) Load torque and developed torque responses



(c) Three phase stator currents

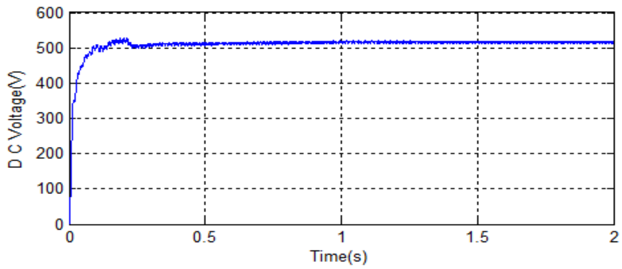


(d) Three phase stator voltages

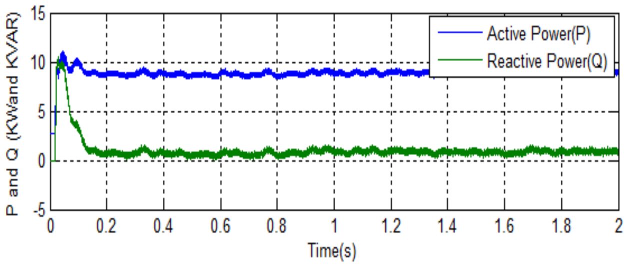


(e) Alpha-Beta components of stator current

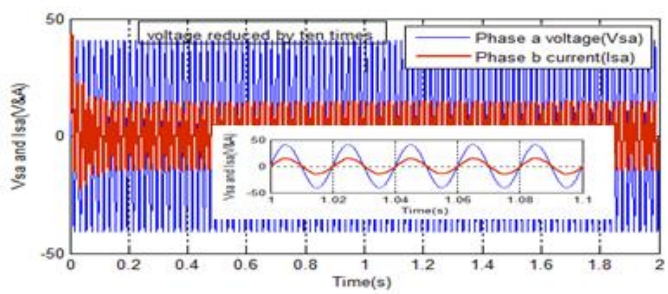
Fig. 8 Dynamic response of proposed ac-dc converter fed linearized induction motor with load perturbation with passive filter



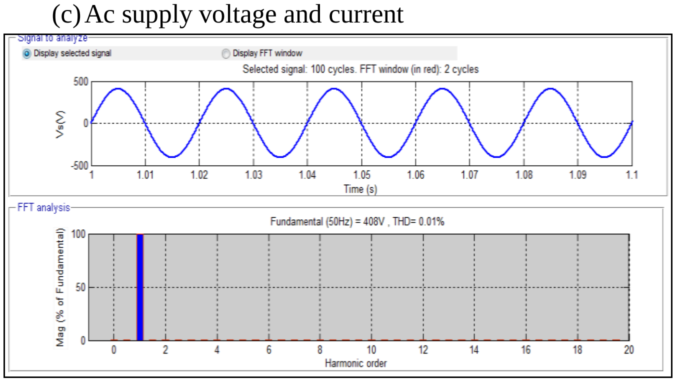
(a) DC link voltage response



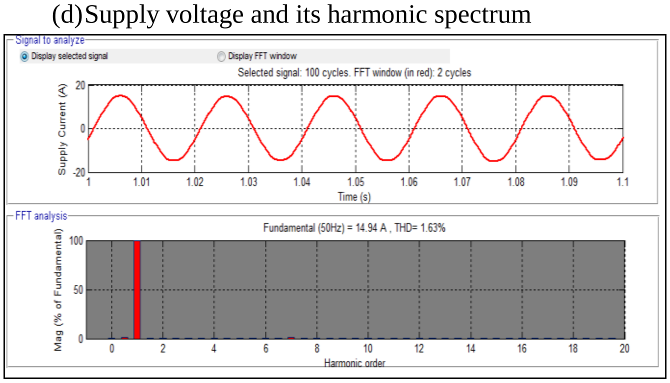
(b) Active and reactive power responses



(c) Ac supply voltage and current



(d) Supply voltage and its harmonic spectrum



(e) Supply current and its harmonic spectrum

Fig. 9 Input performance characteristics with passive filter