

## Improved Power Quality Converter Fed Variable Speed Induction Motor Drive for Air Conditioning

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### Abstract

*This paper deals with the performance analysis of an improved converter fed vector controlled induction motor drive for variable speed operation of an air conditioner. A single phase boost converter at input improves the power quality of AC mains in terms of unity power-factor and sinusoidal current and provides a constant DC voltage source to feed an inverter supplying variable frequency currents to cage motor even under fluctuating AC mains voltage. Vector controlled induction motor drive with reduced number of sensors, results in low cost and high efficiency of total system. Closed loop control of converter and inverter fed cage motor drive employing two PI (proportional integral) controllers, provides precise control and energy conservation in AC distribution system, cage motor and compressor of air conditioning system. The complete system is modeled and its simulated behavior demonstrates the above mentioned features to justify its application over a wide range of ratings of air conditioners.*

**Keywords:** PFC Converter, Vector Control, Inverter, Induction Motor, Air-conditioning

### Introduction

The air conditioning (AIRCON) load is now becoming a major constituent of electric power consumption in urban areas. Conventional on/off control of AIRCON employing single-phase squirrel cage induction motor has almost become unaffordable due to poor efficiency of overall system and increased cost of electrical energy. Variable speed control of AC motors (Mohan *et al.* 1995, Saied 1999, Gorgette *et al.* 1998 and Erickson 1999) is considered the obvious choice, which saves the electrical energy in the compressor system, the motor and AC mains, which was mainly due to poor power-factor and frequent start/stops of the motor. Moreover, with precise and intelligent control, it gives better comfort due to narrow range of temperature control, reduced size and rating of compressor motor and faster response.

Normally uncontrolled single-phase diode bridge rectifier is used to feed inverter controlled AC motor, which causes poor power-factor and harmonic injection into AC mains resulting in increased losses and disturbance to nearby consumers (Gorgette *et al.* 1998 and Erickson 1999).

Since converter technology (AC to DC conversion) has been revolutionized recently due to the introduction of new breed of improved converters (Wall and Jackson 1997, Zhou *et al.* 2000) and simple single-phase boost converter with single-switch can eliminate the problems of poor power-factor and harmonics injection. Therefore, in this investigation, an attempt is made to analyze the performance of an improved power quality converter fed variable speed vector controlled 3-phase, squirrel cage induction motor drive with a view to design and develop a low cost, energy efficient, compact and intelligent controlled AIRCON system.

## System Configuration and Principle of Operation

Fig.1 shows the schematic diagram of proposed improved power quality converter fed variable speed, induction motor drive for AIRCON system. A boost converter is employed to convert single-phase AC supply into a constant voltage DC to feed the current controlled voltage source inverter (CC-VSI). The power-factor correction (PFC) converter (Wall and Jackson 1997; Zhou *et al.* 2000) offers the advantages of unity power-factor, elimination of harmonic currents, and well regulated output DC voltage even under fluctuating AC mains voltage. The PFC converter is controlled employing a proportional integral (PI) DC voltage controller to regulate its DC output voltage. The output of PI voltage controller is limited to safe value and is considered as an amplitude of an inductor current ( $I_{Lm}^*$ ). This amplitude is multiplied with rectified sinusoid unit amplitude current template ( $u_d$ ) to derive the reference inductor current ( $i_L^*$ ). A PWM (pulse width modulation) current controller is employed over sensed inductor current ( $i_L$ ) and its reference value ( $i_L^*$ ) to generate gating signal to an IGBT (insulated gate bipolar transistor) of boost converter. The carrier frequency of PWM current control is taken 20 kHz to reduce the noise below audible level.

In response to the gating of the IGBT, PFC converter regulates the output DC voltage even under nonlinear DC load of inverter input DC link current ( $i_{dc}$ ) and varying AC input voltage ( $v_s$ ) and maintains sinusoidal AC input current ( $i_s$ ). A current controlled voltage source inverter (CC-VSI) is used to convert DC-regulated voltage from PFC converter into variable frequency AC voltage to feed 3-phase, squirrel cage motor employed to drive an AIRCON compressor. This CC-VSI feeds a three-phase, squirrel cage motor system is controlled in field orientation control (as also named as

Vector Control) with reduced number sensors (Rajashekara *et al.* 1996; Xue *et al.* 1990) to reduce the cost and size of inverter and motor with fast, smooth and precise control. A well-verified speed sensorless algorithm (Xue *et al.* 1990) is used to estimate the speed of the motor using voltage and current signals of the motor. The well-established techniques (Green and Williams 1989, Xu and Novotny 1991) are used to derive the motor current ( $i_{as}$ ,  $i_{bs}$  and  $i_{cs}$ ) from DC link current ( $i_{dc}$ ) of the inverter (Green and Williams 1989) for its current control. The motor terminal voltages ( $v_{as}$ ,  $v_{bs}$ ,  $v_{cs}$ ) are derived from DC link voltage ( $v_{dc}$ ) and switching logic signals (SA, SB, SC) (Xu and Novotny 1991) to estimate the speed of the motor. The proposed strategy reduces the number of sensors to one current sensor ( $i_{dc}$ ) and one voltage sensor ( $v_{dc}$ ) resulting in reduced cost of the system.

A PI speed controller is used to maintain the speed of the motor ( $\omega_r$ ) to its desired reference value ( $\omega_r^*$ ). The output of PI speed controller is limited to maximum safe value and considered as reference torque ( $T^*$ ). A field weakening controller gives the reference exciting current of the motor ( $i_{mr}^*$ ) from the speed of the motor ( $\omega_r$ ). The well-established indirect vector control method (Xu and Novotny 1991) is used to generate the reference 3-phase AC motor currents ( $i_{as}^*$ ,  $i_{bs}^*$  and  $i_{cs}^*$ ). A PWM current controller over the winding currents ( $i_{as}$ ,  $i_{bs}$  and  $i_{cs}$ ) and their reference value ( $i_{as}^*$ ,  $i_{bs}^*$  and  $i_{cs}^*$ ) is used to generate gating signal to IGBT of the CC-VSI. In response to these gating signals, CC-VSI impresses the PWM AC voltages across the motor terminals resulting in sinusoidal currents in its winding and controls the speed of the motor in the desired manner for smooth, precise and fast control of AIRCON system. A worst caseload pattern of constant rated torque of air compressor is considered to demonstrate the effective control of proposed control strategy.

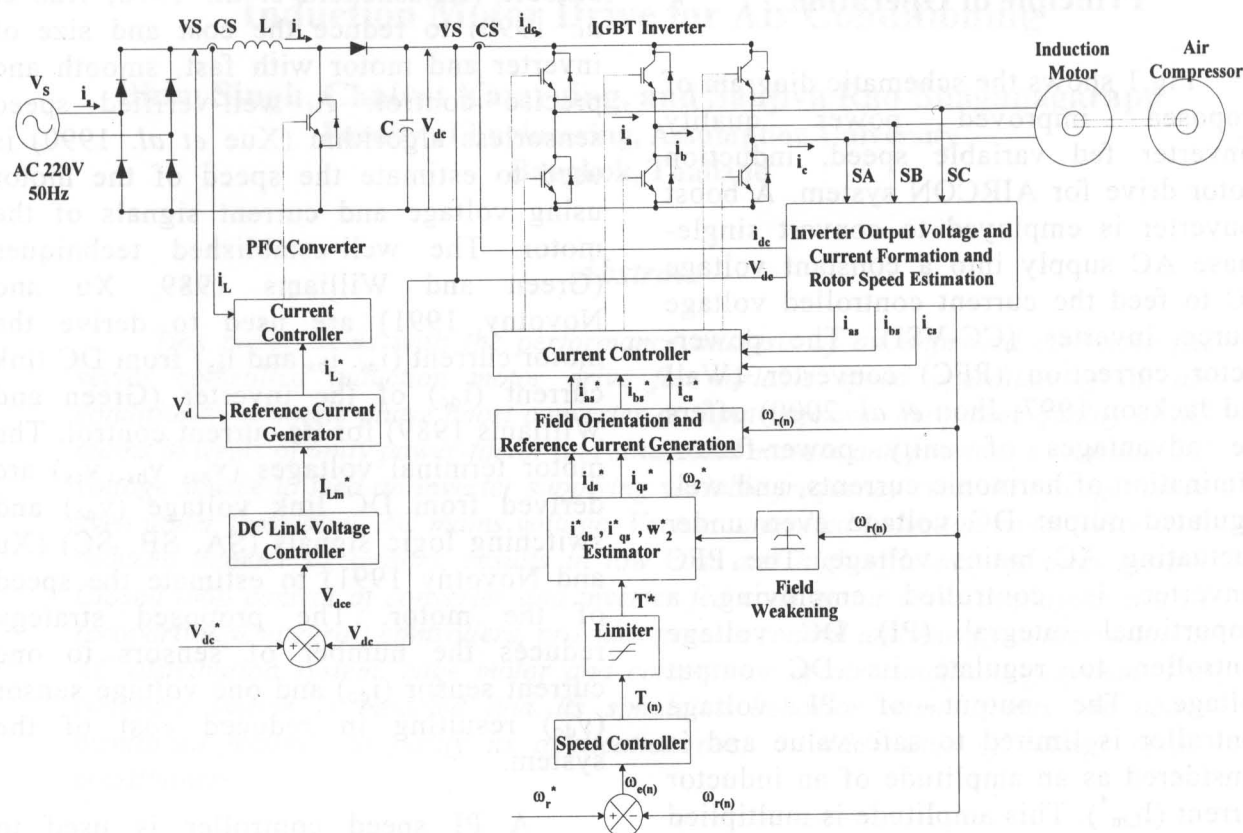


Fig. 1. Schematic diagram of improved power quality converter fed variable speed induction motor drive for air conditioning

## Modeling of the System

Different parts of the variable speed induction motor drive for AIRCON system are modeled separately in sequence and then integrated together in order to get the complete model of the system. The modeling of the proposed system is divided into the following subsections.

## DC Link Voltage Controller of PFC Converter

A PI voltage controller is used over the sensed DC link voltage ( $v_{dc}$ ) and its reference value ( $v_{dc}^*$ ). The output of PI controller is as:

$$I_{Lm}^* = I_{Lm(n-1)}^* + K_{pd}v_{dce(n)} + K_{id}(v_{dce(n)} - v_{dce(n-1)}) \quad (1)$$

Where  $I_{Lm}^*$  and  $I_{Lm(n-1)}^*$  are the output (limited safe values) of DC voltage controller

at  $n^{\text{th}}$  and  $(n-1)^{\text{th}}$  sampling instants.  $K_{pd}$  and  $K_{id}$  are proportional and integral gain constants of PI voltage controller.  $v_{dce(n)}$  and  $v_{dce(n-1)}$  are the DC link voltage error at  $n^{\text{th}}$  and  $(n-1)^{\text{th}}$  sampling instants. The DC voltage error at  $n^{\text{th}}$  sampling instant is estimated as:

$$V_{dce(n)} = V_{dc}^*(n) - V_{dc(n)} \quad (2)$$

### Reference Inductor Current Generator ( $i_L^*$ )

The reference inductor current ( $i_L^*$ ) is derived using sensed diode rectifier output voltage ( $v_d$ ) as:

$$i_L^* = I_{Lm}^* u_d \quad (3)$$

Where  $u_d$  is unit current template derived as:

$$u_d = v_d/V_{sm} \quad (4)$$

Where  $V_{sm}$  is the amplitude of single-phase AC voltage and  $v_d$  is the rectified output of diode rectifier defined as:

$$v_d = |v_s| \quad (5)$$

Where  $v_s$  is the AC supply voltage as:

$$v_s = V_{sm} \sin \omega t \quad (6)$$

Where  $\omega$  is the AC supply frequency in rad/sec.

### PWM Inductor Current Controller of PFC Converter

The inductor current error ( $\Delta i_L = i_L^* - i_L$ ) in PWM current controller is amplified and compared with carrier frequency PWM wave to generate gating signal for IGBT of PFC converter. If amplified current error is more than the instantaneous value of carrier wave then IGBT is made ON and switching function of PFC converter (SFC) is considered one (SFC = 1). If amplified current error is lower than value of carrier wave, the IGBT is made OFF and switching function (SFC) is considered zero (SFC = 0).

### Modeling Equations of PFC Converter

The PFC converter is modeled through two first order differential equations of inductor current ( $i_L$ ) and DC link capacitor voltage ( $v_{dc}$ ) as:

$$p i_L = (v_d - v_p) / L - R (i_L / L) \quad (7)$$

$$p v_{dc} = (i_L - i_{dc}) / C_{dc} \quad (8)$$

Where,  $p$  is the differential operator ( $d/dt$ ).  $R$  is the resistance of the inductor  $L$ ,  $v_p$  is the PWM voltage across the IGBT and defined as:

$$v_p = v_d(1 - \text{SFC}) \quad (9)$$

The DC link load current ( $i_{dc}$ ) is computed as:

$$i_{dc} = i_{as} SA + i_{bs} SB + i_{cs} SC \quad (10)$$

Where  $i_{as}$ ,  $i_{bs}$  and  $i_{cs}$  are the 3-phase inverter output currents flowing into the motor windings and SA, SB and SC are the switching functions of the inverter derived by the logic circuit shown in Fig. 1.

### PI Speed Controller

The output of speed controller at  $n^{\text{th}}$  sampling instant is given as:

$$T_{(n)}^* = T_{(n-1)}^* + K_p \{w_{e(n)} - w_{e(n-1)}\} + K_i w_{e(n)} \quad (11)$$

The output of speed controller ( $T^*$ ) is limited to safe value and is considered as reference torque. where  $K_p$  and  $K_i$  are the proportional and integral gain constants respectively of the speed controller.  $w_{e(n)}$  and  $w_{e(n-1)}$  are the speed error at  $n^{\text{th}}$  and  $(n-1)^{\text{th}}$  sampling instants. The speed error at  $n^{\text{th}}$  instant is computed as:

$$w_{e(n)} = \omega_{r(n)}^* - \omega_{r(n)} \quad (12)$$

Where  $\omega_{r(n)}$  is the rotor speed of the motor and is estimated from AC voltage and currents of the motor using well established algorithm (Xue *et al.* 1990). Because of limited space it is not included here but can be referred from sensorless algorithms (Rajashekara *et al.* 1996, Xue *et al.* 1990).

### Field Weakening Control

In field weakening control the magnetizing current,  $i_{mr}^*$  is expressed as a function of rotor speed  $\omega_r$  which is given below:

$$i_{mr}^* = I_m \text{ if } \omega_r < \omega_b; i_{mr}^* = K_f I_m / \omega_r \text{ if } \omega_r > \omega_b \quad (13)$$

Where,  $K_f$  is the flux constant.

### Vector Control Structure

The reference torque  $T^*$  and reference magnetizing current,  $i_{mr}^*$  are further processed in vector controlled structure to estimate vector based DC currents and slip frequency as:

$$i_{ds}^* = (di_{mr}^*/dt) + i_{mr}^* \quad (14)$$

$$i_{qs}^* = T^* / (k i_{mr}^*) \quad (15)$$

$$\text{Where, } k = (3/2) (p/2) \{M/(1+\sigma r)\} \text{ and } \omega_{sl}^* = i_{qs}^* / (i_{mr}^*) \quad (16)$$

The slip speed ( $\omega_{sl}^*$ ) is added to the rotor speed  $\omega_r$  and the sum is integrated to obtain the flux angle  $\phi$  between the stator axis and the rotating magnetic field. The current  $i_{ds}^*$  and  $i_{qs}^*$



are in the synchronously rotating frame. The reverse Park's transformation is applied to convert them into the stationary reference frame as:

$$i_{dss}^* = i_{ds}^* \cos \varphi - i_{qs}^* \sin \varphi \quad (17)$$

$$i_{qss}^* = i_{ds}^* \sin \varphi + i_{qs}^* \cos \varphi \quad (18)$$

Where,  $\varphi$  is the flux angle and at  $n^{\text{th}}$  sampling instant is given as:

$$\varphi(n) = \varphi(n-1) + (\omega_r + \omega_{sl}^*) dt_n \quad (19)$$

Where,  $dt_n$  is the sampling period.

Using 2-phase to 3-phase transformation the 3-phase reference motor currents  $i_{as}^*, i_{bs}^*, i_{cs}^*$  are obtained as given below:

$$i_{as}^* = i_{qss}^* \quad (20)$$

$$i_{bs}^* = +(\sqrt{3}/2) i_{dss}^* - (1/2) i_{qss}^* \quad (21)$$

$$i_{cs}^* = -(\sqrt{3}/2) i_{dss}^* - (1/2) i_{qss}^* \quad (22)$$

### Modeling of Current Controller and Current Controlled Inverter

The PWM switching pattern controlling the switching of the inverter devices, is generated by comparison of motor currents with their corresponding reference currents. The current controller compares the motor current with their reference current and the switching on/off pattern resulting from this is used to control the gates of inverter devices which are considered here and are stated below:

SF(switching function) = 1 if upper device OFF inverter is ON

SF(switching function) = 0 if lower device OFF inverter is ON

$$\begin{aligned} \text{if } i_{as} > i_{as}^* + h \quad SA &= 0 \\ i_{as} < i_{as}^* - h \quad SA &= 1 \\ \text{if } i_{bs} > i_{bs}^* + h \quad SB &= 0 \\ i_{bs} < i_{bs}^* - h \quad SB &= 1 \\ \text{if } i_{cs} > i_{cs}^* + h \quad SC &= 0 \\ i_{cs} < i_{cs}^* - h \quad SC &= 1 \end{aligned} \quad (23)$$

The three phase instantaneous voltages  $v_{as}, v_{bs}$  and  $v_{cs}$  at the output of inverter are expressed in terms of switching functions (SFs) as:

$$v_{as} = (v_{dc}/3) (+2SA - SB - SC) \quad (24)$$

$$v_{bs} = (v_{dc}/3) (-SA + 2SB - SC) \quad (25)$$

$$v_{cs} = (v_{dc}/3) (-SA - SB + 2SC) \quad (26)$$

Where SA, SB and SC are switching functions of phase a phase b phase and phase c respectively and  $v_{dc}$  is the DC link voltage. These stator voltages are expressed in the stationary reference frame of dq variables as:

$$v_{qs} = (v_{bs} - v_{cs}) / \sqrt{3} \quad (27)$$

$$v_{ds} = v_{as} \quad (28)$$

### Induction Motor Modeling

The first order differential equations used for modeling an induction motor are given below (Rajashekara *et al.* 1996):

$$p[I] = L^{-1} ([V] - [I] [R] - w_r [G] [I]) \quad (29)$$

$$pw_r = (T_e - T_L)/J \quad (30)$$

$$T_e = (3/2)(L_m)(i_{ds}i_{qr} - i_{dr}i_{qs}) \quad (31)$$

$$[I] = [i_{ds} \ i_{qs} \ i_{dr} \ i_{qr}]^T \quad (32)$$

$$[V] = [v_{ds} \ v_{qs} \ v_{dr} \ v_{qr}]^T \quad (33)$$

$$[R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \quad (34)$$

$$[L] = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ 0 & -L_m & 0 & L_s \\ -L_s & 0 & L_m & 0 \end{bmatrix} \quad (35)$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & L_r \\ -L_m & 0 & -L_r & 0 \end{bmatrix} \quad (36)$$

The set of seven first order differential equations (7,8,29,30) along with other essential expressions defines the model of the proposed system. These equations are integrated using fourth order Runge-Kutta method to simulate the transient and steady state behavior of the proposed system.

## Discussion of Results

Performance characteristics of improved converter fed variable speed drive induction motor drive for AIRCON system is shown in Fig.2 demonstrating its transient and steady state behavior for starting and change in reference speed. The necessary parameters are given in Appendix. From these results the following observations are made.

### Starting Performance of the Proposed Drive System

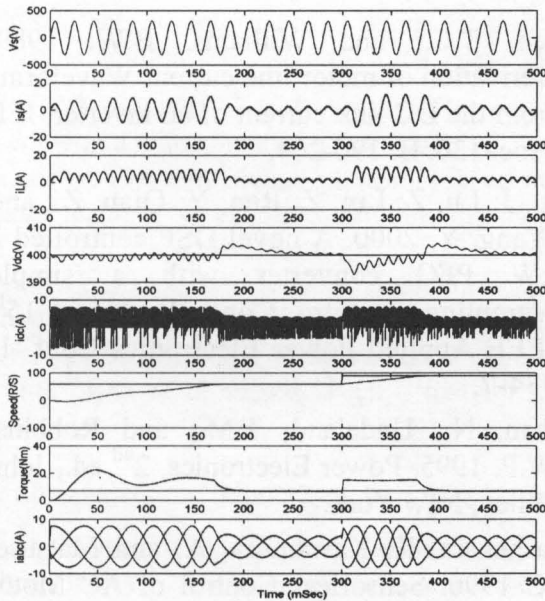


Fig. 2. Performance of improved converter fed variable speed induction motor drive for AIRCON system.

Fig. 2 shows single-phase AC supply voltage ( $v_s$ ), current ( $i_s$ ) and PFC inductor current ( $i_L$ ), DC link voltage ( $v_{dc}$ ) and its reference value ( $v_{dc}^* = 400V$ ), DC link current ( $i_{dc}$ ), rotor speed ( $\omega_r$ ) and its reference value ( $\omega_r^*$ ), developed torque ( $T_e$ ), load torque ( $T_L$ ), and 3-phase motor winding currents ( $i_{as}$ ,  $i_{bs}$ ,  $i_{cs}$ ). It may be observed from this figure that supply current remains sinusoidal and in phase with input AC supply voltage resulting in unity power-factor and harmonic free current during starting of the motor. This supply current increases with the speed during starting because the system needs more power at higher speeds of the motor with almost constant

torque. Once the motor has started, the supply current is reduced because the required power is less under normal running of the motor due to PI controller action. But the ripples in DC link voltage are slightly increased due to increased load current ( $i_{dc}$ ). The PFC converter controls the DC link voltage to almost constant value and maintains sinusoidal input current even under such a highly nonlinear load as can be seen from DC link current ( $i_{dc}$ ). The motor accelerates from zero speed to reference speed (60rad/s) with varying frequency constant amplitude currents decided by the PI speed controller. As the rotor speed reaches reference value the developed torque becomes equal to load torque and accordingly winding currents and AC supply current are reduced to steady state values. It is observed from these results that air compressor motor is started smoothly and with reduced disturbance to supply system resulting in reduced energy consumption. Moreover, the proposed system does not need frequent start/stops it only regulates the speed of the compressor smoothly from low to high values depending upon required cooling.

### Performance during Change of Reference Speed of the System

Initially the reference speed is set to 60rad/sec and at 0.3 Sec. it is increased to 90 rad/sec. The PI speed controller becomes active and it increases the winding currents and the developed torque to maximum permitted value. The AC supply current is increased and a dip is also observed in DC link voltage. At the same time, PFC controller comes into action and recovers the DC link voltage to its reference value. Once the motor reaches reference speed the developed torque becomes equal to load torque (7 Nm) and accordingly winding currents and AC supply current are reduced to steady state values. The DC link voltage has small overshoot (1% only) and recovers quickly to normal value (400V). With the proposed variable speed drive system there is no need to frequently start and stop the motor. The compressor motor speed is adjusted according to the required cooling and the drive system draws reduced power during dynamic and under steady state operation.

## Conclusions

It has been observed that the proposed improved converter fed variable speed induction motor drive is capable of smooth starting against full load torque of the compressor and smooth speed control with fast response and precise control of AIRCON system. The PFC converter has improved the power quality of AC mains in terms of unity power-factor and reduced harmonic current and has regulated output DC voltage under such a highly nonlinear inverter-motor load especially during dynamic conditions. The proposed vector control strategy for motor control results in fast response, accurate control, reduced rating of the motor and low cost due to reduced number of sensors. The complete control scheme can be implemented using a low cost micro-controller thus resulting in compact, reliable and intelligent control of AIRCON system. It is hoped that this investigation will encourage the design engineers to develop inverter AIRCON systems. The proposed scheme is being implemented using TMS320F240 DSP and the test results will be reported very soon in a companion paper.

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## Appendix

*PFC Converter Parameter:*  $V_{sm}=220\sqrt{2}V$ ,  $\omega=314$  rad/sec.,  $L=2.4mH$ ,  $R=0.1\Omega$ ,  $K_{pd}=1.275$ ,  $K_{id}=0.3298$ ,  $C_{dc}=4700\mu F$ ,  $V_{dc}^*=400V$ ,  $I_{Lmax}^*=25A$ .

*Inverter-Motor Parameters:* 1.1 kW, 50 Hz, 4 Pole, 2.65 A, 1410 rpm,  $R_s=7.523\Omega$ ,  $R_r=6.531\Omega$ ,  $X_{ls}=X_{lr}=5.65\Omega$ ,  $X_m=133.27\Omega$ ,  $J=0.044$  Kg-m<sup>2</sup>,  $K_p=1.59$ ,  $K_i=0.0195$ ,  $T_L=7.0Nm$ ,  $T_{max}=15.0Nm$ ,  $I_m=1.65A$ .

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