



Induction Motor Control with a Small Dc-Link Capacitor Inverter Fed by Three-Phase Diode Front-End Rectifiers

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Abstract

The main objective of the work presented in this paper is to design and simulate a new and simple 3-phase, Space Vector Modulated (SVM) front end rectifier feeding induction motor drive for near unity power factor operation with low supply current harmonics. The indirect vector controlled induction motor drive is used as load, but any load which is capable of regenerating can be employed. The various design considerations for linear operation of SVM front end rectifier are discussed. The expression to compute the required value of line inductance, a method based on modulation index control for regulating dc link voltage and a method based on instantaneous phase compensation for achieving unity power factor operation are proposed. These methods are computationally less complex. A prototype system for 5-HP 3-ph induction motor is implemented in a MATLAB/SIMULINK environment. The dc link voltage, reference speed tracking and line side phase current are observed and total harmonic distortions (THD) are recorded. The unity power factor operation with acceptable current THDs and stiff dc link voltage conform the validity of control scheme.

Keywords: Space Vector Modulation (SVM), PWM Rectifier, Front End Rectifier, Space Vector Modulated Rectifier, Unity Power Factor Operation, Total Harmonic Distortion (THD), Induction Motor Drive.

Introduction

The AC motor drives with cage-type induction machines are widely used in industry for variable-speed applications over a wide power, ranging from fractional horsepower to multi- megawatts. The total harmonic distortion factor (THD) for supply current should be maintained within specified limits as specified in various standards and guide lines (i.e. IEEE 519 in USA and IEC 61000-3 in U.K. etc)[1]. The diode or SCR based front end rectifier suffers from the problems of poor power quality in terms of line side current harmonics and power factor, slowly varying rippled dc output at load end, low efficiency, and large size of ac and dc filters.

An exhaustive review of three-phase improved power quality ac-dc converter (IPQC) configurations is presented in[2]. The solution using active power filters (APFs) is attractive for already installed systems. However, the better option for new installations is to incorporate the current harmonics and power factor controllability within the AC-DC converter itself. The pulse width modulated (PWM) rectifier offers a promising solution[2-4].

Various methods proposed for control of powers in PWM rectifiers [5-14] can be broadly classified as indirect power control or direct power control methods. The simple, fast and accurate Hysteresis Current Control (HCC) suffers from variable average and instantaneous switching frequency as

DC load current varies causing excessive stress on switching devices[5]. The voltage-oriented control (VOC) [6-10] for indirect power control offers high dynamic and static performance via internal current control loops at constant switching frequency. In VOC, the computation of forward and inverse Clark and Park transformations are employed which requires computation of unit vectors at every sampling instant making system complex. In hysteresis based DPC[11,12], the problem of variable switching frequency still remains. The advanced DPC techniques[13,14] offer improved performance at the cost of

increased system complexity.

In this paper a simple control technique employing instantaneous phase compensator for unity power factor operation and modulation index control for dc power control is proposed. As both the controls are employed separately, it is effectively a decoupled control as in VOC and DPC, but with less complexity.

The design considerations for PWM boost rectifier like current control limit, waveform distortion limit, required value of boost inductance and feedback control strategy for stiff dc output voltage are discussed first. Next the indirect vector control of induction motor is reviewed followed by selection of dc voltage and line inductance for required operation of SVM boost rectifier for reliable control of induction motor drive system. Finally the simulation of the proposed PWM rectifier/inverter linked system is done, results are interpreted and conclusions are drawn.

Control Scheme

The proposed scheme is shown in figure 1. The system at the output of the dc link capacitor is induction motor drive (indirect vector controlled drive is considered in this study). The system at the left of dc link capacitor is PWM boost rectifier.

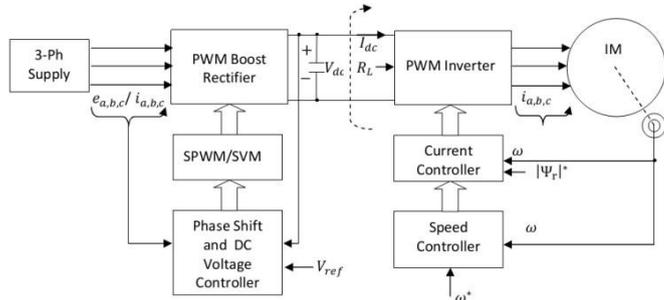


Figure 1: PWM front end rectifier driving induction motor drive

Design considerations

DC link voltage and supply current control :

Figure 2a shows schematic diagram of 3-ph PWM active rectifier. Figure 2b shows equivalent circuit considering line impedance (R-L) as load excited by two AC sources, one being AC line source and other being VSI controlled AC source which in turn is considered to be excited by DC output voltage of rectifier. The DC output voltage is inversely proportional to modulation index *m* for voltage source inverter (VSI). Thus active power through dc link can be controlled by controlling *m*.

Design consideration-1:

The following design considerations must be observed so that phase currents track the sinusoidal reference waveforms[15]. The PWM rectifier losses control (‘loss of control limit’) when following inequality is violated.

$$V_{dc} > \frac{\sqrt{6}E}{\pi}$$

(1)

Where, *E* = RMS value of phase voltage.

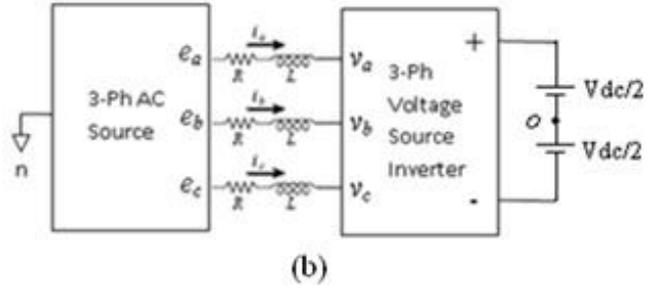
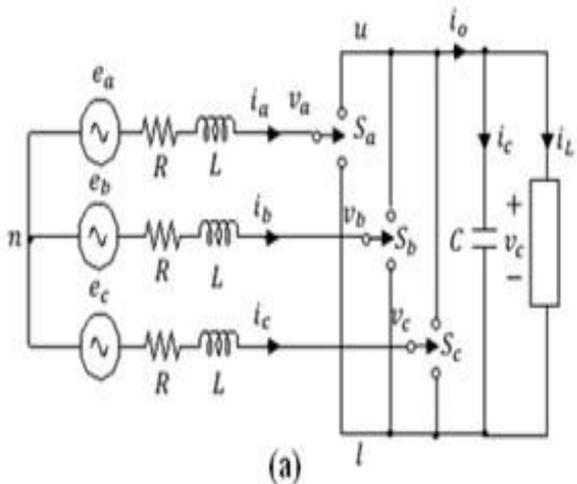


Figure 2: (a) Three Phase PWM boost rectifier and (b) R-L load of line excited by two AC sources

The current distortion starts if the following ‘current waveform distortion limit’ is violated.

$$V_{dc} > \sqrt{6}E$$

(2)

Design consideration-2:

The second design consideration is Power Matching in Modulators[15]. It is possible only when capacitor is charged above value corresponding to loss of control limit given in (1) prior to application of load and must be maintained at that level over full range of load current demand.

The above-mentioned requirements are simultaneously fulfilled by ensuring that the voltage *V_d* across the dc link is regulated at a level well above both the loss of control limit and the current waveform distortion limit.

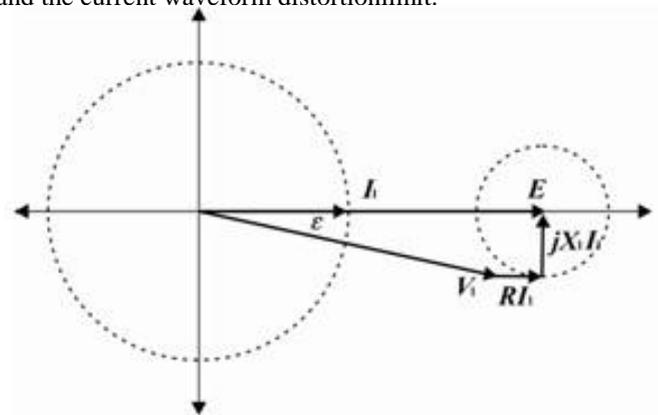


Figure 3: Rectification at unity power factor

Figure 3 shows vectorial representation of 3-Ph PWM rectifier for rectification operation, where *V₁*=Rms value of the fundamental of converter phase voltage, *E*= Rms value of the of supply phase voltage, *I₁*= Rms value of the fundamental of supply phase current and *X₁*=Reactance of *L* at fundamental frequency. It can be seen that the phase and amplitude of line current can be controlled indirectly by controlling phase angle and amplitude of fundamental of converter voltage *|V₁|*. Referring to figure 2 and figure 3, the rms value of fundamental of supply phase current for unity power factor operation is



$$k = \frac{V_{dc} I_{dc} 3}{E} \tag{3}$$

The DC voltage of rectifier from (2) is,

$$V_{dc} = \frac{\sqrt{6}E}{m} = \frac{V_{dcmin}}{m} \tag{4}$$

and

$$V_{dmin} = \sqrt{6}E \tag{5}$$

Required value of Inductance:

The expression to select the value of inductance for unity power factor operation for linear modulation was computed from figure 2b and figure 3 as

$$L = \frac{E - I_1 R}{2\pi f I_1} t[\cos^{-1}(a)] \tag{6}$$

Where,

$$a = \frac{\sqrt{6}(E - I_1 R)}{m V_{ref}} \tag{7}$$

V_{ref} = required dc link voltage.

$$I_1 = \frac{I_{ref}}{3R} \text{ for fixed load} \tag{8}$$

$$I_1 = \frac{I_{ref}}{3R} \text{ for variable load} \tag{9}$$

R_{Lmin} corresponds to maximum dc load current.

$V_{ref} = V_{refmin} a = m_{max} = 1$. From (4),

$$V_{ref} = \frac{V_{refmin}}{m_{ref}} \tag{10}$$

Note that for positive and real value of L , the value of a must be within range $0 \leq a \leq 1$. If $a > 1$, then L will be complex which is not allowed.

Design consideration-3:

$L \leq L_{min}$ was computed using I_1 given by (9).

Active Power Control:

The active power through rectifier was controlled instantaneously by controlling output dc voltage. The regulated voltage was obtained by adjusting modulation index m which was computed as follows.

$$m_{ref} = m_{max} + \Delta m \tag{11}$$

$$m_{req} = \frac{V_{dcmin}}{V_d} + \frac{V_d - V_f}{V_{dc}} \tag{12}$$

Various parameters were limited as follows.

$$\begin{cases} 0 < m_{ud} < 1 \\ 0 < \Delta m < 1 \\ m_{min} < m_{ref} < 1 \end{cases}, m_{min} = \frac{V_d - V_f}{V_{dc}} \tag{13}$$

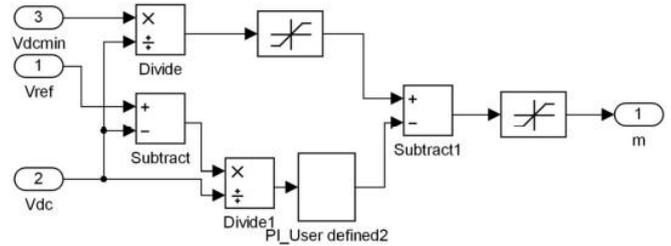


Figure 4: Modulation index control for active power control

Reactive Power Control (Unity power factor operation):

The unity power factor operation is obtained by phase control of fundamental of converter output voltage vector as shown in figure 5. The instantaneous angular displacement between supply voltage space vector and supply current space vector is computed. A new voltage space vector is generated by subtracting this displacement from supply voltage space vector. The three phase sinusoidal reference signals are produced as real parts of this new voltage vector. The modulating signal is obtained using signal output of figure 5 and modulation index computed using (12) and gate signals are obtained as shown in figure 6 [16].

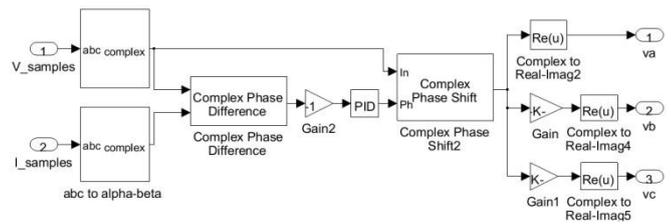


Figure 5: Instantaneous phase compensator for generating reference sinusoidal signals for SVM

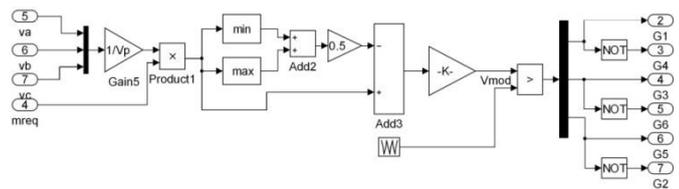


Figure 6: Gate signal generation for SVM

Indirect Vector Control of Induction Motor:

Design consideration-4: The rectifier must be able to support the operation of drive for full range of speed from zero to rated and even in field weakening mode when loaded with zero to rated torque. Hence, it is required to calculate the minimum and maximum dc current drawn by drive and the line side inductance is to be selected for proper operation over full range of speed and load torque.

The commanding equations for indirect vector control of induction motor are [10]

$$i_{ds}^* = \frac{|\psi_r|^*}{L_m} \tag{14}$$



$$|\psi_r|_{est} = \frac{L_m i_{ds}}{1 + \tau s} \tag{15}$$

where, $\tau_r = \frac{L_r}{R_r}$ = the rotor timeconstant.

$$i_{qs}^* = \frac{2}{3} \cdot \frac{2}{L_m} \cdot L_r \cdot \frac{T_e^*}{|\psi_r|_{est}} \tag{16}$$

$$\omega_s = \frac{L_m}{|\psi_r|_{est}} \cdot \frac{R_r}{L_r} \cdot i_{qs} \tag{17}$$

$$\theta_e = \int \omega_e dt = \int (\omega_s + \omega_r) dt = \theta_s + \theta_r \tag{18}$$

The dynamics of cage type induction motor is described by,

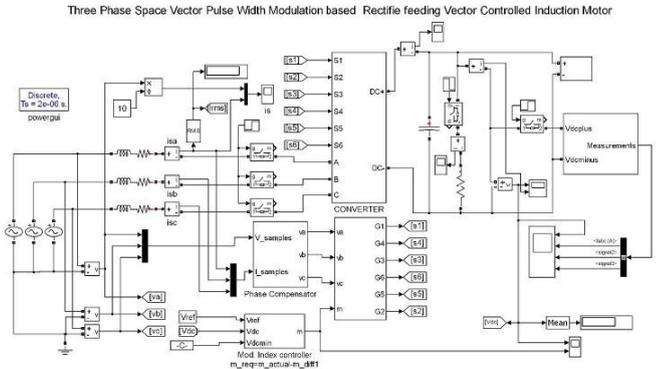
Where,

- i_{ds}^* = direct component of reference stator current
 - i_{qs}^* = quadrature component of reference stator current
 - v_{ds}/v_{dr} = direct component of stator/rotor voltage
 - v_{qs}/v_{qr} = quadrature component of stator/rotor voltage
 - $|\psi_r|^*$ = magnitude of reference rotor flux
 - $L_l = L_m - L_s$ = Stator leakage inductance,
 - L_m = Mutual Inductance (air gap inductance)
 - $L_{lr} = L_m - L_r$ = Rotor leakage inductance
 - R_s = Stator resistance
 - R_r = Rotor resistance
 - ω_e/ω_{sl} = synchronous/slip speed
 - ω_r/ω_m = rotor electrical/mechanical speed
 - S = complex frequency
- The induction motor with following specifications was used:
 5 HP, 460 V, 60 Hz, 1750 rpm (183.2 mech rad/sec), 4 pole
 $R_s = 1115 \Omega, L_s = -L_m = 5974 \text{ mH}$,
 $= 1083 \Omega, L_r = L_r - L_m = 5974 \text{ mH}$,
 $L_m = 0.2037 \text{ H}$, Inertia $J = 0.02 \text{ Kg. m}^2$,
 Friction factor $B = 0.005752 \text{ N. m. s}$

Simulation Results and Discussion:

The indirect vector control drive using (14) through (21) was designed for above specifications of motor. The rectifier was designed to feed dc power for no load to full load torque to be delivered by drive under steady state as well as starting conditions. The reference dc link voltage, $V_{ref} = 780 \text{ V}$, line side voltage, $E = 230 \text{ V rms/phase}$ and line inductance of

$L = 15 \text{ mH}$ was computed using above equations. Simulation of rectifier/drive system was performed for different operating conditions using MATLAB®/SIMULINK®. Figure 7 shows the schematic of SIMULINK model of whole rectifier/drive system. The indirect vector control drive is shown as a subsystem block.



Various waveforms at drive side are shown in figure 8. The drive was connected to dc source at $t = 0.2 \text{ s}$. The motor was loaded with 10 N. m . and a soft speed command of 157.08

electrical rad/s (1500 rpm) was applied at $t = 0.2 \text{ s}$. The capacitor of rectifier was pre-charged by an auxiliary rectifier up to 710 Vdc (greater than minimum dc voltage and less than $V_{ref} = 780 \text{ V}$) till 0.05 s , i.e. 2.5 supply cycles. The gate signals to the rectifier were inhibited during pre-charging period. The maximum command torque of the drive was limited to 1.5 times full load torque (30 N. m). As can be seen from the waveforms that the actual speed followed the command speed, with little lag at every speed command change as the generated torque was limited to 30 N. m . The dc voltage was maintained stiff under all operating conditions. The electromagnetic torque was also tracking the load torque. A step change from 10 N. m to 20 N. m was applied at $t =$

1.4 s , because of which speed slightly reduced but then settled to set speed within a second. The load torque was then step reduced to zero at $t = 2.4 \text{ s}$ at which time speed slightly increases and then settled down to set value. It was observed that rectifier output voltage regulated to remain stiff even at step application and removal of load torque. To observe whether the rectifier was capable of regenerating or not, the speed command was suddenly reduced to 31.416 rad/s (300 rpm) at $t = 2.4 \text{ s}$. It was seen that the dc output voltage across capacitor increased slightly during the transition period while speed was catching up with the set speed of 300 rpm. The energy stored in the capacitor was fed back to ac source. Figure 9, 10 and 11 show the waveforms of supply voltage (attenuated by a factor of 10) and supply phase current after motor was loaded respectively with full load torque $T_L = 20 \text{ N. m}$., half load torque $T_L = 10 \text{ N. m}$. and no load torque $T_L = 0 \text{ N. m}$. It can be verified that the input power factor was maintained around unity for all conditions.

The total harmonic distortion (THD) was measured using FFT tool available with MATLAB/Simulink for 5 cycles of supply

phase current. The results for various values of inductance and switching frequency are presented in table 1.

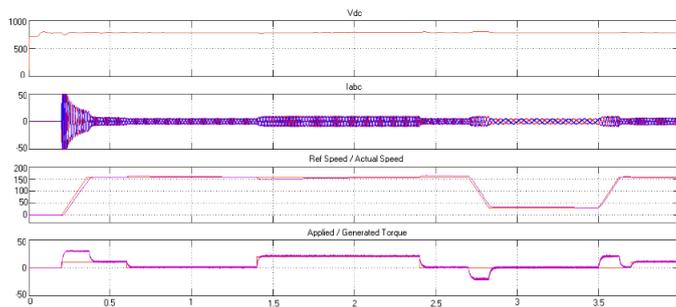


Figure 8: Waveforms for vector controlled drive (dc link voltage, motor phase currents, reference and actual speed and applied and generated torque)

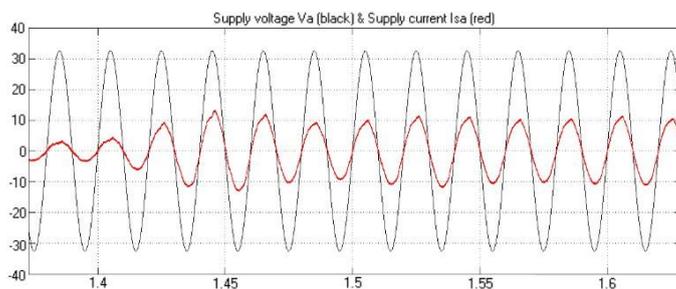


Figure 9: Supply voltage (black-attenuated by 10) and current (red) when motor loaded with $T_L = 20$ N. m

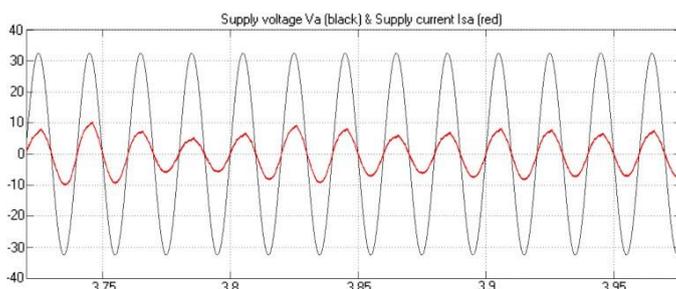


Figure 10: Supply voltage (black-attenuated by 10) and current (red) when motor at no load ($T=10$ N. m)

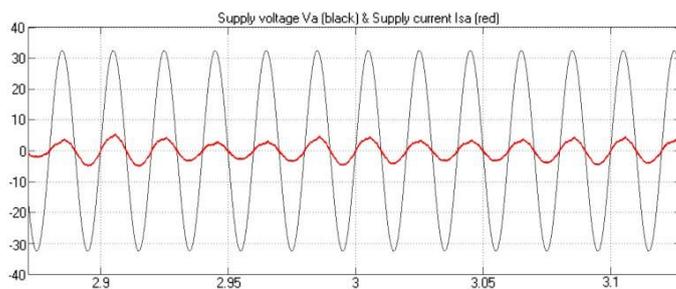


Figure 11: Supply voltage (attenuated by 10) and current when motor at no load ($T_L = 0$ N. m)

It can be seen that the *THD* decreases as the switching frequency increases. The best results for whole range of

operation are available at switching frequency of 20 to 22 kHz and boost inductance of 15 mH (just less than calculated value). It has been observed (which is not presented here) that for much lower value of *L*, the time constant *L/R* is very low, resulting much larger excursions of current about fundamental and resulting in high *THD* and too high value of *L* causes *L/R* to be high enough forcing supply current to fail to trace its fundamental and consequently high *THD*. It is also been observed that increasing switching frequency further makes it impossible for output dc voltage not to be able to catch up with the reference value. The reason for this behavior may be the fact that the sufficient energy may not have been stored in inductance when the active switch in the lower arm of the leg in on. Hence, the boosting operation beyond certain operation would not be possible.

Table 1: Total Harmonic Distortion (THD) of supply phase current

<i>L</i>	09 mH	12 mH	15 mH	20 mH	24 mH
Load Torque (T_L N. m.)	Switching frequency = 15 kHz.				
0	14.93%	12.69%	10.13%	19.46%	11.59%
10	09.4%	06.55%	14.08%	13.31%	08.63%
20	16.26%	07.54%	12.42%	11.74%	10.43%
	Switching frequency = 20 kHz.				
0	14.99%	13.49%	08.72%	17.42%	24.15%
10	08.87%	10.89%	11.82%	13.05%	14.40%
20	06.83%	04.45%	04.39%	04.96%	04.47%
	Switching frequency = 22 kHz.				
0	12.44%	17.93%	07.17%	24.09%	18.97%
10	06.85%	05.72%	11.89%	15.47%	15.99%
20	04.88%	05.24%	04.67%	03.37%	02.07%
	Switching frequency = 25 kHz.				
For all load conditions	The dc output cannot catch up to the reference value.				

Conclusion

The complete design procedure for PWM rectifier feeding indirect vector control drive is discussed. The new simple method based on modulation index control and instantaneous phase compensation is proposed. The simulation results show that the rectifier designed based on this method is capable of maintaining stiff dc voltage and providing very near unity power factor operation with low current THD at supply side. The rectifier designed is found to be very sturdy because it provided quiet satisfactory performance against wide range of step changes in load dynamics (load torque and speed in both rectifying and regenerating operation).

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