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Vector Control of Active Front-End Rectifier for Electric Motors under Unbalanced Condition

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Abstract: ***The situation when the voltage source inverter is supplied with unbalanced system of voltages is investigated. This can cause problem in the operation of an electric drive as the voltage pulsations can arise in the DC bus. As a solution to such a problem, Active Front-End rectifier is employed for the motor application before the inverter stage. With the vector control of front-end rectifier the effect of unbalance voltage supply can be mitigated and a constant power is drawn from the power network at the input of the voltage source inverter. With this the drive performance is improved while solving the power quality issue. Vector control method is discussed in the paper. Space Vector Pulse Width Modulation (SVPWM) technique is used to generate switching sequence for the front-end rectifier. While various types of unbalance is simulated using MATLAB/SIMULINK, the results obtained proved the control system to be effective.***

Keywords: Unbalanced voltage supply, DC link voltage pulsations, SVPWM technique, and Vector field control.

1. Introduction

Inverters containing DC buses are commonly used to feed the electrical machines. Diode bridge rectifier, which is the simplest configuration was previously employed. However, they provide only a constant or a fixed DC voltage which cannot be controlled. Such that the power flow cannot be controlled and the power regeneration was not possible. Moreover, it generates high harmonics when supplying capacitive load [1]. Nowadays, the front end stage of the Inverter for a motor application consists of controlled AC/DC converter instead of diode rectifier. Such a drive puts great demands on the power supply quality. The voltage supply from the power grid is not ideally symmetric, but certain unbalance is present. This unbalance is caused due to network failure or due to unbalanced load in the vicinity of an affected drive. When the voltage source inverter feeding a motor, is supplied with the unbalanced source voltage it causes voltage pulsations in the DC bus and will have negative impact on the drive performance such as reduced power capabilities, excessive rise in motor temperature, uncontrollable speed, and torque pulsations.

Basically, there are three major ways available to mitigate the problem of unbalanced voltages. First, is to provide a modulation technique to inverter so that the pulsating DC link voltage can be taken into account. This results in additional limitations of operating regions of the drive and decreases its overall controllability and performance. Second, increasing the energy storage capability of the DC bus would enable the machine to run over its entire operating region. This could be achieved by either increasing the capacitance of DC capacitors or by introducing the active filter into the DC bus. This technique increases the size of the converter. Last, the effect of the unbalanced supply voltage may be eliminated by suitable control of front end rectifier so that the DC voltage ripples are eliminated and motor is provided with a constant power.

In this paper Active front end rectifier controlled by Vector Field method is proposed for the Induction motor application. The AFE rectifier provides better power factor, offering stable power quality which remains unaffected from the mains power fluctuations, providing extremely high drive dynamic performance and reduced harmonics. With the advent of controlled semiconductor switches such as Integrated Gate Bipolar Transistors (IGBT's), Integrated Gate-Commutated Thyristors (IGCT's) etc., AFE rectifiers are being increasingly used in applications requiring controlled DC source such as DC Drives, battery charging and household applications and are becoming an effective solution for power factor correction. Vector control strategy is used because of its advantages of being fast and having a dynamic response to control the AFE rectifier [2]-[6]. The switching sequence for the AFE rectifier is generated using Space vector pulse Width Modulation technique so that a constant voltage across the DC bus can be maintained [7],[8]. In this paper various unbalanced voltage conditions have been considered and their influence on the drive system has been taken care of using the Vector Control method. The system was simulated using MATLAB/SIMULINK and the simulation results shows the effectiveness of the system.

2. Control Method

The proposed system consists of AFE rectifier, DC link capacitor, voltage source inverter and motor load. The single phase AC voltage is supplied to the front-end rectifier. AFE rectifier draws a constant input power from the power network even at the unbalanced voltage supply.

A simplified scheme of the drive under investigation is shown in Figure 2. Vector control technique is employed for the front-end rectifier so as to eliminate the DC link voltage pulsations & to obtain the controlled DC output voltage. This

DC is then converted to desirable AC voltage by the voltage source inverter and fed to the motor loads. The switching sequence are generated using Space vector PWM technique. The detailed description of the controlled algorithm presented in this paper is in [9]-[11]. Influence of the circuit parameters on the operating region and their constraints are dealt in [12]. It is assumed that the three phase AC voltage is a balanced and IGBT is ideal Power switch and loss less. The three phase grid voltage are V_a, V_b, V_c are defined as,

$$V_\alpha = V_m \cos(\omega t) \quad (1)$$

$$V_b = V_m \cos(\omega t - 120) \quad (2)$$

$$V_c = V_m \cos(\omega t + 120) \quad (3)$$

Where, V_m is the maximum value of the phase voltage. Transformation of these 3-phase voltage into 2-phase stationary reference frame (α-β reference frame) are given as below:

$$V_\alpha = \frac{2}{3} V_\alpha \quad (4)$$

$$V_\alpha = \sqrt{2} V_m \cos(\omega t) \quad (5)$$

$$V_\beta = \frac{\sqrt{3}}{2}(V_b - V_c) \quad (6)$$

$$V_\beta = \sqrt{2} V_m \sin(\omega t) \quad (7)$$

The voltage can be transformed into a synchronously revolving d-q reference frame, where d-axis and q-axis are aligned 90º. Where θ is angle of the d-axis measured from α-axis. D-q reference frame equation is given as below,

$$V_d = V_\alpha \cos\theta + V_\beta \sin\theta \quad (8)$$

$$V_q = V_\beta \cos\theta - V_\alpha \sin\theta \quad (9)$$

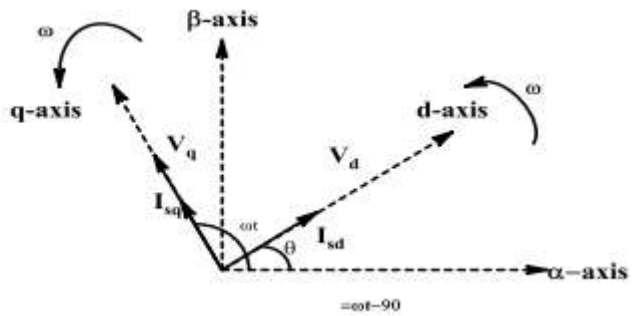


Figure 1: Vector Diagram

The voltage equations of front end rectifier for d-q rotating reference frame are given. R_s, L_s are resistance and inductance respectively.

$$R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega L_s i_{sd} + V_{id} = 0 \quad (10)$$

$$R_s i_{sq} + L_s \frac{di_{sq}}{dt} - \omega L_s i_{sq} + V_{iq} = 0 \quad (11)$$

Here, Dq0 transformation is employed in MATLAB/SIMULINK to simplify the analysis of three phase circuits. Reference signals thus obtained are used for generating switching sequence (using SVPWM technique) for the front-end rectifier.

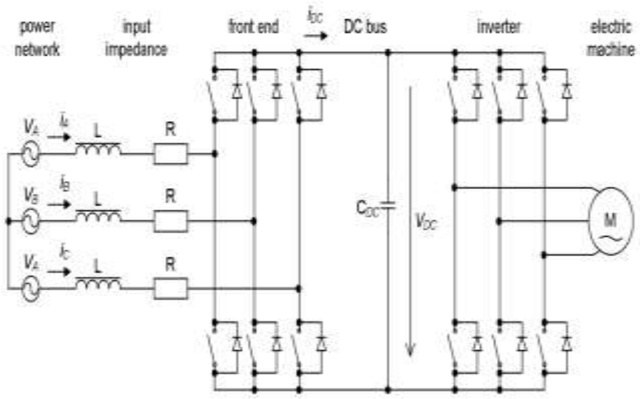


Figure 2: Scheme of the system under investigation

3. Operation of Front-End Rectifier

The control of the active front end rectifier may be represented by positive and negative sequence phasors under the steady-state conditions. The phasor which is rotating in positive direction is mainly responsible for controlling the magnitude of the DC-link voltage whereas during the unbalanced voltage condition, the negative sequence phasor is responsible for eliminating the pulsating component of the DC-link. The unbalance in the supply necessitates the superimposition of these two phasors. The need to generate negative sequence component of the switching functions so as to eliminate the DC link pulsations occurring due to voltage unbalance results in certain reduction of the control region for the positive sequence component of the switching functions [13].

In the individual phases there can be only one switching function at a time hence superimposition occurs and therefore control range is restricted. MATLAB Simulations have been carried out in order to illustrate operation and control of the AFE rectifier under various unbalanced voltage supply conditions. The parameter specific of the components used in the system under investigation are presented in Table 1.

Table 1: Parameters of the system under investigation

Parameter	Value
L	10mH
R	1Ω
C_{DC}	2500µF

The parameters of the input impedance were selected as mentioned in the Table 1. The nominal voltage amplitudes of the input phase voltage was 230 V, with mutual phase shifts of 120° and having nominal frequency of 50 Hz, that forms a perfect three-phase symmetric voltage system. Now, in order to introduce a voltage unbalance, the voltage amplitudes in different phases has to be different. Voltage values for the individual phases are shown in Table 2

Table 2

	Phase A	Phase B	Phase C
Amplitude [V]	200	230	230
Phase [deg.]	0	-120	120

Different types of unbalance were created to investigate the system without the control front-end rectifier. The first unbalance was created by the reducing the magnitude in phase A to 200 V and allowing the magnitudes of phase B and phase C voltages to be at 230 V. Then, a different type of supply voltage unbalance was introduced by reducing the amplitude of the voltage in phase A from 230V to 200V and increasing the amplitude in phase B to 260 V. A similar situation arises when the voltage amplitude in phase A is reduced to 200V and voltage amplitude in phase C increased to 260V. It was noticed that the reduction of voltage in different input phases results in different phase shifts of voltage pulsations in the DC bus [14].

4. Simulation of the proposed system

The circuit of the active front end rectifier for electric motors is implemented using MATLAB/SIMULINK. The vector control method is employed for the rectifier and switching sequence is provided using space-vector PWM technique. Figure 3 shows complete SIMULINK model of the system comprisng of three phase power supply, front-end rectifier, DC bus, voltage source inverter and Induction motor. The front-end rectifier comprises of six IGBT's which are triggered by the gate pulses generated by SVPWM method.

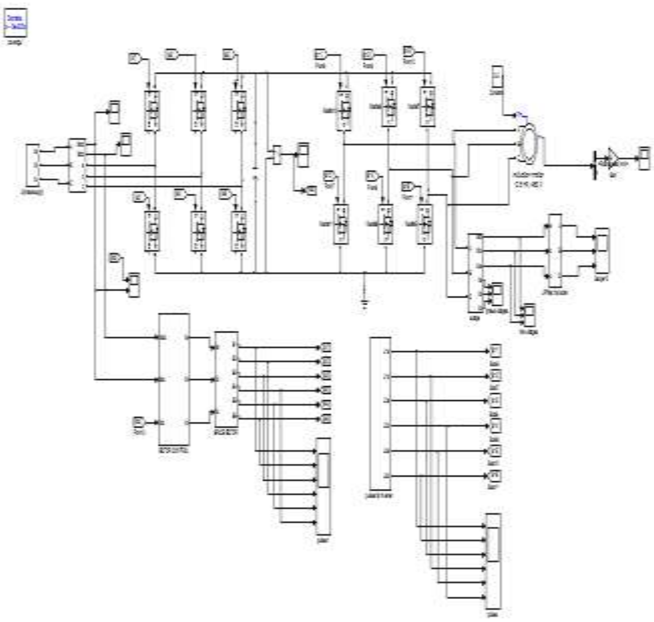


Figure 3: SIMULINK model of the complete system

The voltage source inverter is provided with PWM pulse technique. The subsystem block of Vector control in the SIMULINK model is shown Figure 4.

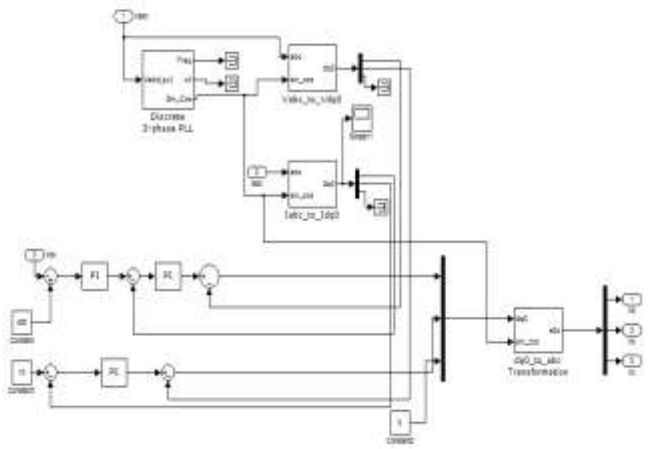


Figure 4: Sub-models of the Vector Control subsystem in SIMULINK

The front-end rectifier is used to regulate the DC link voltage and it is possible by providing proper control technique. The technique choosen for this purpose is space-vector PWM. Three phase voltages are transformed into two phase dq0 quantity to make the three phase analysis easier and then is compared with the reference DC voltage (V_{dc}) (obtained from the front-end output) and fed to the PI controller which increases the speed of the response and also eliminates the steady state error. Similarly three phase currents are also transformed to d-q reference frame then compared with an external reference and fed to the PI controller. Now the dq0 voltages are converted to three phase voltages (ABC) and these are fed to the space vector PWM block as reference voltages. The Kp and Ki values of the PI controller used are shown in Table 3.

Table 3: Design values of PI controller

Type of controller	Kp	Ki
voltage	0.81	0.0049
current	0.14	0.01

5. Results and Discussions

Various Waveforms obtained by simulating the system in MATLAB/SIMULINK are shown and discussed.

5.1 Input Voltage

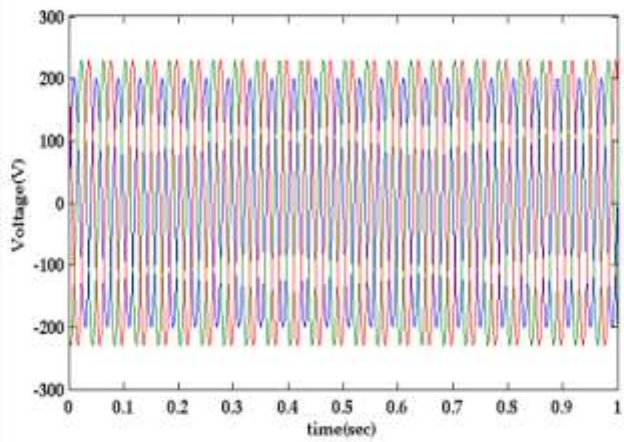


Figure 5: Waveform showing three phase unbalance voltage

Figure 5 shows, unbalanced system of three phase voltages is formed by reducing the phase A voltage to 200V while keeping the phase B and phase C voltage at 230V

5.2 Input current

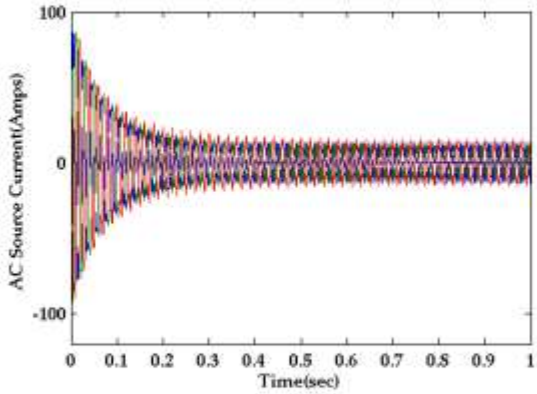


Figure 6: Waveform showing three phase input current

Figure 6 shows, input current is in same phase with the source voltage with the control of front-end rectifier. Hence, unity power factor operation is performed.

5.3 DC Output Voltage

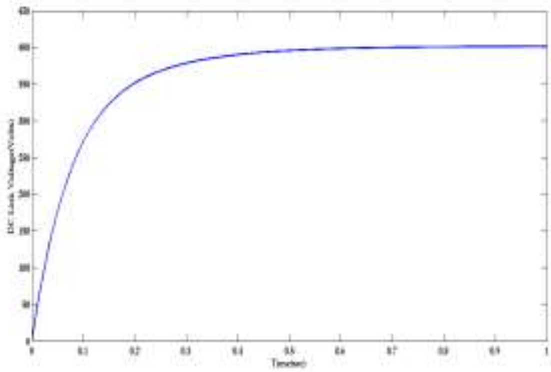


Figure 7: Waveform showing DC link voltage

Figure 7 shows constant voltage obtained at the DC link of the voltage source inverter. The DC bus voltage was set to be 400 V by the closed loop vector control of front-end rectifier.

5.4 DC Output Current

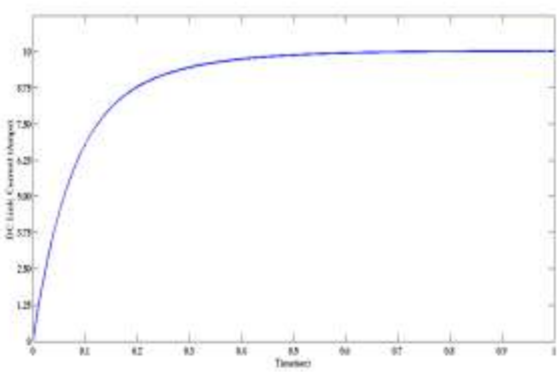


Figure 8: Waveform showing DC link current

Figure 8 Shows constant DC link current obtained at the input of the voltage source inverter. The DC bus current was maintained at 10A by current controller of the vector control block.

5.5 Three Phase Space Vector PWM Signal

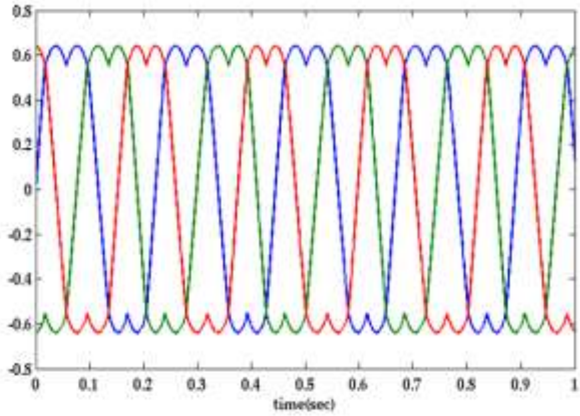


Figure 9: Waveform showing space vector control signals

Figure 9 shows three phase SVPWM signals for the voltage source inverter. The SVPWM method is employed with a carrier frequency of 5 KHz.

5.6 Unit Vectors

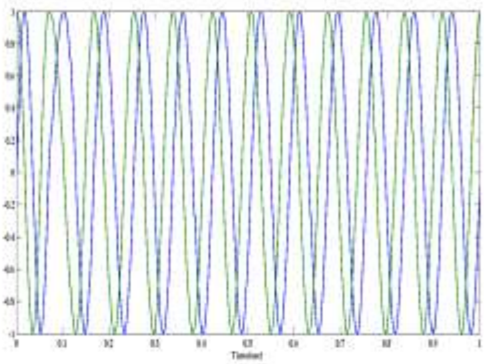


Figure 10: Sine and Cosine Unit Vectors

Figure 10 shows the unit vectors. The components of the revolving unit vector i.e., sine and cosine are generated. The control algorithm will be initiated as soon as these quantities reaches steady state.

5.7 Three Phase Inverter Voltages

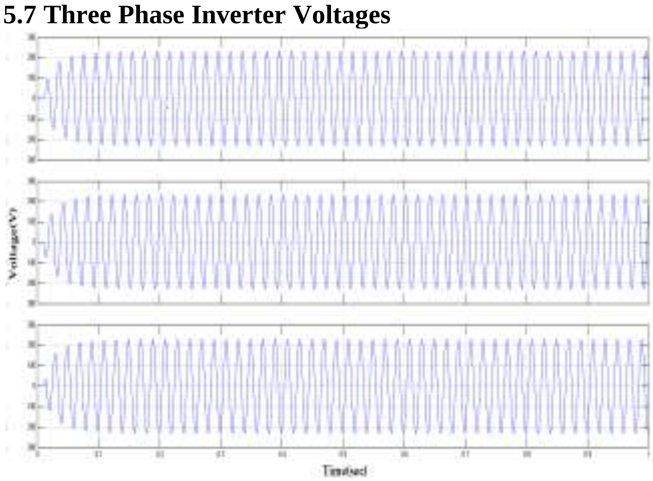
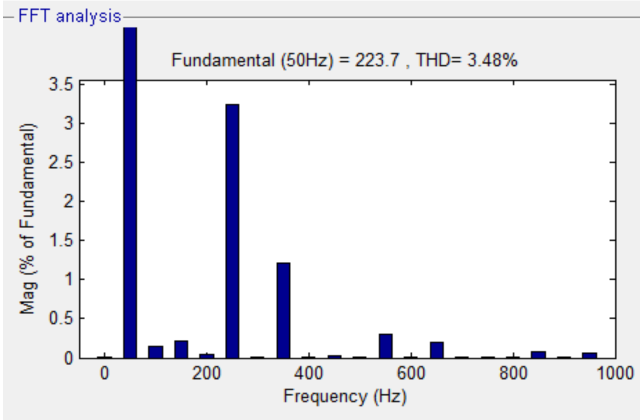


Figure 11: Waveform showing three phase VSI voltages

Figure 11 shows three phase voltage of the inverter with an amplitude of 223.7V.

5.8 Total Harmonic Distortion

Figure 12 shows the THD value of phase A of the inverter output voltage to be 3.48%.



6. Conclusion

In this paper Active front end rectifier is used for an Induction motor and vector control strategy applies. The steady state design considerations for the front end rectifier have been discussed. The block diagram for Vector control have been developed using MATLAB/SIMULINK and satisfactory results are obtained. With the use of AFE rectifier THD value is reduced to 3.48%. Hence, AFE rectifier is effective in eliminating DC-link voltage pulsations occurring due to the unbalance while operating in unity power factor.

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