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# Intelligent Control Techniques for AC-DC-AC Converter fed PMSM Drives

**Parin H. Chauhan*[1], Vishal G. Jotangiya[2], Divyesh J. Vaghela[3], Mehulsinh G. Jadeja[4], Pulinkumar J. Purohit[5], Dilip Dobariya[6]**

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***Abstract:*** This paper describes the modeling, simulation and analysis of AC-DC-AC converter fed PMSM drives in steady state and dynamic loading condition. Front End Converter (FEC) is proposed in PMSM drive for rectification purpose as it will absorb current harmonics generated in source by nonlinear load. Robust control algorithm is used in FEC to get unity power factor on source side and constant dc link voltage on output side in steady state and dynamic loading condition. Unbalancing of grid side voltage may lead to disturb the performance of drives. This paper proposed robust control algorithm to maintain drive parameters and load regulation during grid side supply unbalance. Vector control algorithm is used to get variable speed during constant load and vice-versa. The proposed AC-DC-AC converter gives unity power factor on source side and low % Total harmonic Distortion (THD) on load side as per IEEE standard. The Proposed controller presents good dc link voltage regulation during dynamic loading conditions. Mathematical analysis of vector control algorithm is present and Simulink model is prepared in MATLAB Simulink environment. The proposed controller allows regeneration of power from load to source in PMSM drive is present. Hysteresis current controller works good during over modulation and unbalancing of supply system without any disturbance on load side is presented.

***Keywords:*** *Front End Converter, Field Oriented Control, Hysteresis current controller, Permanent Magnet Synchronous Motor, Total Harmonic Distortion*

## 1. Introduction

Recent year, large development in power electronics devices, power electronic based application is widely increase in home electronics appliance and industrial applications [1]. Generally diode bridge rectifier is employed for such a system [1]. These rectifiers are nonlinear in nature and generate harmonics currents in source (grid) side. The high harmonic in source side leads to poor power factor of the system [1, 2]. To reduce this problem, development of control methods in pulse width modulation (PWM) techniques and high speed digital signal processor, insulated gate bipolar transistor (IGBT) based boost rectifier (Power converter or PWM rectifier) have greater advantageous as a replacement of conventional diode based rectifier for dc regulated power supply[1,3]. IGBT based boost rectifier provide better dc voltage regulation on output side as well as improve power factor nearer to unity by smoothing current waveform in supply side [2]. For adjustable speed drives (ASD), good speed regulation and reduce torque ripple will prime focus on designing accurate and highly efficient industrial drive to reduce power consumption and improve power quality of overall system [3]. IGBT based inverter with various PWM techniques plays a vital role for better performance of ASD [4]. Good dc input voltage with less ripple will be provided by three-phase IGBT based boost rectifier [4]. Because of IGBT based three-phase converter on both side i.e. supply side and load side (AC-DC-AC), overall system performance of ASD improve and power quality of system greatly increase to a great extent[5]. This paper present IGBT based AC-DC-AC bidirectional converter fed adjustable Permanent Magnet Synchronous (PMSM) drive with improved power quality and system performance using Field Orientation Control (FOC) techniques. Conventional hysteresis current control techniques employed on front side converter (AC to DC) and field oriented control (FOC) on load side converter (DC to AC). Details waveforms analysis of front end side converter and load end side converter is presented in this paper. Fig. 1 shows three-phase bidirectional fed PMSM drives [10].

## 2. Active Front End Converter (AC to DC Converter)

Conventionally, SCR based rectifier is used for ac to dc rectification purpose and output dc voltage control application but it will lead to increase in input current harmonics due to nonlinear load as shown in Fig.2 [11]. In case of high power drives, diode bridge rectifier provides required dc voltage which acts as an input of inverter [12].

For diode bridge rectifier, a large capacitor is used to remove ripple content present in output of bridge rectifier. So rectifier with large capacitor introduce non sinusoidal source current with large number of lower order harmonics in source current and very poor power factor [13].

To overcome conventional rectifier drawback and improve power quality of supply system, IGBT based PWM rectifier or Front End Converter (FEC) is preferred [14]. IGBT based PWM rectifier are well famous for its good bidirectional power flow capability [14], no line supply voltage fluctuations, extremely

*[1, 2]Electrical Engineering Department, Lukhdhirji Engineering College, Morbi, Gujarat, India*
*ORCID ID: [1]0009-0000-1345-435X [2]0009-0001-0050-6015*
*[3,4,5,6] Electrical Engineering Department, Vishwakarma Government Engineering College, Ahmedabad, Gujarat, India*
*ORCID ID: [3]0000-0001-5144-8997 [4]0009-0003-3945-8182*
*[5]0009-0006-0336-5357 [6]0000-0002-7306-7121*
** Corresponding Author Email: chauhanparin@gmail.com*

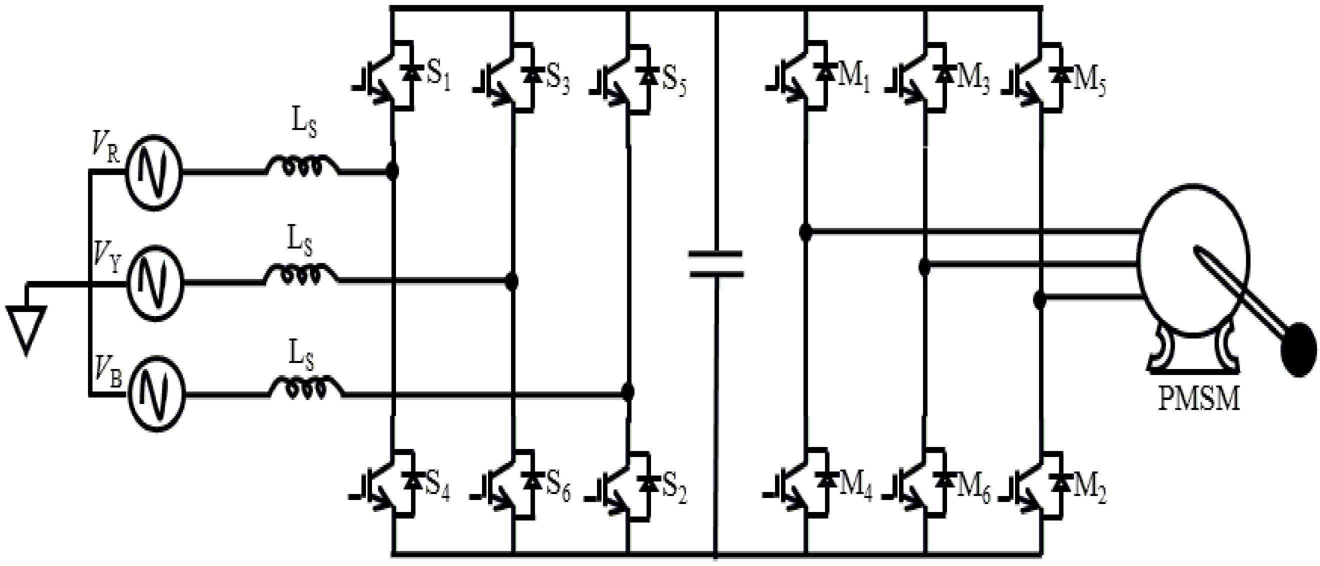



**Fig. 1.** Three-phase bidirectional converter (AC-DC-AC) fed PMSM drive

high drive dynamic performance, ability to improved power quality in terms of smoothing source current waveforms so as to get unity power factor on source side [15]. Fig. 3 shows IGBT based three –phase Front End Converter (FEC) power circuit diagram.

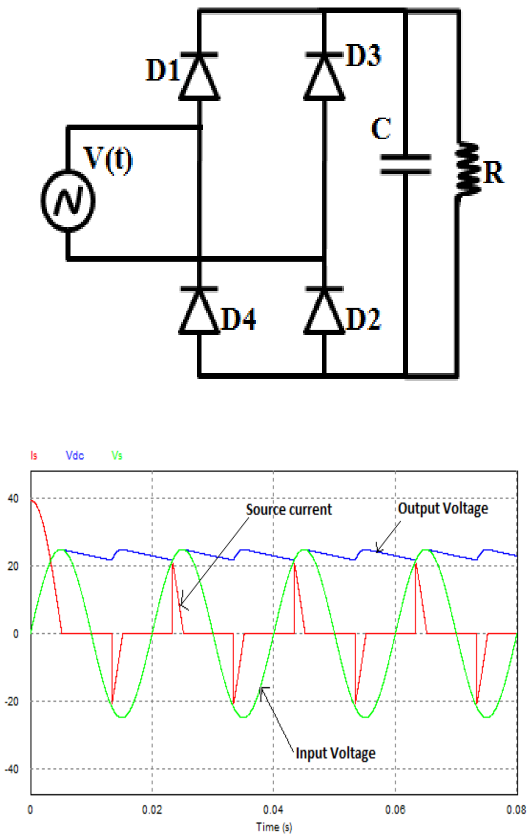



**Fig. 2.** Conventional diode rectifier and its input and output voltage and input current waveform

For gating unity power factor on source side and variable dc on load side with dynamic performance, control structure of FEC should be robust [16]. Hysteresis current controller is employed for generating gate pulses for IGBTs. Hysteresis controller is very fast dynamic response and does not require any modulation. Fig. 4 shows power and control circuit of FEC [17].

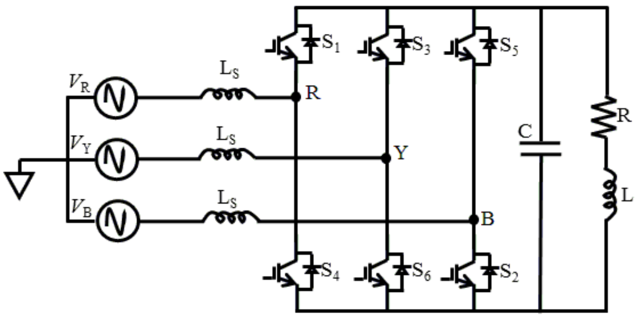



**Fig. 3.** Power Circuit diagram for IGBT based Front End Converter

The control circuit should be able to control source current and output dc link voltage Vdc in steady state as well as dynamic condition. Vdc reference set to get required output dc voltage. Magnitude of current drawn from source decided based on output of PI controller and that depends on required reference voltage. Output of PI controller is multiplied with sine template of source voltage to generate reference current [18]. This generated reference current given to hysteresis controller to get required gate pulses. Fig. 5 shows hysteresis current controller for one phase only.

Hysteresis current controller consists of two comparator C1 and C2 and logic generator flip flops. Depending upon comparison, flip flops generate gate signal for IGBTs. Hysteresis band ΔI is very depending upon load requirement. Hysteresis current controller gives random switching frequency depending upon hysteresis band value [19]. Comparator compares Iref and inductor current and depending upon its comparison of these two current pulses is generated. Fig. 6 shows working of hysteresis current controller. When Iref crosses upper band limit it will turn off upper (Positive 1, 3, 5) IGBTs and turn on lower (Negative 2, 4, 6) and when Iref

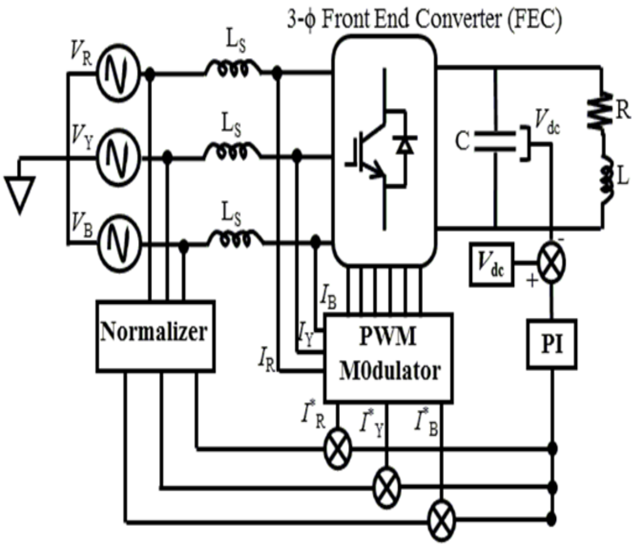



**Fig. 4.** Control and power circuit of Front End Converter

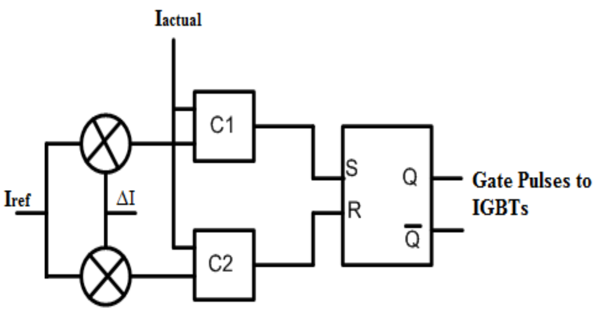



**Fig. 5.** Hysteresis current controller

crosses lower band limit, it will turn on upper IGBTs and turn off lower IGBTs. Using this fundamental principle, hysteresis current controller limits current flowing through the inductor as well as shape source current with unity power factor.

Front End Converter able to main constant dc link voltage during steady state and dynamic load conditions as control algorithm track all the parameters according to change in load or speed. It also maintains unity power factor and constant dc link voltage on output side during unbalancing of voltage in any of phase in supply system. During the overloading on motor side, speed of motor will reduce as many converters not able to supply excess of current to supply torque demand. So to overcome this problem, vector control algorithm with FEC fed dc link voltage as a input of dc to ac converter develop to cater the overloading condition and maintain speed of motor during overloading of motor.

## 3. Vector Control of PMSM Drive

In early 1950s, permanent magnets with high energy density lead to development of dc machine with permanent magnet replacing the electromagnetic field excitation system in dc machine. With the advancement in semiconductor devices and converter topology, will replace mechanical commutator with electronically fed commutator system and with replacement of conventional rotating field excitation system in rotor circuit with PM excitation system causes the development of PM synchronous motor and brushless dc machines. The replacement of mechanical commutator with electronics commutator will lead to fixed armature on stator side

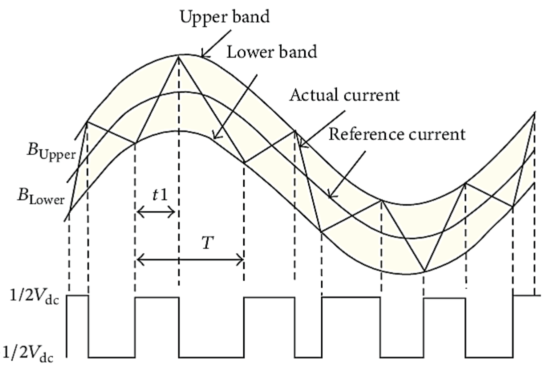



**Fig. 6.** Principle of hysteresis current controller

with rotating PM field excitation system which will result in easy cooling system as well as higher voltage capability can be achieved.

Based on direction of field flux, PMSM can be classifying as redial field and axial field motor [10]. In radial field, the flux direction is along the radius of machine and in axis field, flux direction is in parallel to the rotor shaft [10]. PMSM also classify based on wave shape of induced emf (Sinusoidal and trapezoidal). In PMSM, induced emf is sinusoidal type and in PM dc brushless dc machines, induced emf is trapezoidal type [11]. This paper presents, PM synchronous motor with sinusoidal type induced emf is chosen for better steady state and dynamic operation.

A simple control structure like v/f is good for limited performance operation but for steady state and high dynamic performance, a complex control structure may be needed to be applied [8]. With the help of advanced microcontroller and digital signal processor, large mathematical operation can be handling very easily so using this fundamentals complex control strategy utilize mathematical transformation of decoupling the torque component and flux component individually [8]. Field Orientation Control (FOC) uses this principle for highly dynamic performance of PMSM drive.

Similar to separately excited dc motor, in FOC flux (aligned with d axis) and torque (aligned with q axis) can be control independently [8].

## 4. Vector control algorithm or Decoupling control theory

Fig. 7 shows basic block diagram of speed control of PMSM using vector control algorithm. The vector control separates the torque and flux components in the machine through its stator excitation input. Vector control of PMSM is derived from its dynamic model. Considering current as a inputs, the three phase currents are:

$$i_a = i_s \sin(w_r t + \delta) \tag{1}$$

$$i_b = i_s \sin\left(w_r t + \delta - \frac{2\pi}{3}\right) \tag{2}$$

$$i_c = i_s \sin\left(w_r t + \delta + \frac{2\pi}{3}\right) \tag{3}$$

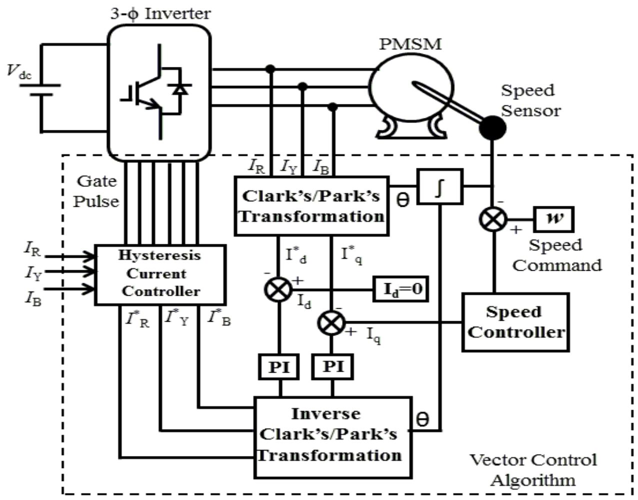



**Fig. 7.** Basic block diagram of speed control of PMSM using vector control (FOC algorithm)

Where wr is electrical rotor speed & δ is angle between the rotor field and stator current phasor known as torque angle.

The rotor field is travelling at a speed of wr rad/sec. Hence, the q and d axis stator currents in the rotor reference frame for a balanced three phase operation are given by:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos w_r t & \cos(w_r t - \frac{2\pi}{3}) & \cos(w_r t + \frac{2\pi}{3}) \\ \sin w_r t & \sin(w_r t - \frac{2\pi}{3}) & \sin(w_r t - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

Substituting the equation of ias in ics to equation A gives the stator currents in the rotor reference frames:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = i_s \begin{bmatrix} \sin \delta \\ \cos \delta \end{bmatrix} \quad (5)$$

The q and d axis currents are constants in rotor reference frames, since δ is a constant for a given load torque. As these are constants, they are very similar to armature & field currents in the separately excited dc machine.

Substitute above equation in electromagnetic torque expression gives the torque:

$$T_e = \frac{3}{2}\frac{P}{2}\left\{\frac{1}{2}(L_d - L_q){i_s}^2 \sin 2\delta + \lambda_{af} i_s \sin\delta\right\} \quad (6)$$

For $\delta = \frac{\pi}{2}$

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{af} i_s \quad (7)$$

$$T_e = k_1 \lambda_{af} i_s \text{ N-m.} \quad (8)$$

$$k_1 = \frac{3}{2}\frac{P}{2} \quad (9)$$

If the torque angle is maintained at 90 degree & flux is kept constant (id = 0) then torque is controlled by stator current magnitude, giving an operation very similar to that of armature controlled separately excited dc motor.

The electromagnetic torque is positive for motoring action, if δ is positive.

$i_q$ = Torque producing component of stator current= $i_T$

$i_d$ = Flux producing component of stator current = $i_f$

Torque angle is given by $\theta_T = \delta$

Torque reference is a function of the speed error & speed controller is usually of PI type.

Constant torque- angle control (δ = 90) (zero direct axis current control)

In this control the torque angle δ is maintained at 90 degree, hence the field or direct axis current is made to be zero leaving only the torque or quadrature axis current in the place.

This is the mode of operation for speed lower than the base speed.

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{af} i_q = T_e = \frac{3}{2}\frac{P}{2}\lambda_{af} i_s \quad (10)$$

And torque per unit stator current is constant

$$\frac{T_e}{i_s} = \frac{3}{2}\frac{P}{2}\lambda_{af} \quad (11)$$

Relevant equation to determine the steady state performance of the PMSM drive with this control strategy is derived in the following:

The q and d axis voltage in steady state are:

$$V_q = (R_s + L_q\, p) i_s + w_r \lambda_{af} \quad (12)$$

$$V_q = R_s i_s + w_r \lambda_{af} \quad (13)$$

$$V_d = -w_r L_q i_s \quad (14)$$

Note that rate of change of current is zero in the rotor reference frame because the current are constant in steady state.

The magnitude of the voltage phasor is given by:

$$V_s = \sqrt{{V_q}^2 + {V_d}^2} \quad (15)$$

And from the phasor diagram and axis voltage and power factor is obtain as

$$\cos\emptyset = \frac{V_q}{V_s} = \frac{V_q}{\sqrt{{V_q}^2 + {V_d}^2}} \quad (16)$$

This equation implies that the power factor deteriorate with increasing rotor speed as well as with increasing stator current.

The maximum rotor speed with this control strategy for a given stator current is obtained from the voltage magnitude expression as follow:

$$w_{rn(\max)} \cong \frac{V_{sn(\max)}}{\sqrt{1 + {L_{qn}}^2 {i_{sn}}^2}} \quad (17)$$

Where Vsn (max) is obtain from the dc link voltage,

$$V_{sn(\max)} = \sqrt{2} \times 0.45\, V_{dc} \quad (18)$$

The vector control consists of controlling the components of the motor stator currents, represented by a vector, in a rotating reference frame d, q aligned with the rotor flux. The vector control system requires the dynamic model equations of the induction motor and returns the instantaneous currents and voltages in order to calculate and control the variables. The Clarke transform uses three-phase currents ia, ib and ic to calculate currents in the two-phase orthogonal stator axis: ia and ib. These two currents in the fixed coordinate stator phase are transformed to the isd and isq currents components in the d,q frame with the Park transform. These currents isd, isq and the instantaneous flux angle θ, calculated by the motor flux model, are used to calculate the electric torque of an AC induction motor.

## 5. Mathematical equation for Clark's and Park's transformation

The mathematical transformation called Clarke transform modifies a three phase system to a two-phase orthogonal system:

$$i_\alpha = \frac{2}{3} i_a - \frac{1}{3}(i_b - i_c) \quad (19)$$

$$i_\beta = \frac{2}{\sqrt{3}}(i_b - i_c) \quad (20)$$

Where $i_\alpha$ and $i_\beta$ components are in an orthogonal reference frame. The two phases a, b frame representation calculated with the Clarke transform is then fed to a vector rotation block where it is rotated over an angle q to follow the frame d,q attached to the rotor flux.
The rotation over an angle θ is done according to the formulas:

$$i_d = i_\alpha \cdot \cos(\theta) + i_\beta \cdot \sin(\theta) \quad (21)$$

$$i_q = i_\alpha \cdot \sin(\theta) + i_\beta \cdot \cos(\theta) \quad (22)$$

The vector in the d, q frame is transformed from d, q frame to the two phases a, b frame representation calculated with a rotation over an angle q according to the formulas:

$$i_{\alpha(inv)} = i_d \cdot \cos(\theta) - i_q \cdot \sin(\theta) \quad (23)$$

$$i_{\beta(inv)} = i_d \cdot \sin(\theta) + i_q \cdot \cos(\theta) \quad (24)$$

The modification from a two-phase orthogonal a, b frame to a three-phase system is done by the following equations:

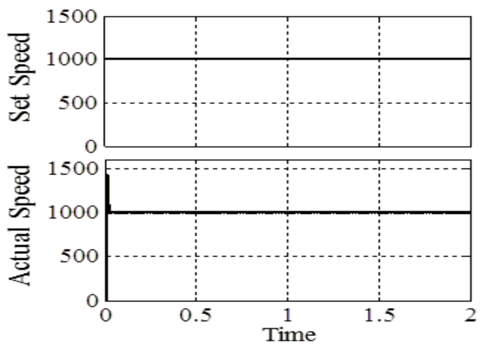
$$i_a = i_\alpha \quad (25)$$

$$i_b = -\frac{1}{2} i_\alpha + \frac{\sqrt{3}}{2} i_\beta \quad (26)$$

$$i_c = -\frac{1}{2} i_\alpha - \frac{\sqrt{3}}{2} i_\beta \quad (27)$$

## 6. Simulation Results and Discussion

### 6.1. Steady state condition (Speed-Load-Vdc are constants)

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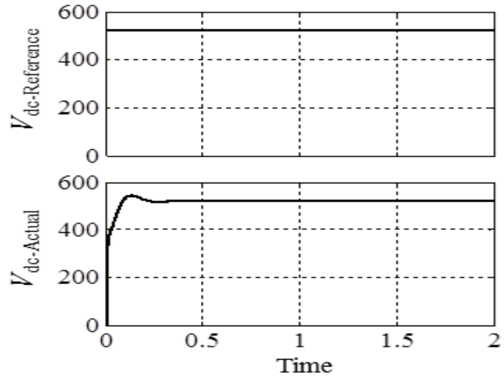


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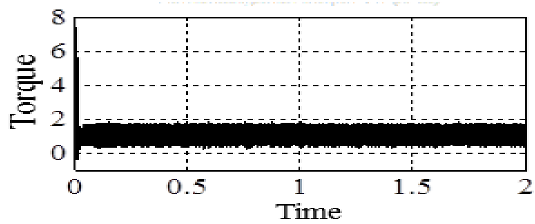


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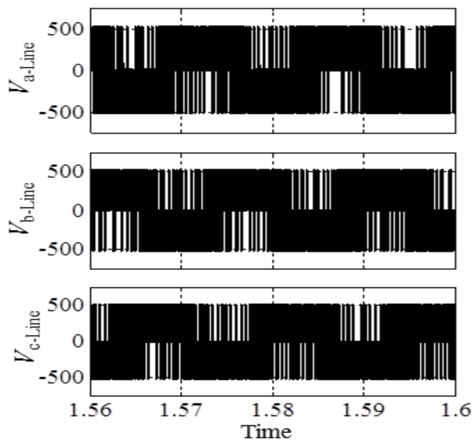


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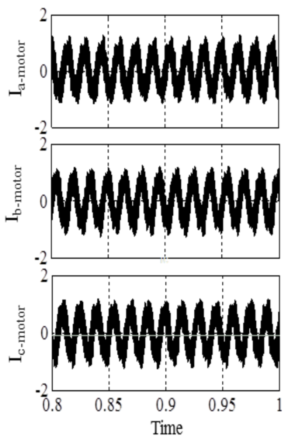
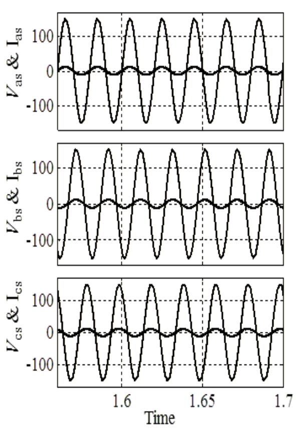
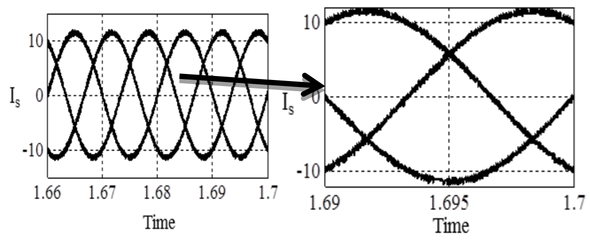



**(e)** **(f)**

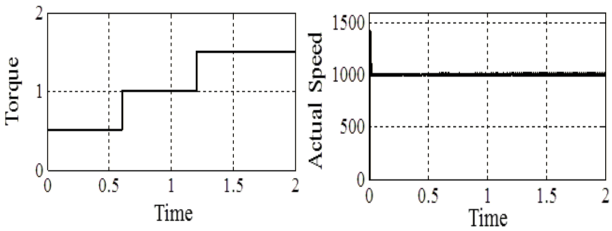



**(g)** **(h)**

**Fig. 8.** PMSM drives under steady state condition (Speed and Load are constant) (a) actual and reference speed of motor, (b) Actual and reference value of dc link voltage Vdc, (c) Motor Torque, (d) inverter line-line voltage, (e) motor current, (f) source current and voltage waveform, (g, h) Three phase source current waveform and its zoom view.

Fig. 8 show different waveforms under steady state condition. Under steady state load and speed conditions, FEC give good load regulation and dc link remain constant at set value as well as on source side, maintain unit power factor. Inverter operates satisfactorily as it controls the flow of current to the motor as per desired speed.

### 6.2. Variable Load condition (Variable-Load, Speed, Vdc are constant)

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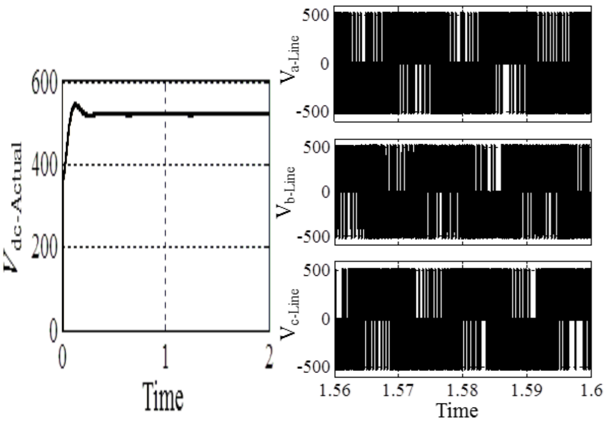
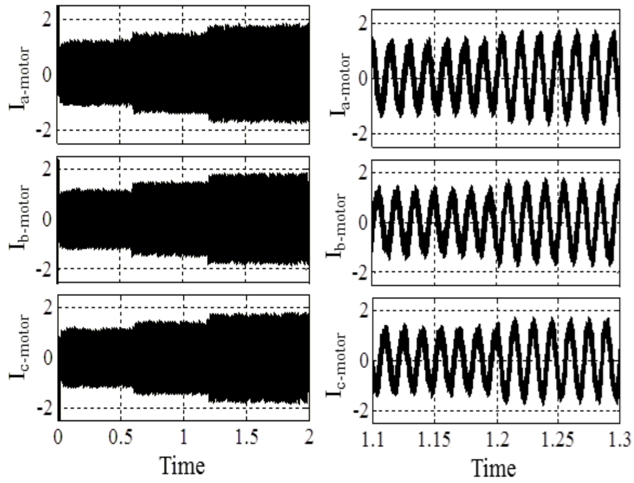



**(c)** **(d)**

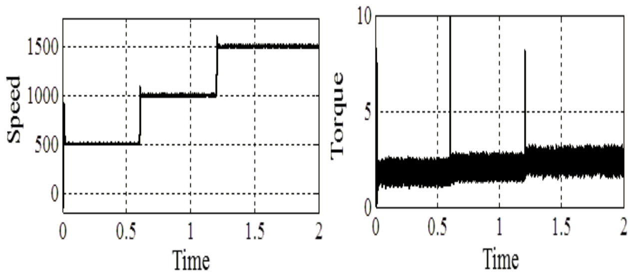
Fig. 9 shows variation of dynamic condition of motor under load variation and speed andVdc are remain constant. Fig. 9 shows set value of load torque, actual value of motor speed and actual value of dc link voltage Vdc under dynamic loading condition. It depicts that under dynamic loading condition when load is continuous changing, control algorithm is unaffected and speed, dc link capacitor and unity power factor on FEC side remain same as steady state condition.



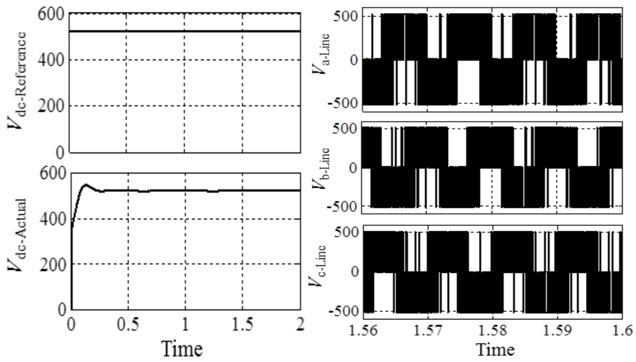

**(e)** **(f)**

**Fig. 9.** PMSM drive under dynamic loading condition (Variable load with speed constant), (a) set value of torque demand, (b) Motor actual speed, (c) dc link voltage Vdc, (d) Inverter line-line voltage, (e) motor load current (Ia, Ib, Ic), (f) Zoom view of motor load current under load change instants.

### 6.3 Variable speed condition (Variable-Speed, Load and Vdc constant)




**(a)** **(b)**




**(c)** **(d)**

**Fig. 10.** PMSM drive under dynamic loading condition (Variable speed with load torque constant), (a) set value of speed demand, (b) Load torque, (c) Actual and reference value of dc link voltage Vdc, (d) Inverter line-line voltage.

Fig. 10 shows variation of speed while load and dc link voltage Vdc are constant. Under speed variation also vector control algorithm work satisfactorily. Also it maintain unity power factor on source side as well as under speed variation, Vdc also remain constant in spite of any change in speed.

### *6.4 Unbalance (b-phase=50 v)*

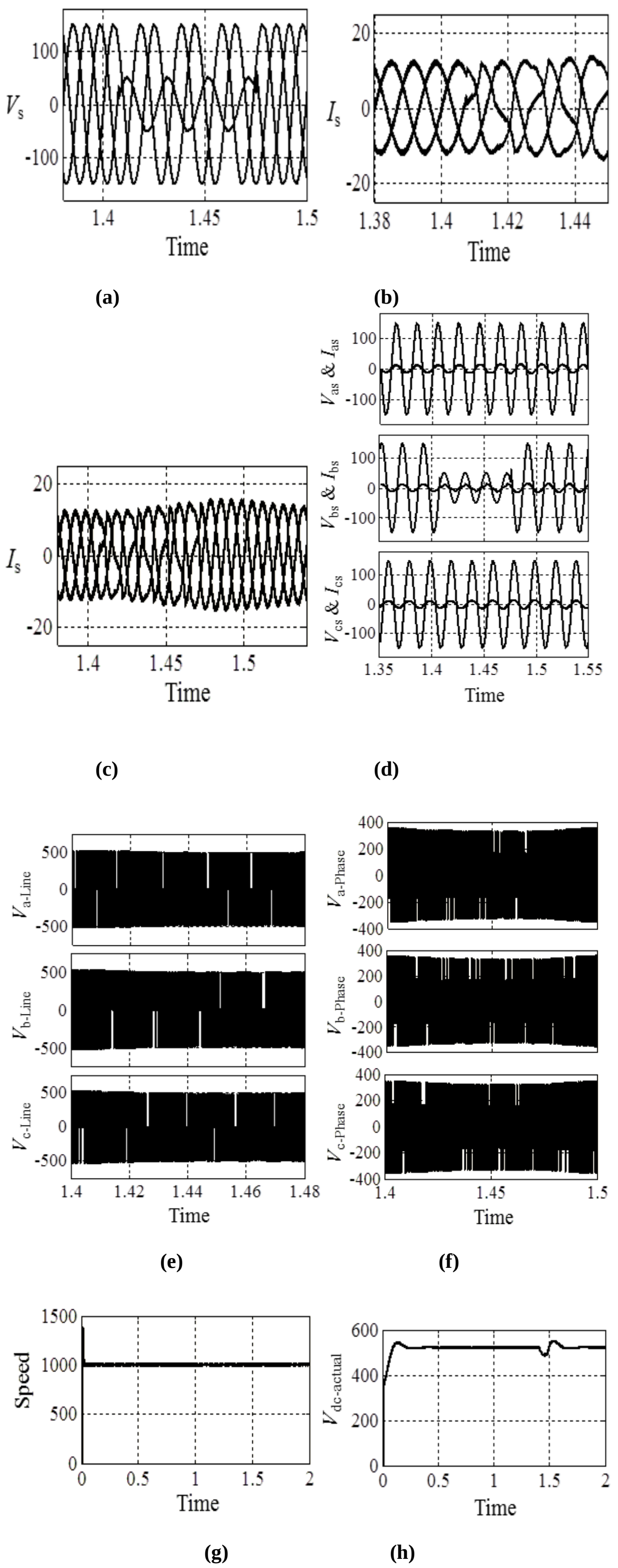



**Fig. 11.** PMSM Drive under unbalance condition (Va=150V, Vb=50V, Vc=150): (a,d) Supply side source voltage waveforms and zoom view, (b,c) Supply side source current and its zoom view under unbalance conditions, (e) Inverter line-line voltage, (f) Inverter phase voltage, (g) Motor speed, (h) Dc link voltage Vdc.

Fig. 11 shows different waveforms under unbalance conditions of supply system. As in grid, many times there is a unbalance in supply voltage and due to that system become instable which disturb performance of drives. But due to this system algorithm, in any unbalance in supply system, it will not reflect on motor speed, dc link voltage and load. All parameters remain unaltered.

### *6.5 Regeneration action*

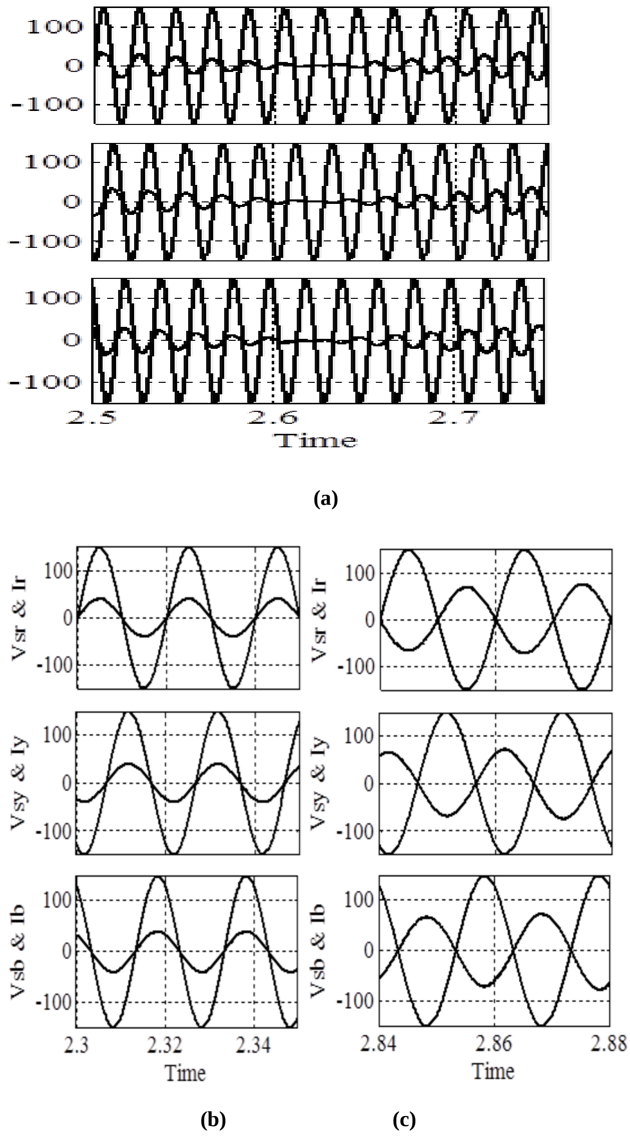



**Fig. 12.** PMSM Drive under regeneration operation: (a) Supply side source voltage and current under regeneration condition, (b) Zoom view of supply side voltage and current waveforms under normal operation, (c) Zoom view of supply side voltage and current waveforms under regeneration operation.

Fig. 12 shows waveforms of regeneration in drive system. Due to front end converter it is possible to create regeneration mechanism in PMSM drives system as when there is access of power is feedback to supply system.

## 7. Conclusion

In this paper robust control algorithm for FEC is develop for controlling dc link voltage Vdc during steady state and dynamic loading condition and it work satisfactorily. Also proposed controller for FEC gives unity power factor on supply side by absorbing current harmonics. Mathematical model of vector control algorithm (field orientation control) and PMSM is developed and analyze using waveforms analysis. During steady state and dynamic loading condition, it maintains constant speed during load variation and constant load during speed variation. From waveforms analysis, it is concluded that AC-DC-AC converter with unity power factor on source side and good load regulation on load side is achieved.

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