Tribhuvan University
Institute of Engineering
Pulchowk Campus
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Unit: V- Sensorless Control of PMSM Drive

Class-16:
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Subject Name
EE: Modelling and Control of Electric Drives

Discussed in the Previous Class

In the previous class discussed the following topics:

- Space Vector PWM Method
- Difference Between VSI and CSI
- Cube Law Between Speed and Power
- Development of Dynamic Models for Electric Drives
- Simulation Tools to Check the Performance of Electric Drive
- Types of Duty Cycles

Lecture Outcomes

- ❖ Introduction of Permanent Magnet Synchronous Motor (PMSM) Drives
- ❖ Difference Between PMSM and Brushless DC (BLDC) Motor Drives
- ❖ Working Principle of PMSM Drives

IM, PMSM, BLDC, SRM

- ❖ Speed Control of Sensor and Sensorless PMSM Drive
- ❖ Sensorless Operation of PMSM Drive
- ❖ Simulation Results of Sensorless PMSM Drive
- ❖ Lecture remarks: Key points of today's class

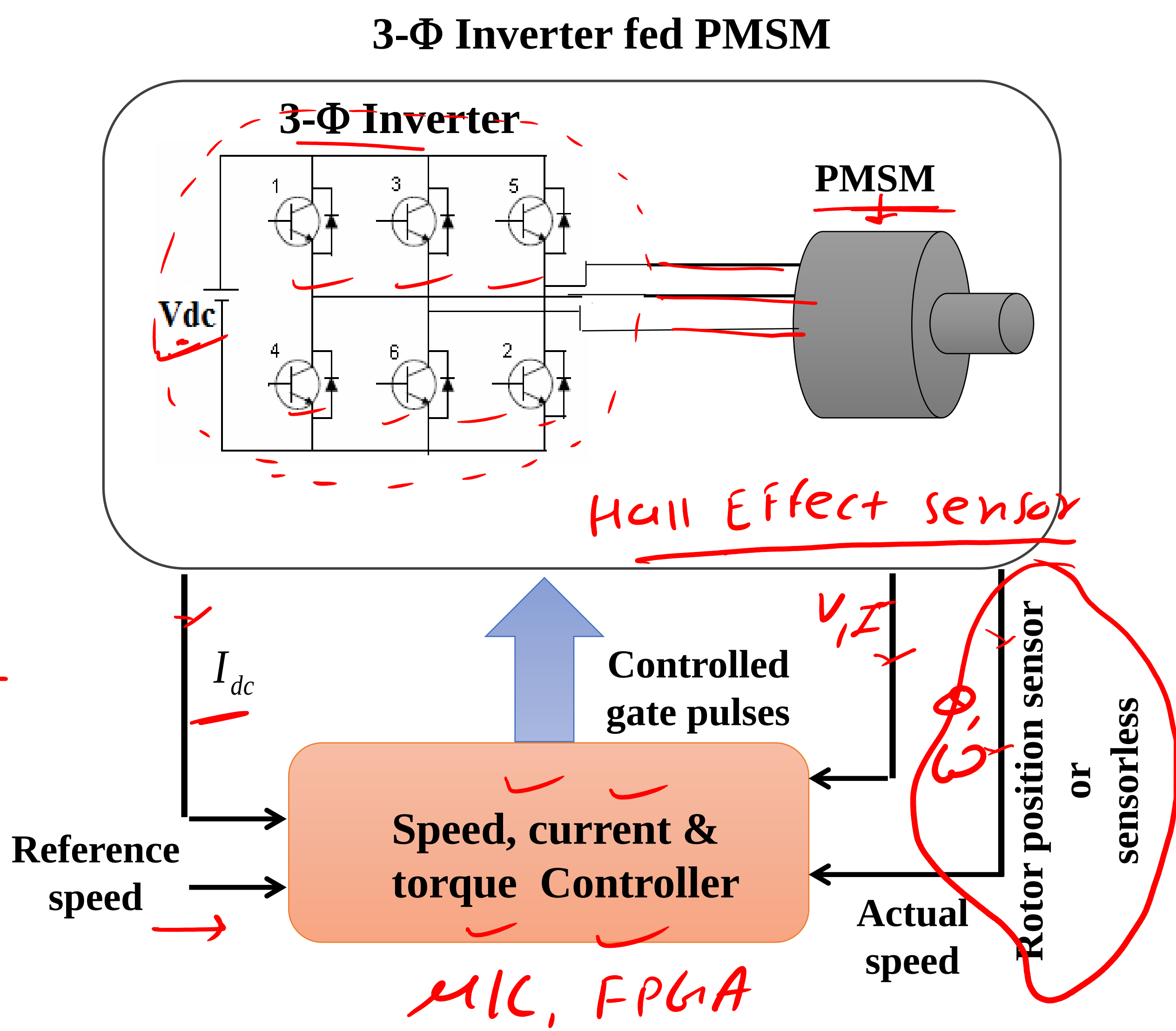
Introduction: PMSM Drive

- The PMSM consists of conventional **three-phase windings in the stator and permanent magnets in the rotor.**

- The purpose of the field windings in the conventional synchronous machine is done by permanent magnets in PMSM.

- The conventional synchronous machine requires an AC and DC supply, whereas the **PMSM requires only an AC supply for its operation.**

- One of the greatest advantages of PMSM over its counterpart is the **removal of DC supply for field excitation**



Introduction: PMSM Drive

- In synchronous motors, the rotor rotates at the speed of the stator revolving field.
- The speed of the revolving stator field is called synchronous speed.
- The synchronous speed (ω_s) can be found by the frequency of the stator input supply (f_s), and the number of stator pole pairs (p).
- The stator of a three-phase synchronous motor consists of distributed sine three-phase winding, whereas the rotor consists of the same number of p-pole pairs as the stator, excited by permanent magnets.

$$\mathrm{N} = \frac{120f}{P} \qquad (1)$$

$p = P/2$

where N is synchronous speed, f *is* frequency of AC supply in Hz; P number of poles; p pole pairs and it is given by (P/2).

Classifications of PM Motors

Direction of Field Flux

- Radial field
- Axial field

Shape of Induce EMF

- BLDC (Trapezoidal)
- PMSM (Sinusoidal)

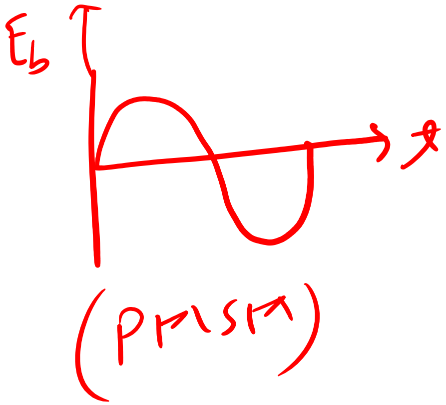
Mounting of the Permanent Magnets

- Surface-mounted magnets (without saliency, SM)
- Internal-mounted magnets (with saliency, IM)

- **Radial field** : The flux direction is along the radius of the machine.
- **Axial field**: The flux direction is parallel to the rotor shaft.
- The IM machine has a **variable reluctance** which varies with the rotor angle.
- The SM machine has quite a fixed reluctance for any rotor angle. Therefore this leads to an **uniform air gap**, resulting in an equal magnetizing inductance for the **direct and quadrature axis (Ld and Lq).**

Classifications of PM Motors

Fig. 1. Concentrated stator winding (BLDC Motor).



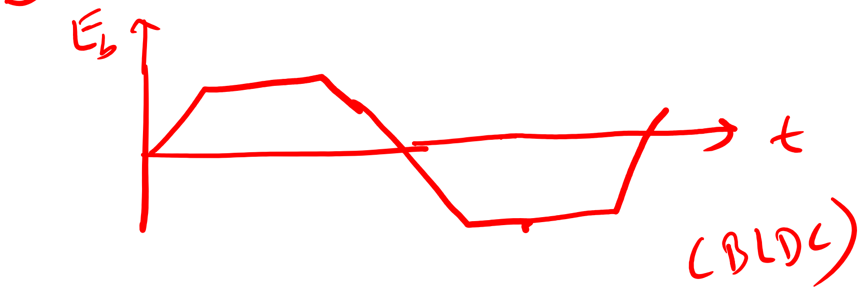
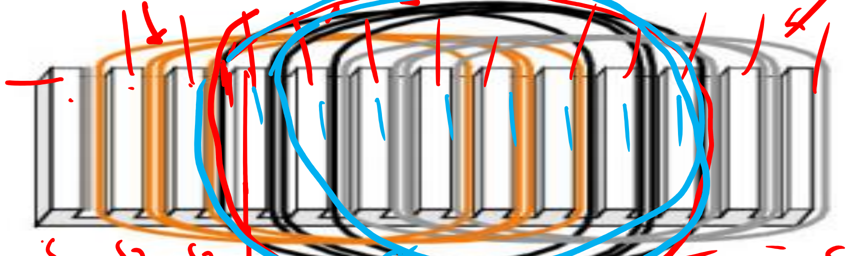


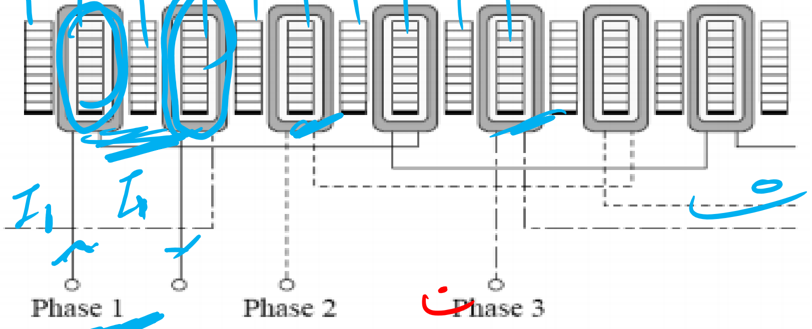
Fig. 2. Distributed stator winding (PMSM).

Same Induction Motor.

Classifications of PM Motors



(a)



(b)

Fig. 1. The three-phase stator winding of PM motors: (a) distribution winding and (b) concentrated winding.

(a)

(b)

Fig. 2. Pictorial view of a stator of PM motors: (a) distributed winding (PMSM) and (b) concentrated winding (BLDC).

PMSM drives	BLDC motor drives
Fed with AC	Fed with DC
Sinusoidal flux density (driven by magnetic design)	Square flux density (driven by magnetic design)
Back EMF is sinusoidal (driven by winding and magnets design)	Back EMF is trapezoidal (driven by winding and magnets design)
Current is sinusoidal (driven by the controller, which makes the controller more complex and costlier)	Current is trapezoidal (driven by the controller, which makes the controller easier and cheaper)
For equal resistive losses, power density is less	For equal resistive losses, power density is 15.4% higher than PMSM
The conduction and switching losses are higher because of three transistors in inverter conduct	The conduction and switching losses are smaller because of only two transistors in inverter conduct
Torque ripple due to the commutation of currents is low	Torque ripple due to the commutation of currents is high
The coils of distributed winding are not co-axial. They are rather distributed in various slots along the air-gap periphery	The coils of the concentrated winding are co-axial. This means, all the winding has the same magnetic axis
The back EMF induced in such winding is independent of pitch and distribution factor **$E=4.44 \times N_{ph} \times f \times \phi$**	The back EMF induced in the distributed winding is dependent on the value of pitch factor “K_p” and distribution factor “K_d”. $E = 4.44 \times N_{ph} \times f \times \phi \times K_p \times K_d$
Torque equation is given by $T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)[(\lambda_f) - (L_d - L_q)I_d]I_q$	Torque equation is given by $T_e = \frac{[(e_a i_a) + (e_b i_b) + (e_c i_c)]}{\omega_m}$ where, $e_a = F_a(\theta_r) \times \lambda_f \times \omega_m$ $e_b = F_b(\theta_r) \times \lambda_f \times \omega_m$ $e_c = F_c(\theta_r) \times \lambda_f \times \omega_m$

Pros and Cons of PMSM Drive

Pros

1. The DC field winding of the rotor is replaced by permanent magnets
2. The advantages of elimination are reduced field copper loss
3. lower rotor inertia
4. higher power density
5. More robust construction of the rotor

Cons

1. Loss of flexibility of field flux control
2. Possible demagnetization effect

Use of PMSM

1. **High Efficiency** **-** Not in Induction Motor
2. **Better Controllability**
3. **Sensorless Operation**
4. **High torque to weight ratio**
5. **High energy Density** **-** Hence compact
6. **Low acoustic Noise** **-** Compared to DC brushed and brush-less Motors
7. **No excitation losses**
8. **Fast dynamic performance**

Speed Control of PMSM Drive (Sensor based)

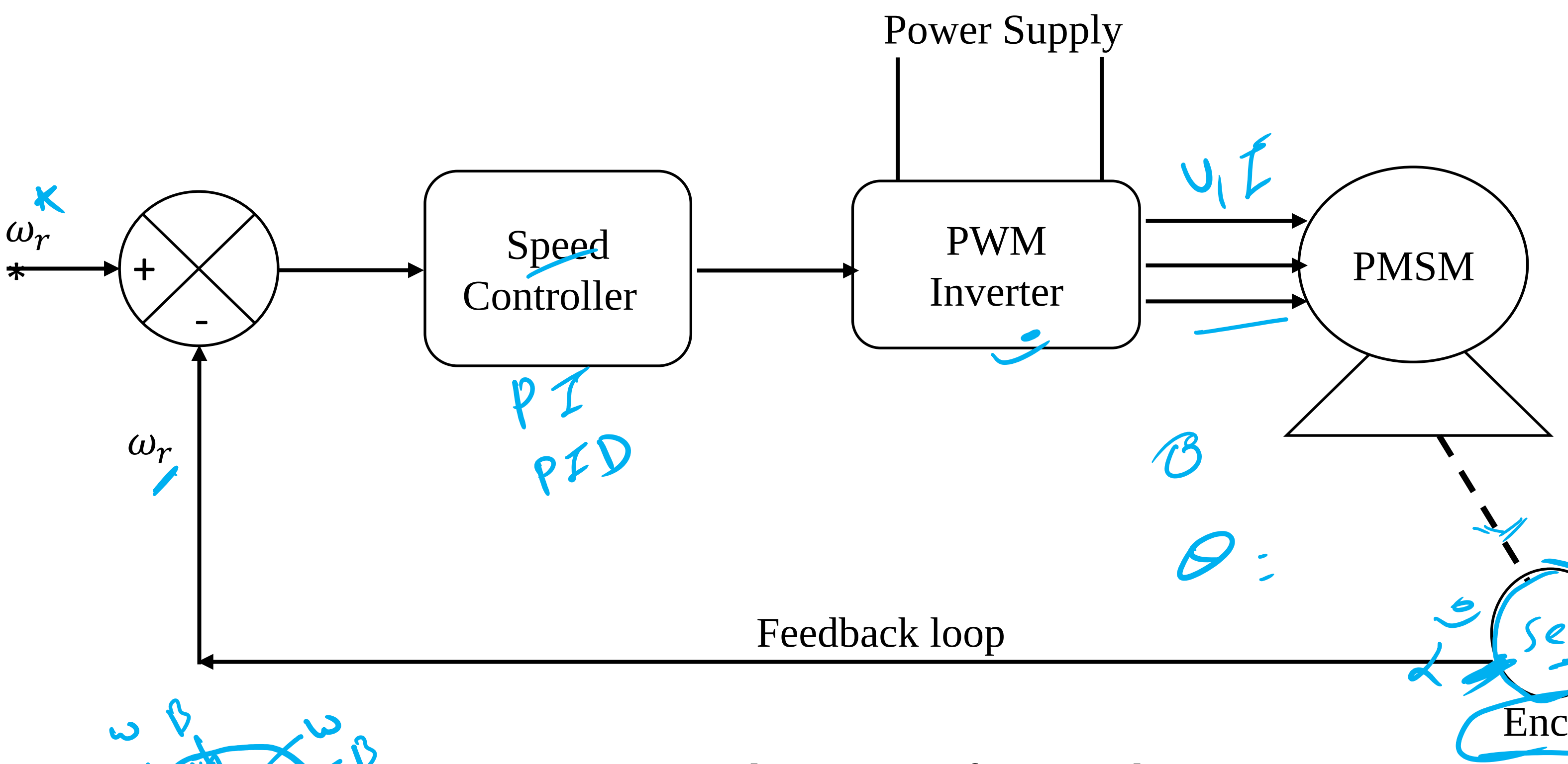


Fig 1. Sensored operation of PMSM drive

To present the sensors have several disadvantages

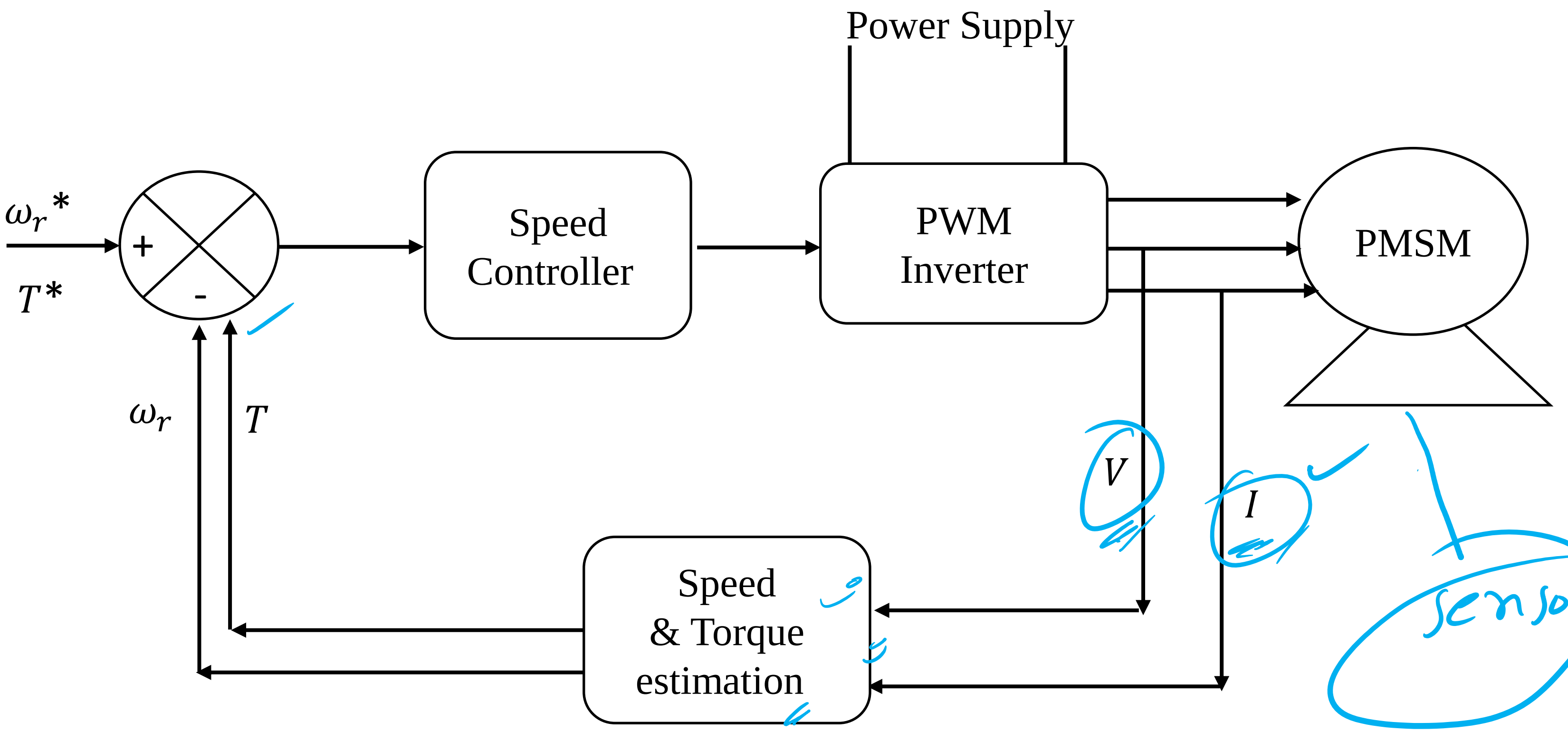
1. **Reduced reliability**
2. **Increased cost**
3. **Weight**
4. **Size**
5. **Increased complexity of the drive system**

Four main devices are there for the measurement of position

1. **The potentiometer**
2. **Linear variable differential transformer**
3. **Optical encoder**
4. **Resolvers**

The most commonly used for motors are **encoders and revolvers**

Speed Control of PMSM Drive (Sensorless)



Advantages

1. **More compact drive**
2. **Low EMI (Absence of connecting leads)**
3. **Cost of position-encoding device is avoided**
4. **Increases mechanical robustness**
5. **Suitable for hostile environments including temperature**
6. **Ensure that the inertia of the system is not increased**
7. **Low maintenance**

- The position of the rotor in electric machines by measuring only their voltages and currents sensing
- These methods are usually designated as sensorless, encoderless, or self sensing [13-14]
- PMSM, the position of the rotor can be determined by the back electromotive force (EMF) or by the position dependence of the inductances, flux linkage sensing etc.

Sensorless Control Methods of PMSM Drive

Sensorless Control Methods

- **Open loop**
  - Back-EMF based
  - Stator inductance calculation
- **Close loop**
  - Sliding Mode Observer (SMO)
  - Model Reference Adaptive System (MRAS)
  - Extended Kalman filter (EKF)
- **Non-ideal property**
  - High Frequency signal injection
  - Low Frequency signal injection

Disadvantages of Sensored based PMSM Drive

- Reduce reliability
- Increase weight
- Increase design complexity
- Increase cost and size of drive

Why Sensorless Operation

- Reduction of hardware complexity & cost
- Increased mechanical robustness & overall ruggedness
- Higher reliability
- Decreased maintenance
- Unaffected machine inertia

Classification of Sensorless Techniques for PMSM Drive

Model based methods

- In this methods use the fundamental model of PMSM, to sense the rotor position
- **e.g. stator phase voltage, current and inductance of PMSM drive.**

Indirect position sensing methods

- In this methods the rotor position is estimated indirectly from sense the position dependent quantities
- **e.g., back EMF components and third harmonic back EMF.**

Saliency based methods

- In this methods the rotor position information is extracted from the position-dependent machine saliency and high frequency excitation is usually required
- **e.g. high-frequency injection method.**

Block diagram for position and speed estimation of PMSM drive

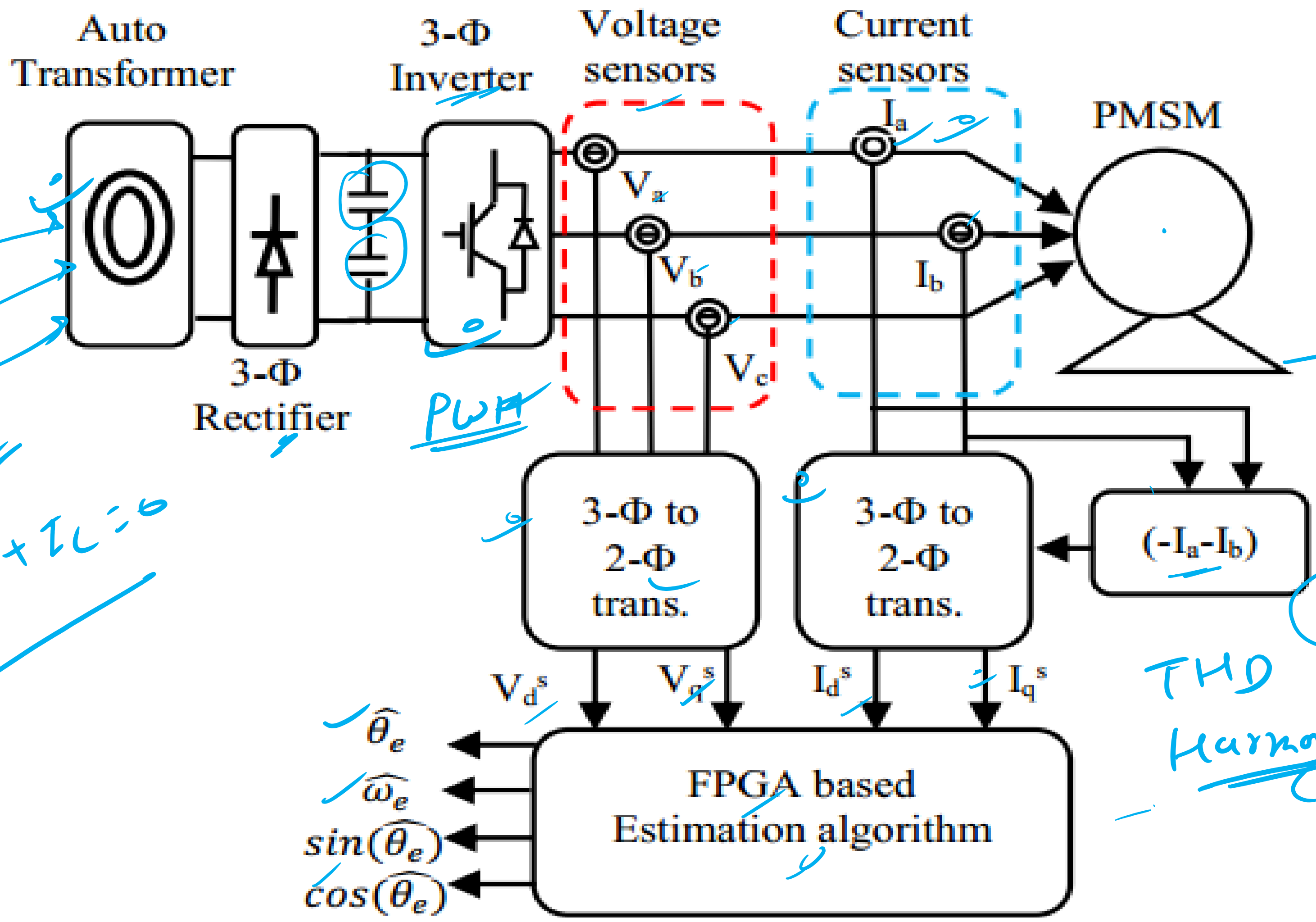


Fig.1. Block diagram for position and speed estimation of PMSM drive

Vector control block diagram of PMSM drive with estimated rotor position

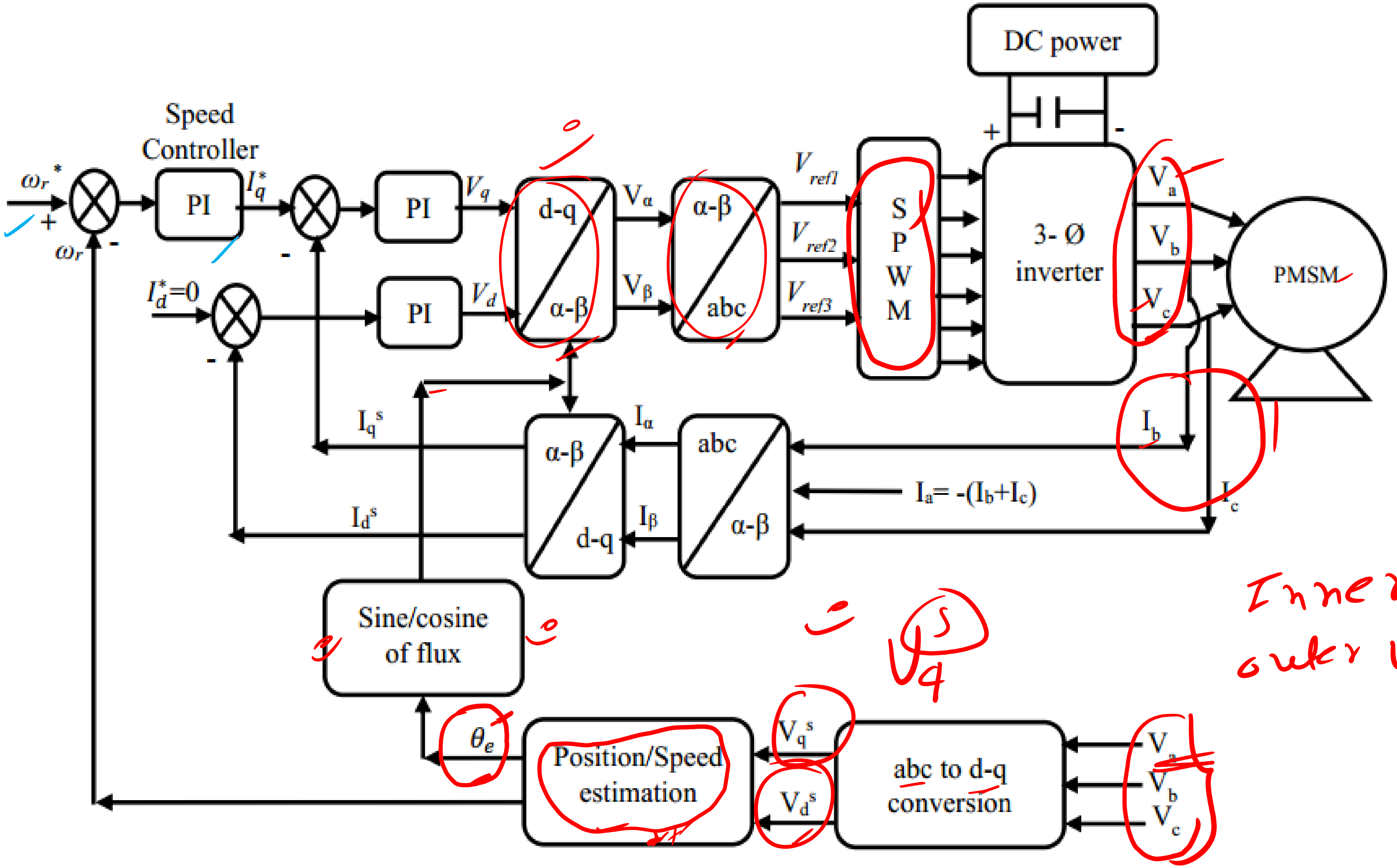


Fig. 2. Vector control block diagram of PMSM drive with estimated rotor position

Mathematical Model of Sensorless PMSM Drive

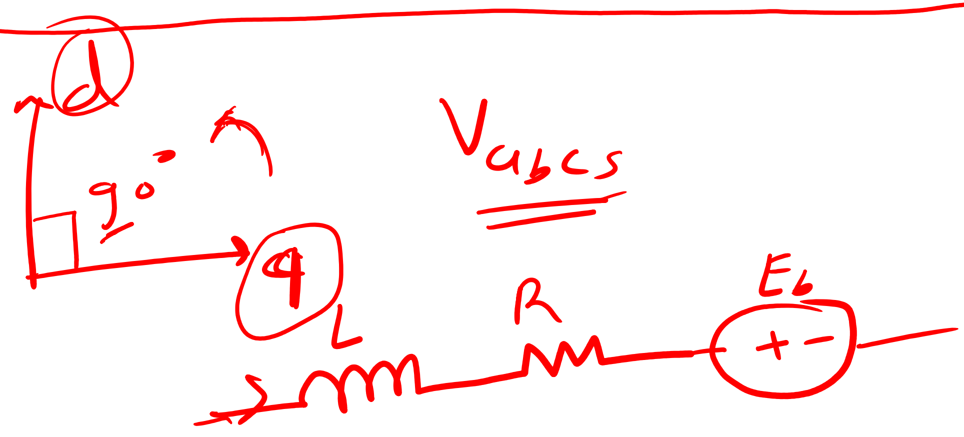
Expressing three-phase stator voltages and currents in terms of stationary reference frame.

$$V_q^s = V_{as} \quad (1)$$

$$V_d^s = \left(\frac{V_{cs} - V_{bs}}{\sqrt{3}}\right) \quad (2)$$

$$i_q^s = i_{as} \quad (3)$$

$$i_d^s = \left(\frac{i_{cs} - i_{bs}}{\sqrt{3}}\right) \quad (4)$$



$$V_d^e = (R_d + pL_d) i_d^e - \omega_e L_d i_q^e \quad (5)$$

$$V_q^e = (R_q + pL_q) i_q^e + \omega_e L_d i_d^e + \omega_e \varphi_f \quad (6)$$

Transforming stationary frame to rotatory frame

$$i_d^e = i_d^s \cos\theta_e + i_q^s \sin\theta_e \quad (7)$$

Mathematical Model of Sensorless PMSM Drive

$$i_q^e = -i_d^s \sin\theta_e + i_q^s \cos\theta_e \quad (8)$$

$$V_d^e = V_d^s \cos\theta_e + V_q^s \sin\theta_e \quad (9)$$

$$V_q^e = -V_d^s \sin\theta_e + V_q^s \cos\theta_e \quad (10)$$

$$\omega_e = \frac{\left[\sqrt{\left\{\left(V_q^s - R_q i_q^s - L_d p i_q^s\right)^2 + \left(V_d^s - R_d i_d^s - L_d p i_d^s\right)^2\right\}}\right]}{\varphi_f} \quad (11)$$

Putting the values of i_d^e and i_q^e from equation (7), (8) in eqn. (5) and (1) and comparing with eq. (10) and (11) we get θ_e

$$\theta_e = \tan^{-1}(x/y) \quad (12)$$

$\theta = \tan^{-1} x/y$

$$x = \left[-V_d^s + R_d i_d^s + L_d p i_d^s - \omega_e (L_q - L_d) i_q^s\right] \quad (13)$$

$$y = \left[V_q^s - R_q i_q^s - L_d p i_q^s - \omega_e (L_q - L_d) i_d^s\right] \quad (14)$$

Simulation Results of Sensorless PMSM Drive

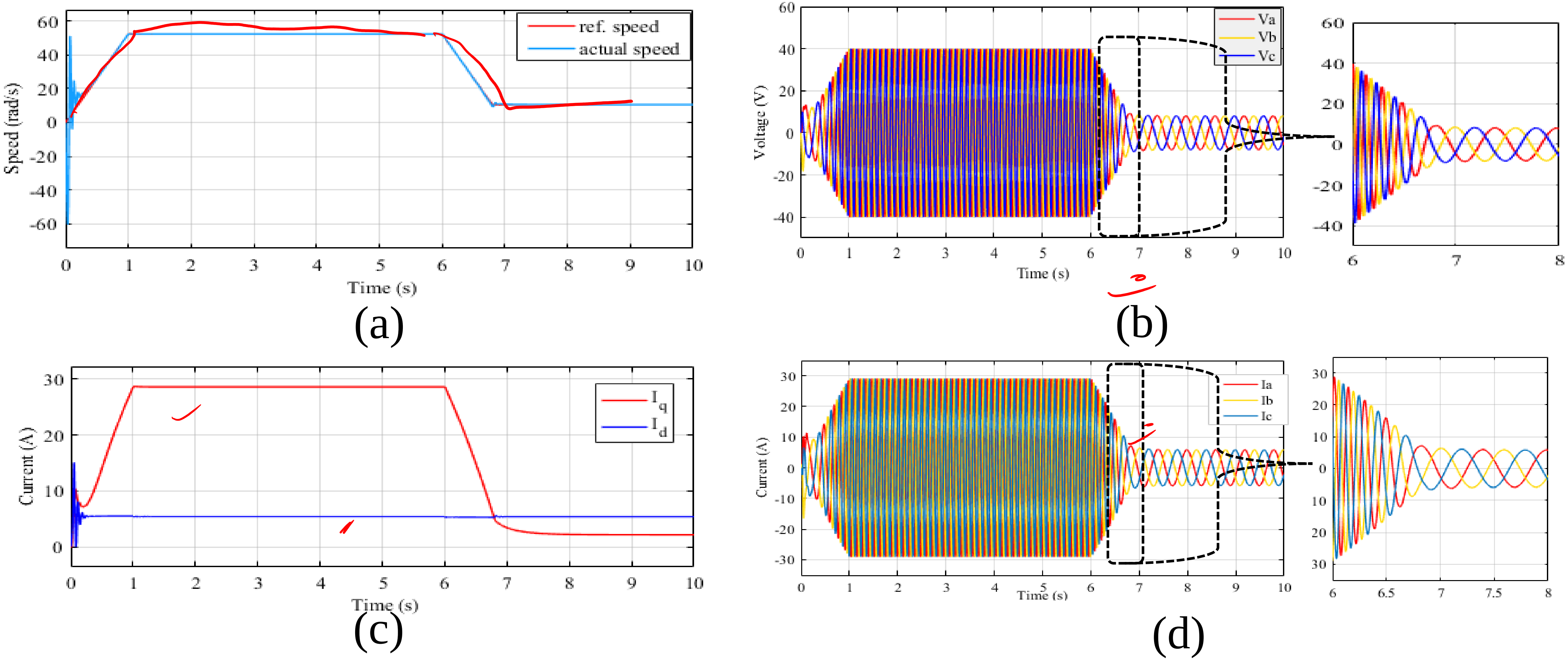
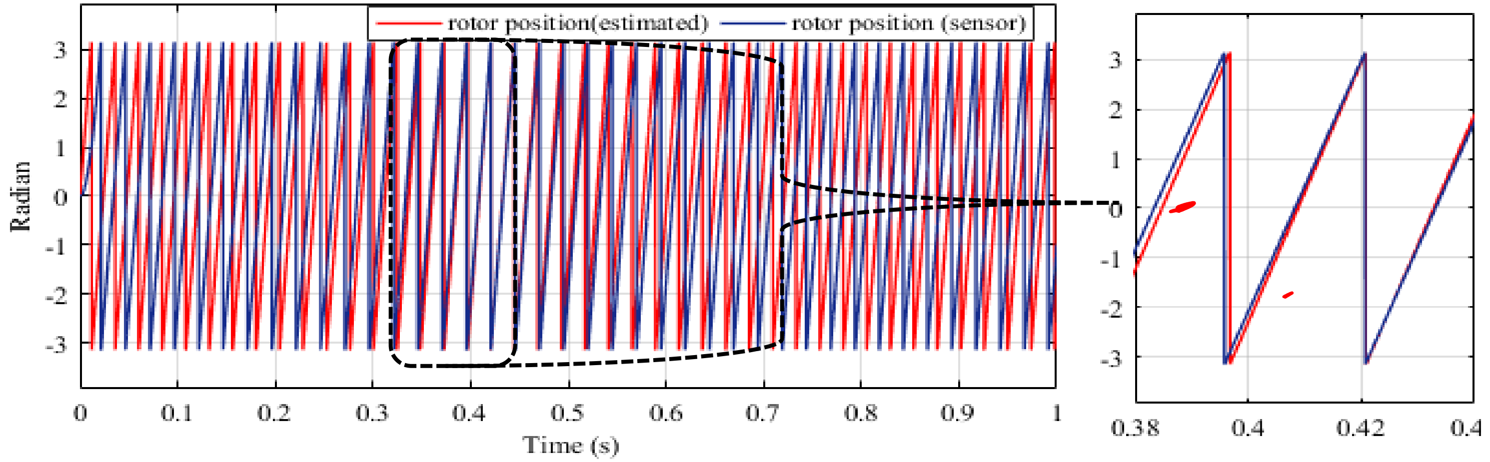
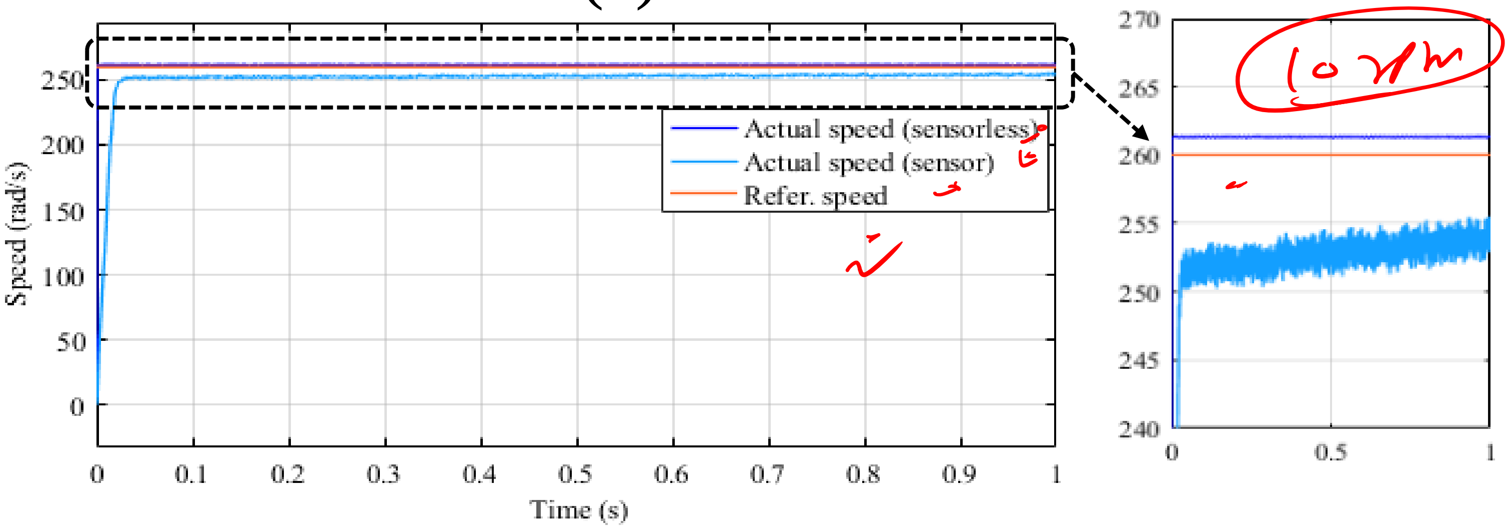


Fig. 3. Simulation results of V/F PMSM drive: (a) reference and actual speed response, (b) three-phase stator phase voltage response, (c) three-phase stator phase current response and (d) I_d - I_q axis current response.

Simulation Results of Sensorless PMSM Drive



(a)



(b)

Comparison of estimated and measured rotor position has been done and it has been plotted between $-\pi$ to π instead of plotting from 0 to 2π.

Fig. 4. Simulation results of sensorless PMSM drive: (a) comparison of sensored and sensorless rotor position response and (b) comparison speed response.

Simulation Results of Sensorless PMSM Drive

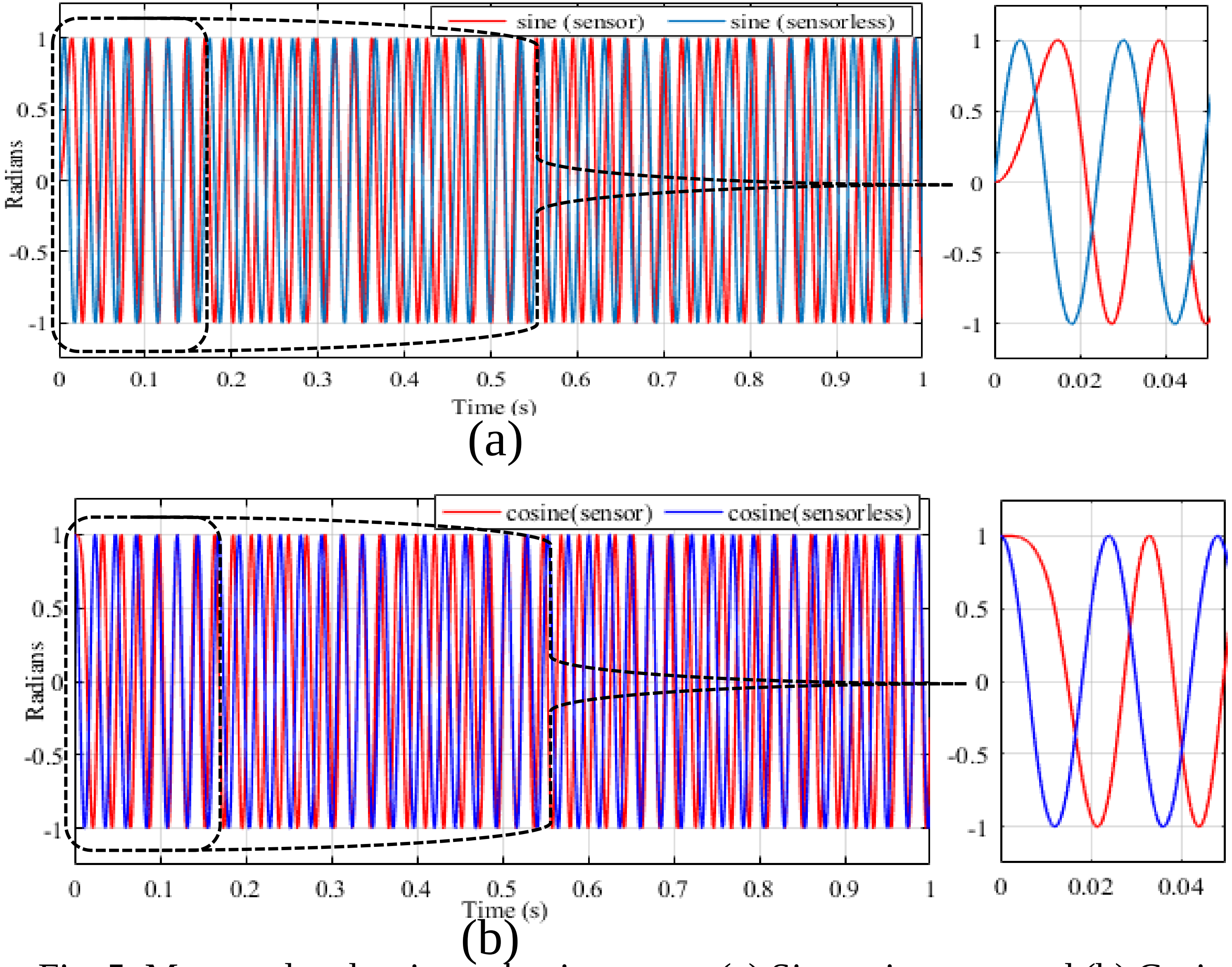


Fig. 5. Measured and estimated unit vectors: (a) Sine unit vector and (b) Cosine unit vector

- Measured and estimated unit vector of sine is compared.
- Both the quantities are coming as a sine wave but having some phase difference between them.

Key Points from Today's Class

- Introduction of PMSM Drives
- Difference Between PMSM and BLDC Motor Drives
- Working Principle of PMSM Drives
- Speed Control of Sensor and Sensorless PMSM Drive
- Sensorless Operation of PMSM Drive
- Simulation Results of Sensorless PMSM Drive

Thank you so much for your attentions

Q & A