4

Field Oriented Control of AC Machines

- The control of AC machines can be classified into ‘scalar’ and ‘vector’ controls.
- Scalar controls are simple to implement and offer good steady-state response; however, the dynamics are very slow because transients are not controlled.
- The vector control idea relies on the control of stator current space vectors in a similar, but more complicated, way to a DC machine.
- The principle of torque and flux control is called ‘field oriented control’ or ‘vector control’ for induction machines and later for synchronous machines.

Induction Machines Control

- It has been claimed that 90% of installed motors in the industry are Induction motors.
- Different control methods are popular in the industry
  - Control of Induction Motor using V/f method
  - Vector Control of Induction Motor
  - Direct and Indirect Field Oriented Control
  - Field Weakening Control

Control of Induction Motor using V/f method

- In this way of control, a constant ratio between the voltage magnitude and frequency is maintained. This is to keep constant and optimal flux in the machine:

$$u_{sx} = R_s i_{sx} + \frac{d\psi_{sx}}{d\tau} - \omega_a \psi_{sy}$$

High Performance Control of AC Drives with MATLAB/Simulink Models, First Edition.
Haitham Abu-Rub, Atif Iqbal, and Jaroslaw Guzinski.

$$u_{sy} = R_s i_{sy} + \frac{d\psi_{sy}}{d\tau} + \omega_a \psi_{sx}$$

The voltage vector magnitude is

$$|u_s| = \sqrt{(R_s i_{sx})^2 + (R_s i_{sy})^2 + (\omega_a \psi_{sx})^2 + 2 \cdot R_s i_{sy} \cdot \omega_a \psi_{sx}}$$

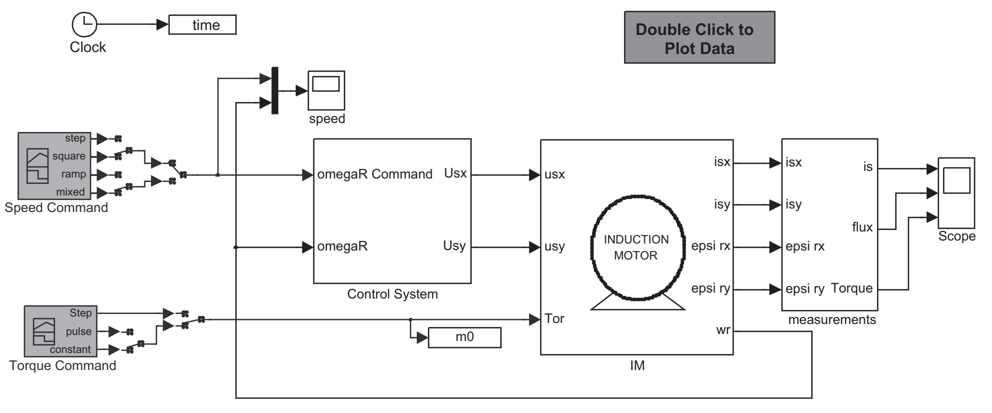

Figure 4.1 V/f control of induction motor

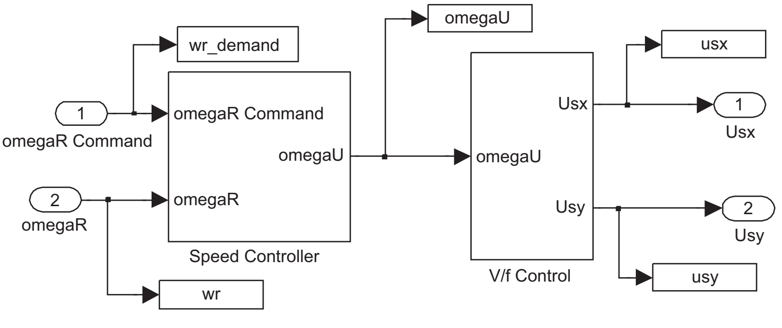

Figure 4.2 V/f control system model

- *Current and flux computation*

$$|I_s| = \sqrt{I_{s\alpha}^2 + I_{s\beta}^2}$$

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2}$$

The motor torque is given by

$$M_e = \frac{L_m}{JL_r}(\psi_{r\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha})$$

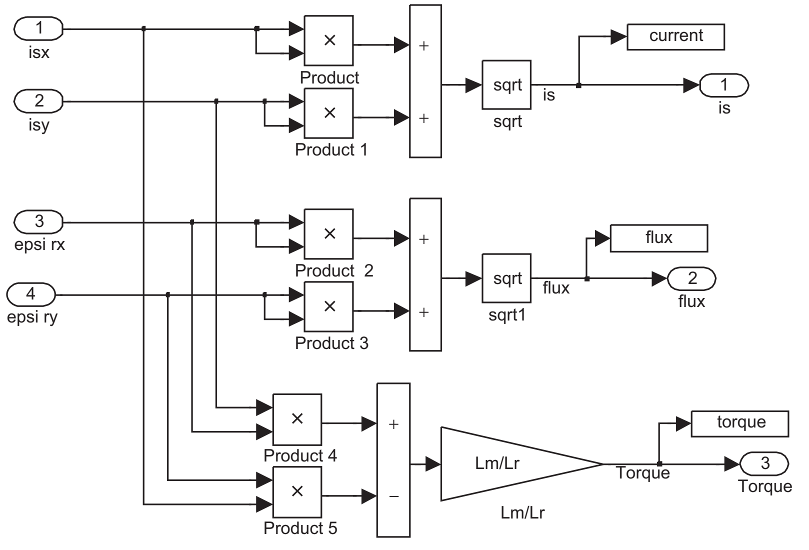

Figure 4.3 Current, flux, and motor torque calculations

- *Control system*

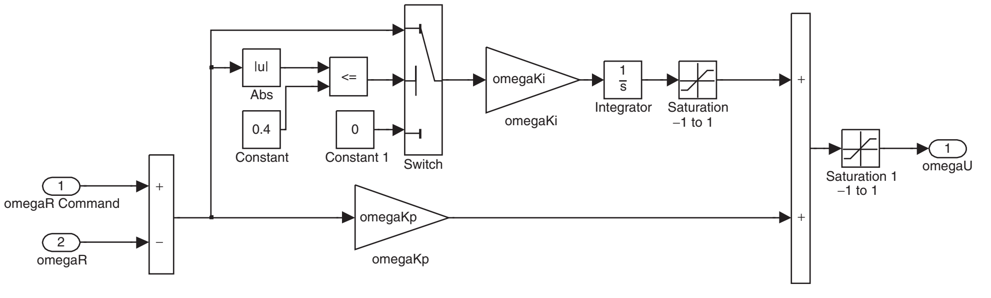

Figure 4.4 Limited authority PI control systems model

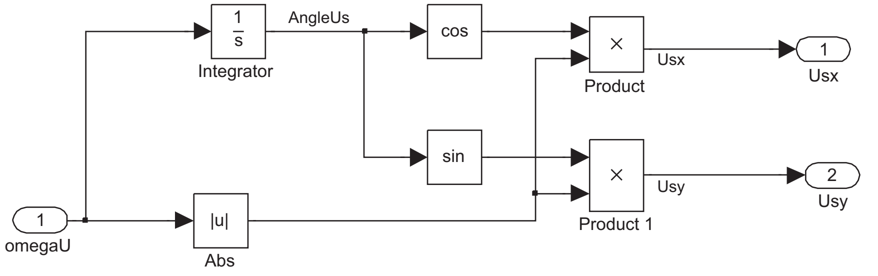

Figure 4.5 V/f control

- *Simulation results*

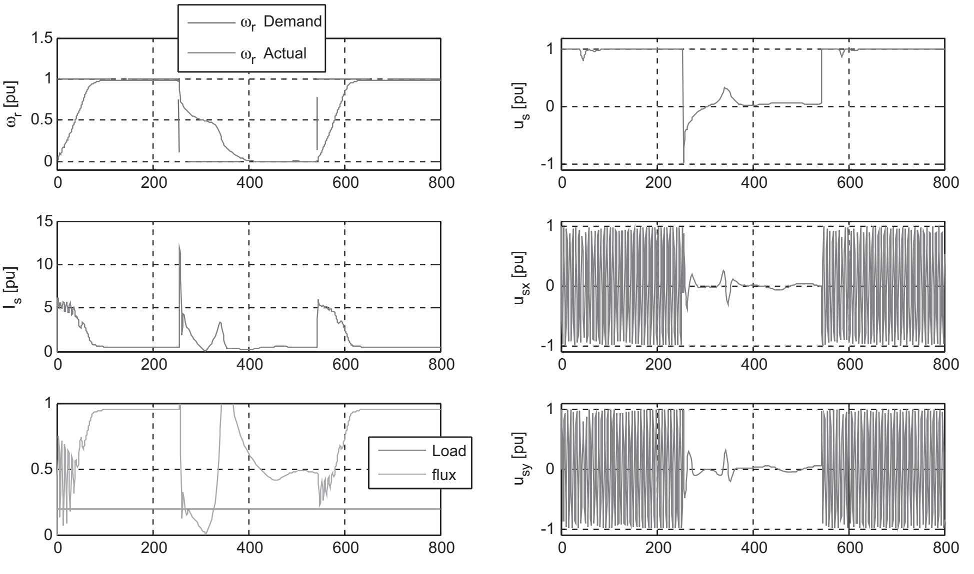

Figure 4.6 Simulation results

Vector Control of Induction Motor

- Proper control of motor speed and produced electromagnetic torque is needed in high performance adjustable speed drives. The torque production depends on the armature current and machine flux.
- The flux oriented control method allows representation of the mathematically complicated induction machine in a similar manner as DC machines for obtaining control linearity, decoupling, and high performance AC drives.
- By using vector representation, it is possible to present the variables in an arbitrary co-ordinate system.

Relationships of motor model in frame *d-q*, rotating with rotor flux in the *d* axis (the *q* flux component is zero $ysq = 0$), as

$$\frac{di_{sd}}{dt} = a_1 \cdot i_{sd} + a_2 \cdot 0 + \omega_{\psi r} \cdot i_{sq} + \omega_r \cdot a_3.0 + a_4 \cdot u_{sd}$$

$$\frac{di_{sq}}{dt} = a_1 \cdot i_{sd} + a_2 \cdot 0 - \omega_{\psi r} \cdot i_{sd} - \omega_r \cdot a_3 \cdot \Psi_r + a_4 \cdot u_{sq}$$

$$\frac{d\Psi_r}{dt} = a_5 \cdot \Psi_{rd} + (\omega_{\psi r} - \omega_r) \cdot 0 + a_6 \cdot i_{sd}$$

$$0 = a_5 \cdot 0 - (\omega_{\psi r} - \omega_r) \cdot \Psi_r + a_6 \cdot i_{sq}$$

$$\frac{d\omega_r}{dt} = \frac{L_m}{L_r J}(\Psi_r i_{sq} - 0 \cdot i_{sd}) - \frac{1}{J} m_o$$

- *Basic control scheme*

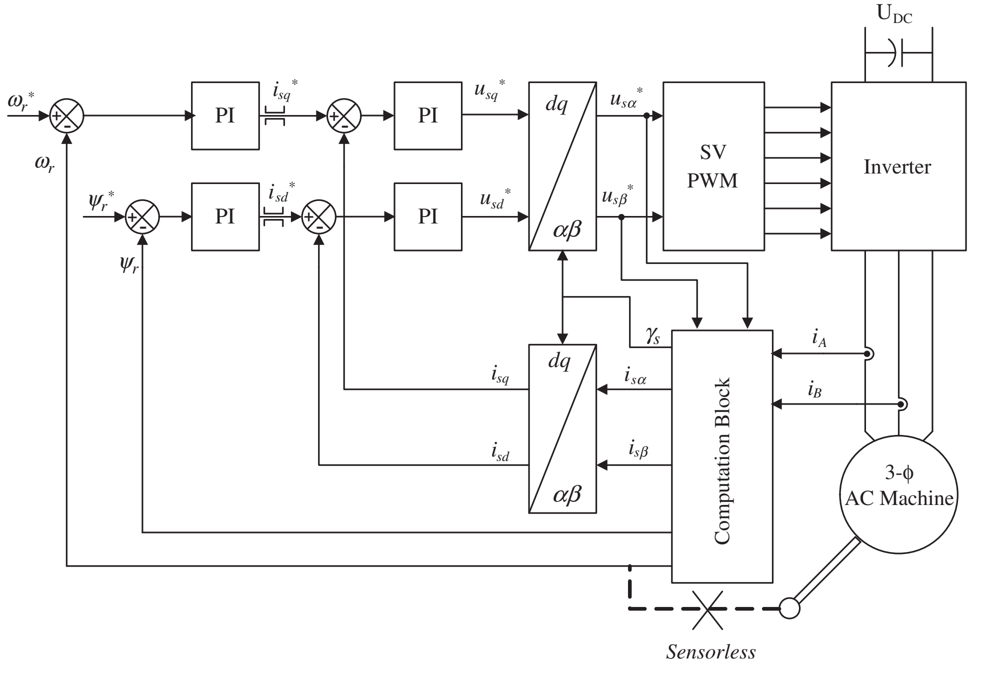

Figure 4.7 Basic scheme of FOC for the three-phase AC machine

- *Matlab/Simulink model for induction motor vector control*

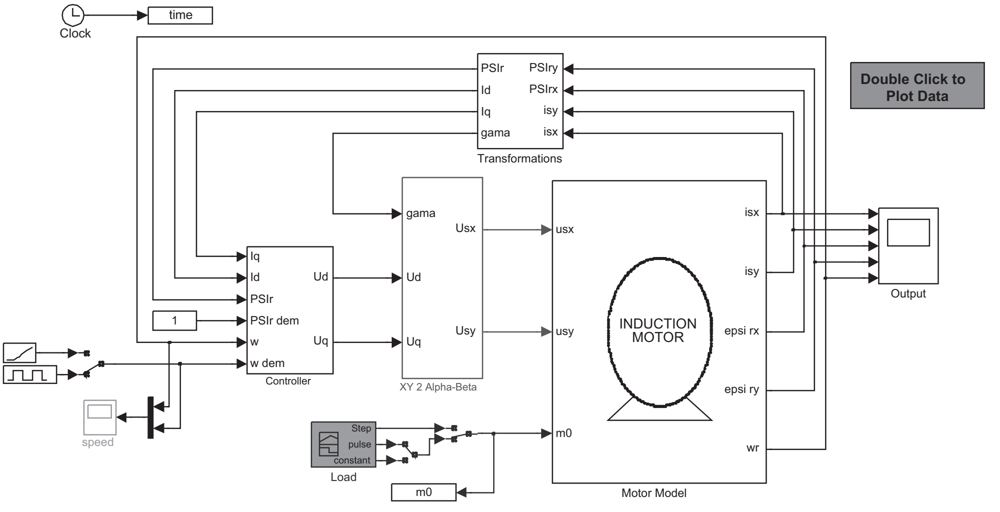

Figure 4.8 Induction motor control

- *Control scheme*

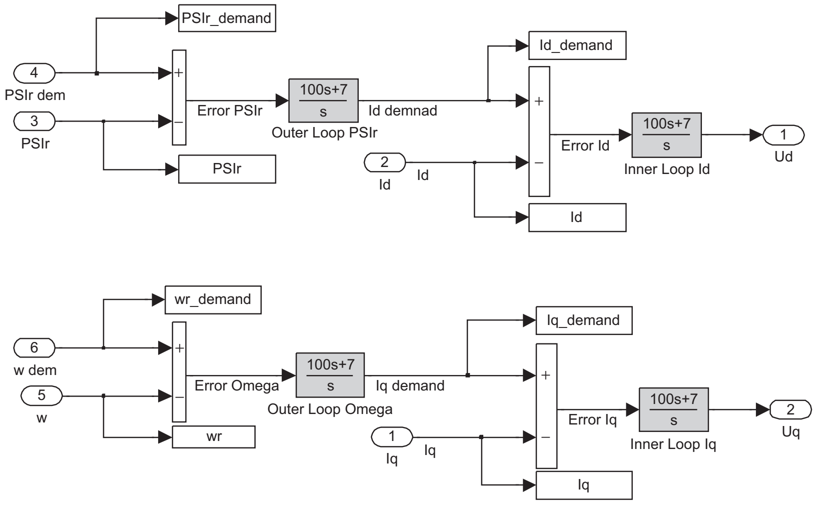

Figure 4.12 Two-loop control system for an induction motor

• *Simulation results*

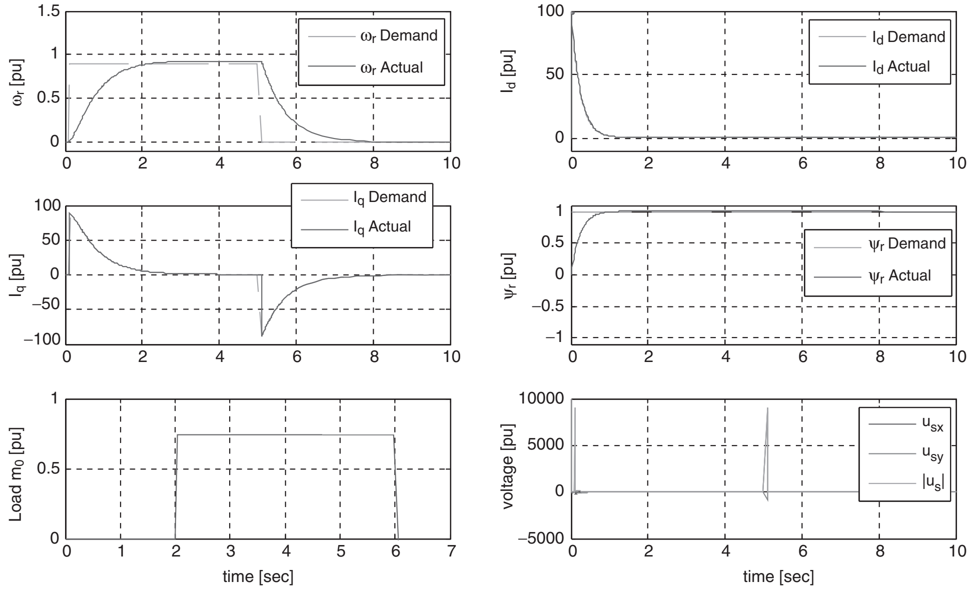

Figure 4.13 Simulation results

Direct and Indirect Field Oriented Control

- Motor state variables may be identified using direct or indirect measurement, using machine models or observers.
- In direct, as well as indirect, control methods, the stator current is measured directly.
- In direct control schemes, the machine's magnetic field is measured using special sensors located in the machine air gap.
- In indirect control schemes, the machine flux is computed using special methods.
- Two basic advanced methods are used for flux computation and control purpose.
- The first method is based on modeling the AC machine by its state space equations. A sinusoidal magnetic field in the machine is assumed. The machine models are defined as open-loop models.
- The adaptive observers are receiving more attention than open loop models because of their robustness against parameters variation and higher computation precision.

- Rotor and stator flux computation

  The stator flux vector could be computed from the voltage models:

$$\bar{\psi}_s = \int (\bar{u}_s - R_s \bar{i}_s) dt$$

$$\bar{\psi}_s = L_s \bar{i}_s + L_m \bar{i}_r$$

The rotor flux vector is

$$\bar{\psi}_r = L_r \bar{i}_r + L_m \bar{i}_s$$

The expressions of rotor flux vector components in the stationary coordinate system *(αβ)*:

$$\psi_{r\alpha} = \frac{L_r}{L_m}(\psi_{s\alpha} - \delta L_s i_{s\alpha}) \qquad \psi_{r\beta} = \frac{L_r}{L_m}(\psi_{s\beta} - \delta L_s i_{s\beta})$$

The rotor flux magnitude is computed as

$$|\psi_r| = \sqrt{\psi_\alpha^2 + \psi_\beta^2}$$

The angle of the rotor flux position is

$$\gamma_s = tan^{-1}\left(\frac{\psi_{r\beta}}{\psi_{r\alpha}}\right)$$

The disadvantage of this method is that it is operationally limited at lower frequencies (below 3%), because of problems with integrating small signals at low frequencies.

- Adaptive flux observers

The full-order observer used for estimating state variables (mostly stator current and rotor flux components) is described as

$$\frac{d}{dt}\hat{x} = \hat{A}\hat{x} + Bu_s + G(\hat{i}_s - i_s)$$

In this, ^ means the estimated value, and G is the feedback observer gain.

One of the most used observers is Luenberger observer. This observer is mainly used for flux and stator current computation.

The equations representing this type of observer are

$$\frac{d\hat{i}_{s\alpha}}{dt} = a_1 \cdot \hat{i}_{s\alpha} + a_2 \cdot \hat{\Psi}_{r\alpha} + \omega_r \cdot a_3 \cdot \hat{\Psi}_{r\beta} + a_4 \cdot u_{s\alpha} + k_i(i_{s\alpha} - \hat{i}_{s\alpha})$$

$$\frac{d\hat{i}_{s\beta}}{dt} = a_1 \cdot \hat{i}_{s\beta} + a_2 \cdot \hat{\Psi}_{r\beta} - \omega_r \cdot a_3 \cdot \Psi_{r\alpha} + a_4 \cdot u_{s\beta} + k_i(i_{s\beta} - \hat{i}_{s\beta})$$

$$\frac{d\hat{\Psi}_{r\alpha}}{dt} = a_5 \cdot \hat{\Psi}_{r\alpha} + -\omega_r \cdot \hat{\Psi}_{r\beta} + a_6 \cdot \hat{i}_{s\alpha} - k_{f1}(i_{s\alpha} - \hat{i}_{s\alpha}) - k_{f2}(i_{s\beta} - \hat{i}_{s\beta})$$

$$\frac{d\hat{\Psi}_{r\beta}}{dt} = a_5 \cdot \hat{\Psi}_{r\beta} + a_6 \cdot \hat{i}_{s\beta} + \omega_r \hat{\Psi}_{r\alpha} + k_{f2}(i_{s\alpha} - \hat{i}_{s\alpha}) - k_{f1}(i_{s\beta} - \hat{i}_{s\beta})$$

Where:

$$a_1 = -\frac{R_s L_r^2 + R_r L_m^2}{L_r w} \quad a_2 = \frac{R_r L_m}{L_r w} \quad a_3 = \frac{L_m}{w} \quad a_4 = \frac{L_r}{w} \quad a_5 = -\frac{R_r}{L_r} \quad a_6 = R_r \frac{L_m}{L_r}$$

$$w = \sigma L_r L_s = L_r L_s - L_m^2 \qquad \sigma = 1 - \frac{L_m^2}{L_s L_r}$$

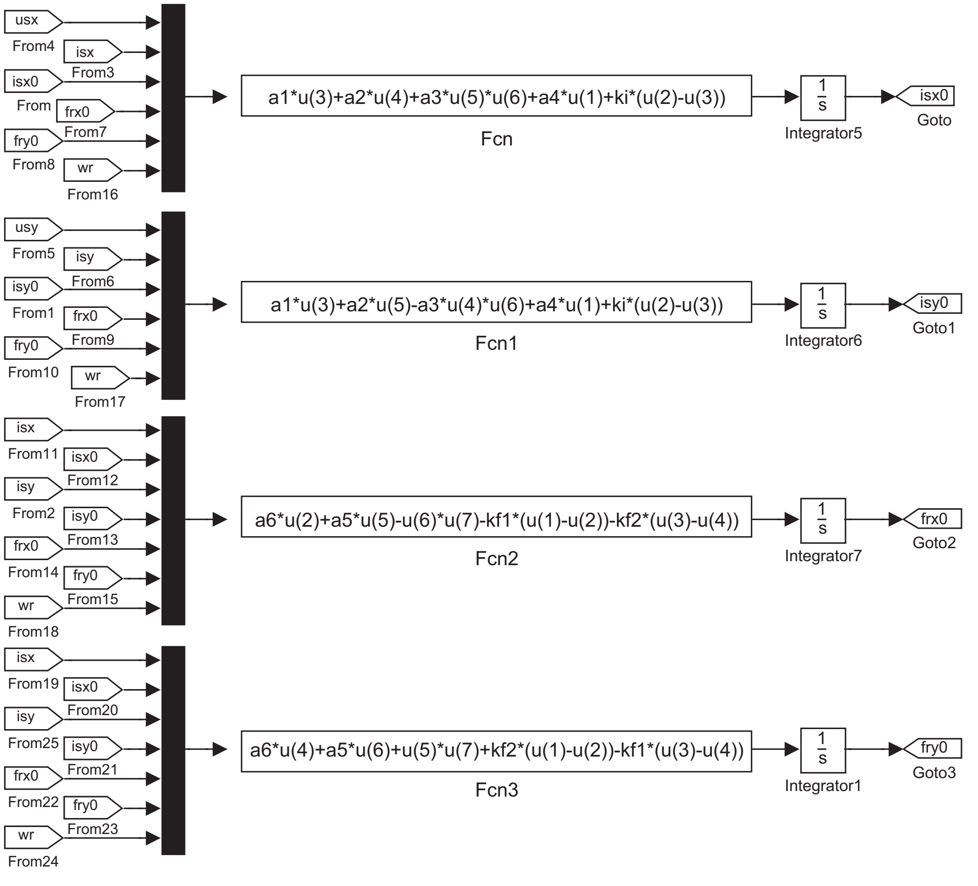

Figure 4.14 Simulink diagram of Luenberger observer for stator currents and rotor fluxes estimator

Stator Flux Orientation

- The operation at the absolute voltage limit of the inverter for maximum torque production eliminates the voltage margin required by the current controllers to adjust the respective current components i_d and i_q.

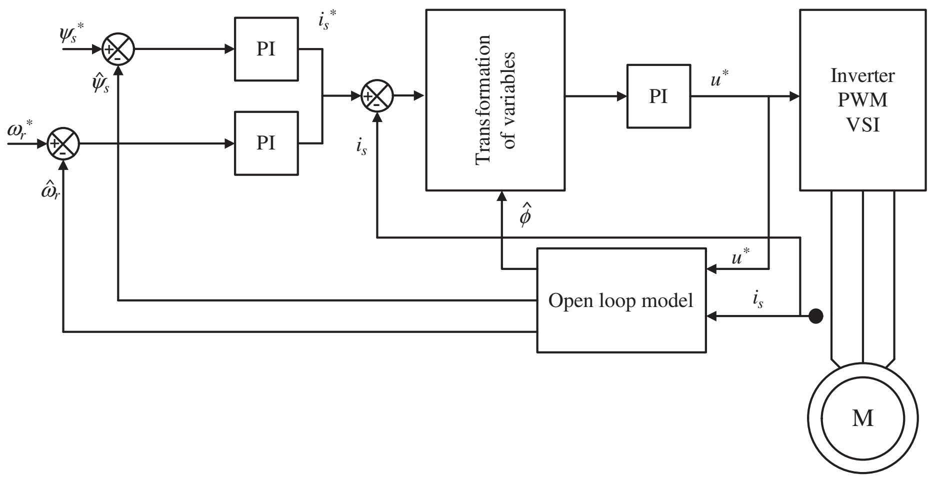

Figure 4.15 Stator flux oriented vector control

Field Weakening Control

- When the machine operates at speeds higher than the rated one, then it is running in the field weakening region, such as spindle and traction drives.
- To increase the produced torque to a maximum level in the field weakening region, it is essential to properly adjust the machine's magnetic field by maintaining the maximum voltage and maximum current.
- The machine flux should be weakened to such a level that it will guarantee a maximum possible torque at the whole speed range called field weakening control.
- Field weakening control can be categorized into three methods:
  1. adjustment of the machine flux in inverse proportion to speed ($1/\omega$),
  2. forward control of the flux based on simplified machine equations, and
  3. closed loop control of the stator voltages to keep a maximum level.
- The voltage control field weakening method ensures maximum torque production in the whole field weakening region when in a steady-state. The method provides maximum required torque during a steady state, and is not dependent to motor parameters and DC link voltage.

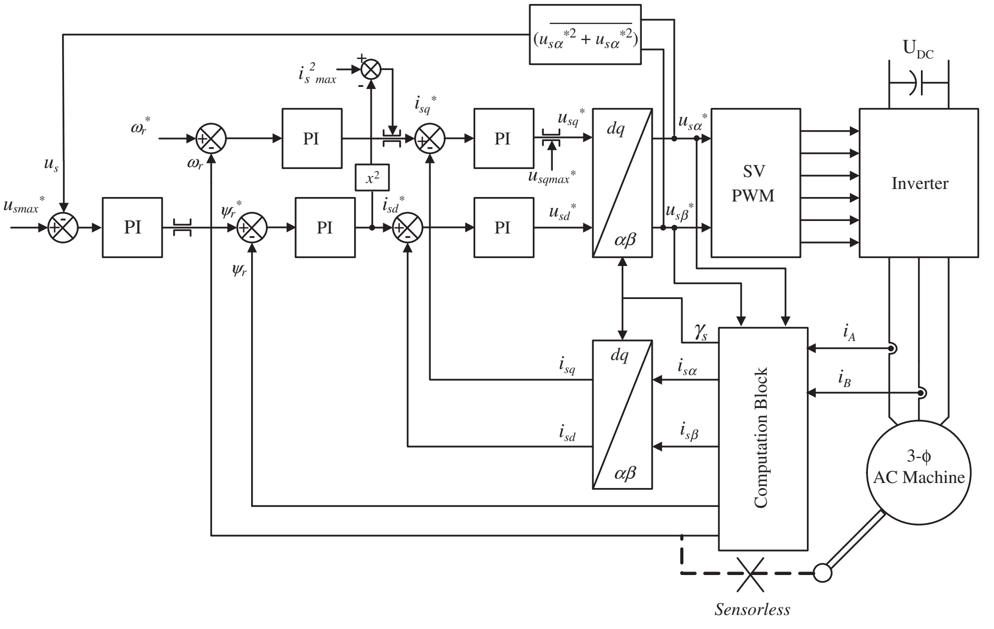

Figure 4.16 A field weakening system

Vector Control of Double Fed Induction Generator (DFIG)

- The DFIG is a rotor-wound three-phase induction machine; the stator windings of the machine are connected to the utility grid without using power converters, and the rotor windings are fed by an active front-end converter.

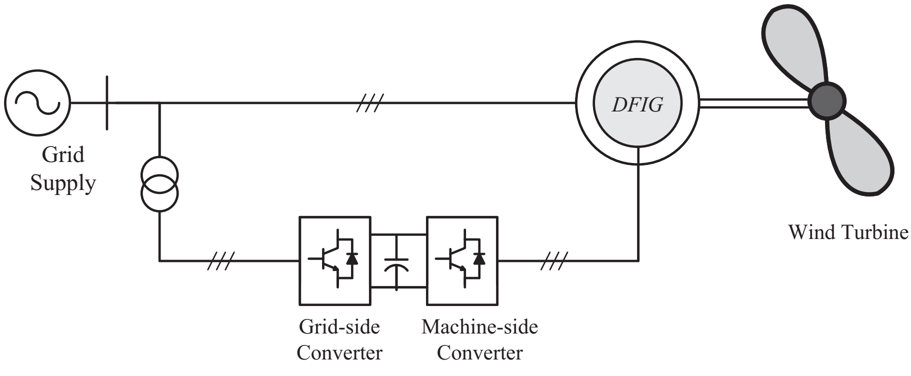

Figure 4.17 General view of DFIG connected to wind system and utility grid

The active and reactive powers of stator and rotor circuits are needed in the control of DFIG and may be described in per unit as

$$P_s = (v_{ds}i_{ds} + v_{qs}i_{qs})$$

$$Q_s = (v_{qs}i_{ds} - v_{ds}i_{qs})$$

$$P_r = (v_{dr}i_{dr} + v_{qr}i_{qr})$$

$$Q_r = (v_{qr}i_{dr} - v_{dr}i_{qr})$$

In practice, vector control of DFIG is similar to the vector control of the squirrel cage induction motor with a difference in controlled variables. The control depends on vector transformation from three-phase to rotating frame.

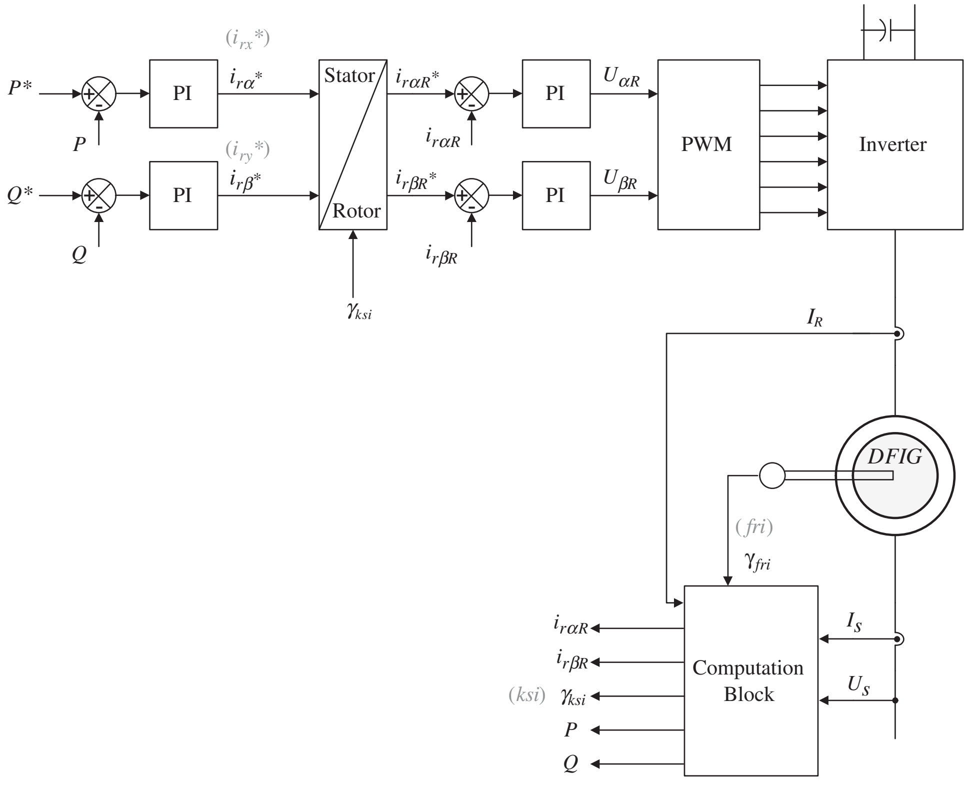

Figure 4.18. Block diagram of the DFIG control system

- *Matlab/Simulink model for DFIG vector control*

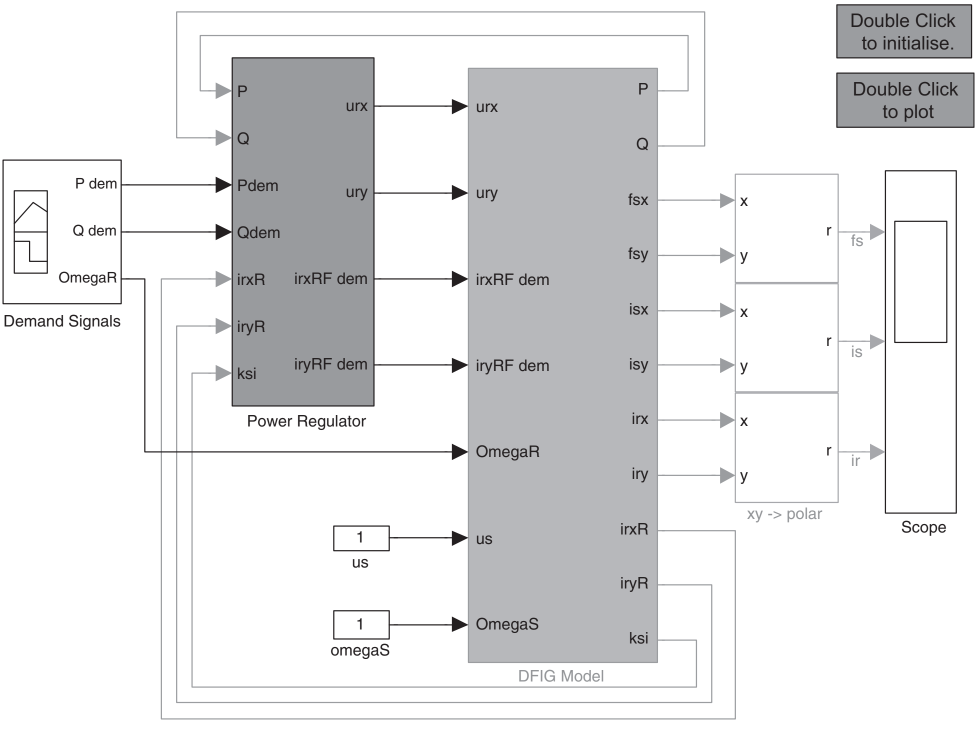

Figure 4.19 DFIG power regulation model

- *Simulation results*

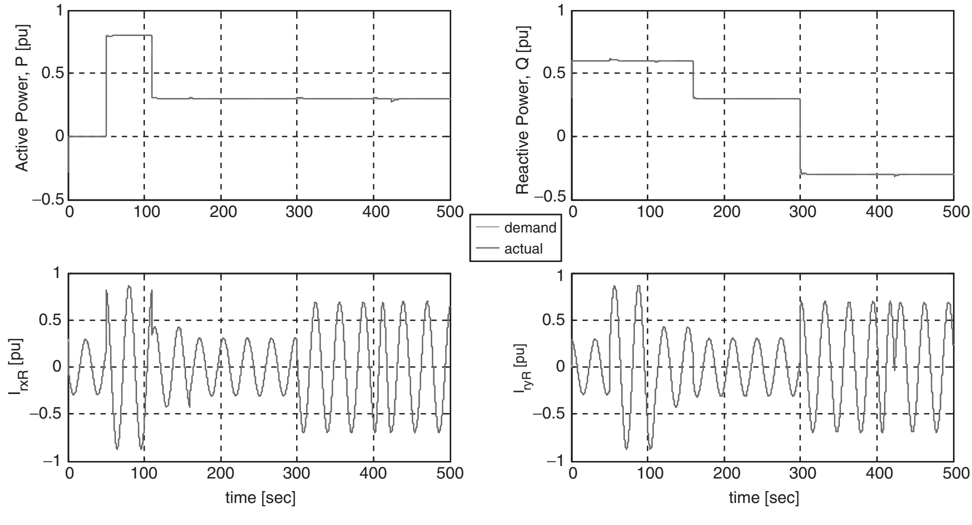

Figure 4.25 Simulation results – tracking

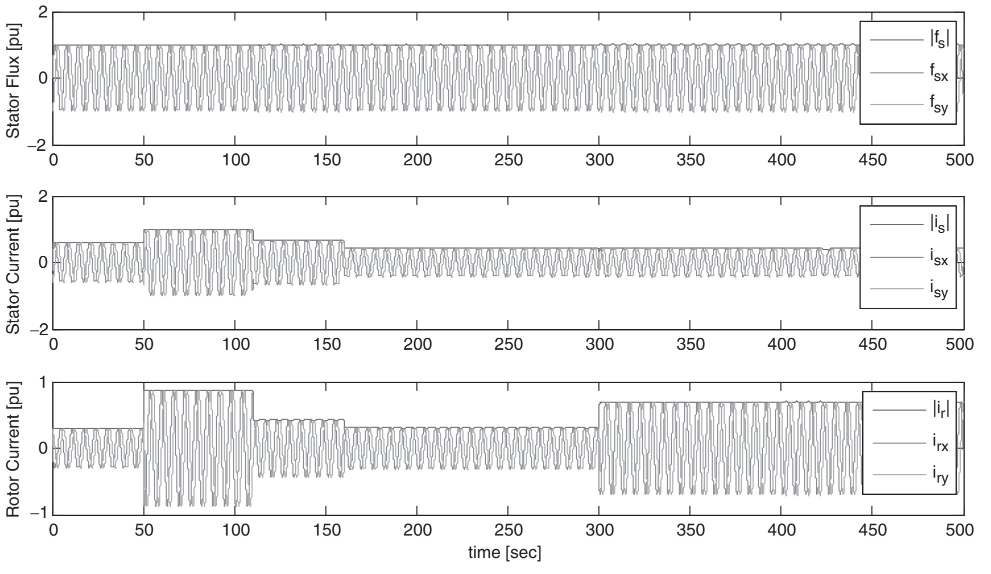

Figure 4.26 Other machine variables

Permanent Magnet Synchronous Machine (PMSM)

Advantages

- Higher torque for the same dimension. For the same power, the dimension is lower by almost 25%
- Lower weight for the same power, around 25%
- Lower rotor losses, which results in higher efficiency of up to 3%

Disadvantages

- In the case of inverter faults, it is not possible to reduce the magnetic field by reducing the torque surge, which forces a use of switch between the motor and the inverter
- It is possible to connect only one motor to the inverter; therefore, group motor work is not possible
- The use of permanent magnet forces using enclosed motor housing complicates the cooling process

Vector Control of PMSM in *dq* Axis

The produced torque of the machine could be presented as

$$T_e = \frac{3p}{2}\left[\Psi_f i_q + i_d i_q (L_d - L_q)\right]$$

And in per unit as

$$T_e = \psi_f i_q + (L_d - L_q) i_d i_q$$

Hence the torque could be expressed as

$$T_e = \psi_f i_s sin\, \beta$$

The torque gets maximum value for β (torque angle) equal to 90 degrees for a given value of stator current. This gives maximum torque per ampere and hence a higher efficiency

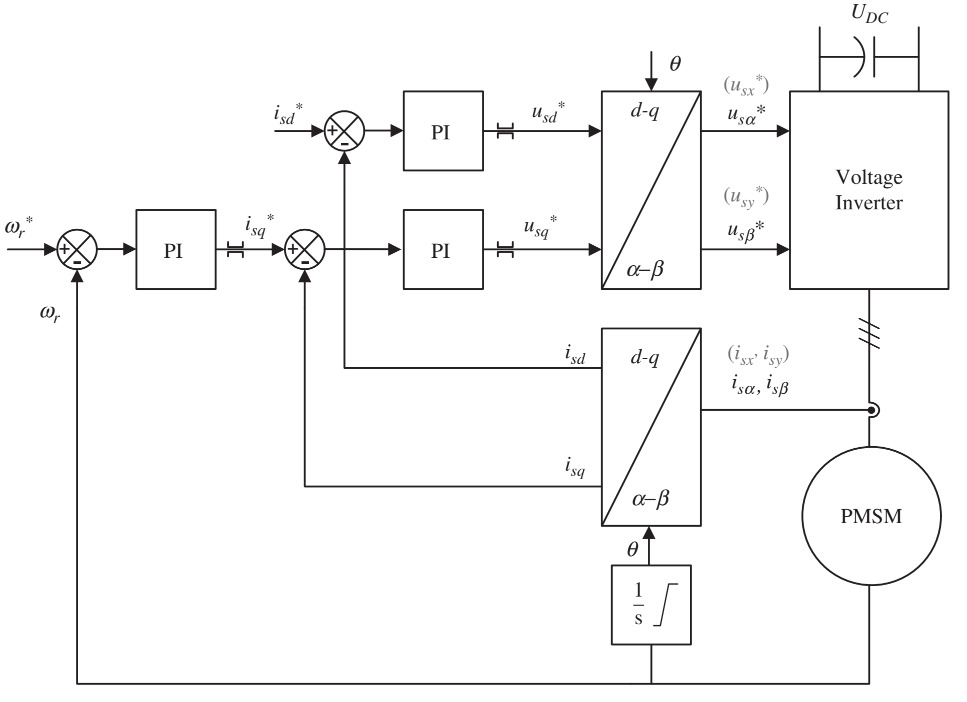

Figure 4.27 Vector control scheme of permanent magnet synchronous machine

- *Matlab/Simulink model for vector control of PMSM*

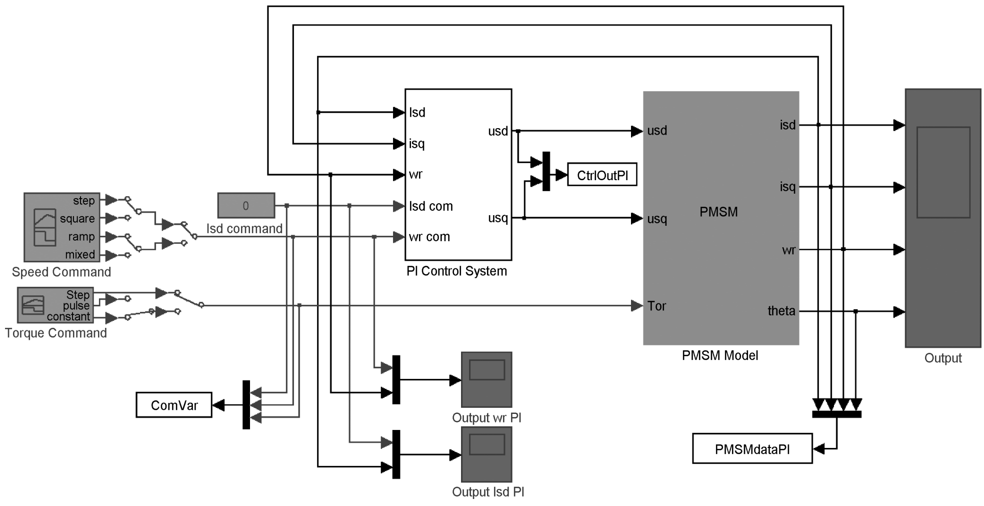

Figure 4.28 Vector control of PMSM

- *Simulation results*

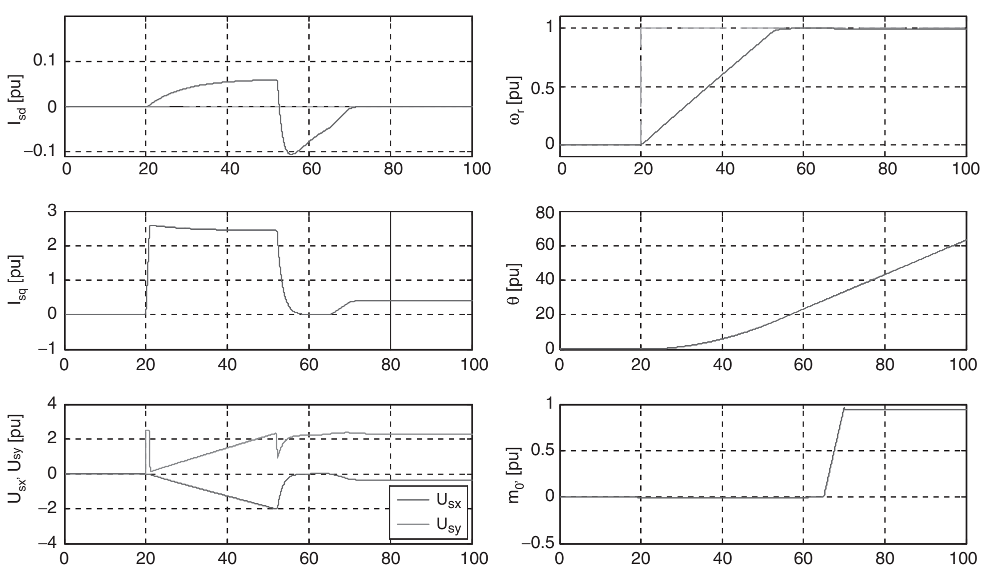

Figure 4.30 Simulation results

Vector Control of PMSM in α-β axis using PI controller

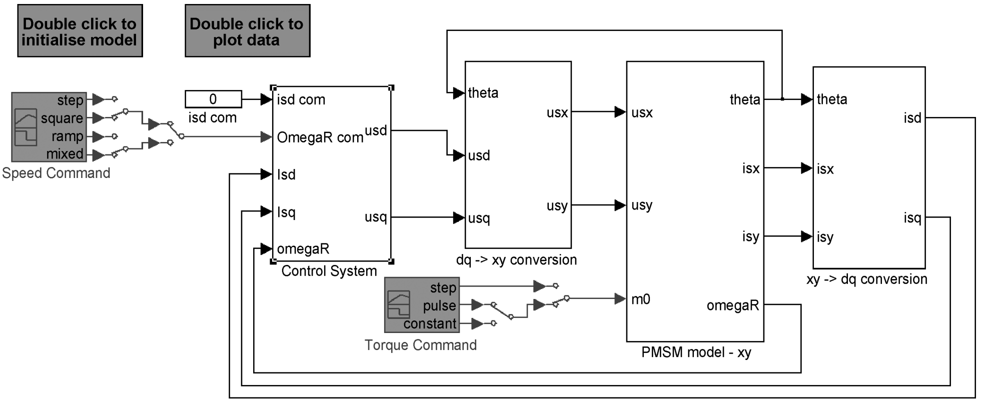

Figure 4.31 Vector control of PMSM

- *Simulation results*

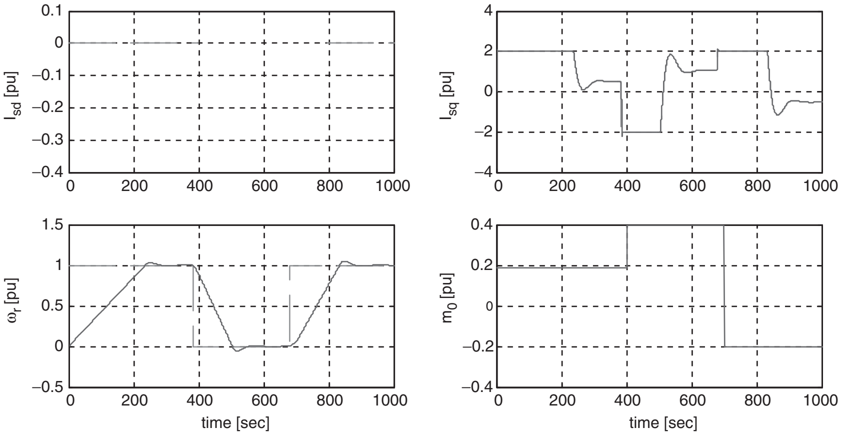

Figure 4.38 Simulation results – tracking

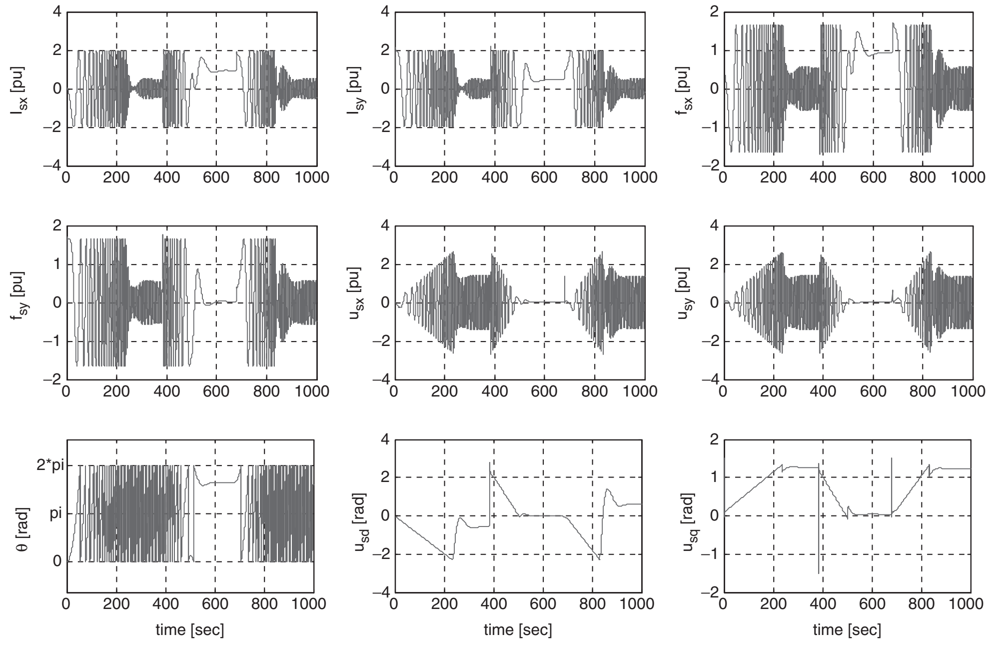

Figure 4.39 Other machine variables

Scalar Control of PMSM

The voltage to frequency ratio should be constant (V/f = const) to maintain constant flux in the machine. Otherwise the machine may reach under- or over-excitation conditions, which are not recommended from stability and economical points of view

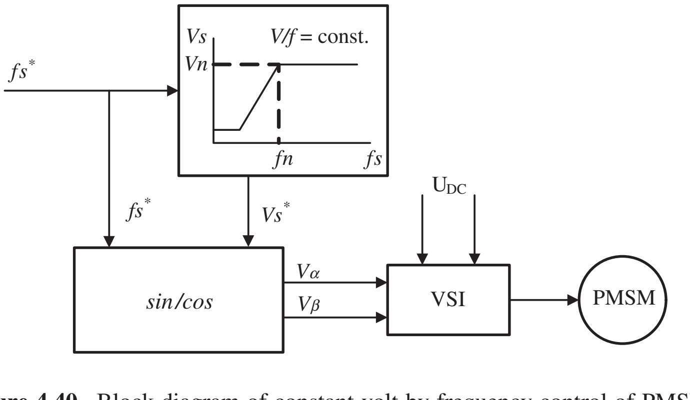

Figure 4.40 Block diagram of constant volt by frequency control of PMSM