Wind Energy Conversion Systems

Assignment 3

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Introduction

This case study investigates the dynamic performance of a 2.45 MW, 4000 V, 53.33 Hz, 400 rpm non-salient pole permanent magnet synchronous generator standalone wind energy system. The generator is loaded with a three-phase balanced resistive load RL and operates at 320 rpm (0.8 pu) at a given wind speed. The loading of the generator can be changed by a switch. When the switch is closed, the load resistance is reduced to RL/2 per phase.

The dq-axis model of the induction generator can be obtained by decomposing the voltage, current and flux linkage space-vectors into their corresponding d- and q-axis components.

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

The PMSG is modeled in the rotor field synchronous reference frame. The synchronous reference frame is derived from dq-axis rotating reference frame by putting θ = $\omega_r t$:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(\omega_r t) & \cos(\omega_r t - \frac{2\pi}{3}) & \cos(\omega_r t - \frac{4\pi}{3}) \\ -\sin(\omega_r t) & -\sin(\omega_r t - \frac{2\pi}{3}) & -\sin(\omega_r t - \frac{4\pi}{3}) \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

Similarly, the two-phase to three-phase transformation in the stationary reference frame, known as αβ/abc transformation, can be performed by:

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} cos(\omega_r t) & -\sin(\omega_r t) \\ \cos(\omega_r t - \frac{2\pi}{3}) & -\sin(\omega_r t - \frac{2\pi}{3}) \\ \cos(\omega_r t - \frac{4\pi}{3}) & -\sin(\omega_r t - \frac{4\pi}{3}) \end{bmatrix}\begin{bmatrix} x_d \\ x_q \end{bmatrix}$$

Part 1: Analysis of Synchronous Generator in Standalone Operation

The PMSG is loaded with a three-phase balanced resistive load RL and operates at 320 rpm (0.8 pu) at a given wind speed. The loading of the generator can be changed by a switch. When S is closed, the load resistance is reduced to RL/2 per phase. It is assumed that the combined moment of inertia of the blades, rotor hub, and generator are very large such that the rotor speed is kept constant at 320 rpm during the transients caused by the changes in load resistance. Since the rotor speed wr is known, it becomes the system input variable.

SCIG dq-axis Reference Frame Model Equations

1. Flux Linkage Equations:

$$\lambda_{ds} = -(L_{ls} + L_{dm})\, i_{ds} + L_{dm}\, I_f = -L_d\, i_{ds} + \lambda_r$$

$$\lambda_{qs} = -(L_{ls} + L_{qm})\, i_{qs} = -L_q\, i_{qs}$$

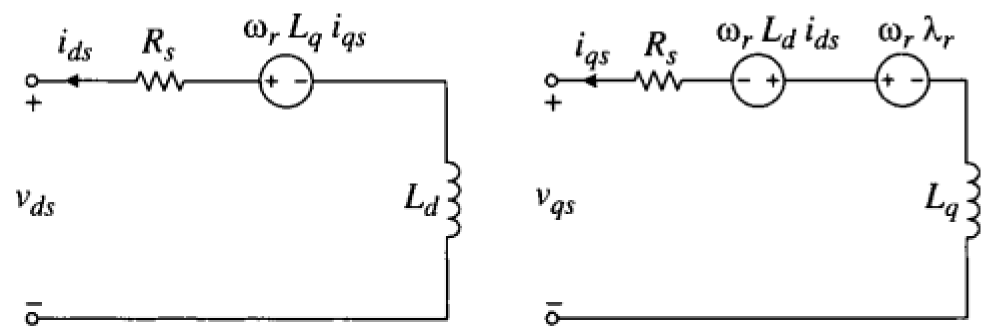
2. Voltage Equations

$$v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - pL_d i_{ds} = R_L i_{ds}$$

$$v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} - pL_q i_{qs} + \omega_r \lambda_r = R_L i_{qs}$$

3. Torque Equation

$$T_e = \frac{3P}{2}\left(i_{qs}\lambda_r - \left(L_q - L_d\right) i_{ds} i_{qs}\right) = \frac{3P}{2}\left(i_{qs}\lambda_r\right)$$



(a) d-axis circuit (b) q-axis circuit

PMSG Machine Constants

1. Rated Line-Line Voltage

$$V_{rated,LL} = 4000\,V(rms)$$

2. Rated Stator Current

$$I_{rated} = 490\,A(rms)$$

3. Base Impedance

$$Z_{base} = 4.6797\,\Omega$$

4. Number of Pole Pairs

$$P = 8$$

5. Rated Stator Frequency

$$f_e = 53.33\,Hz$$

6. Stator Winding Resistance

$$R_s = 24.21 m\Omega$$

7. D-axis Inductance

$$L_q = 9.816 mH$$

8. Q-axis Inductance

$$L_d = 9.816 mH$$

9. Rated Rotor Flux Linkage

$$\lambda_r = 4.971\sqrt{2}\,Wb$$

10. Rotor Speed

$$n_{m,rated} = 400 rpm$$

11. Rated Mechanical Torque

$$T_e = 58458.5\,Nm$$

Initial Conditions (t = 0-)

In this case, the PMSG model in the synchronous reference frame was used, which was realized by setting the speed of the arbitrary reference frame (w = ω_r).

1. The reference frame is synchronous

$$\omega = \omega_r$$

2. Electrical Frequency

$$f_e = 50\ Hz$$

3. Rotor Speed

$$n_m = 0.8 * 400rpm = 320rpm$$
$$\omega_r = P\frac{2\pi}{60}n_m = 268.0825731063290\ rad/s$$

4. Stator Currents

$$i_{ds} = 0.1657\ p.u.$$

$$i_{qs} = 0.3792\ p.u.$$

5. Load Resistance

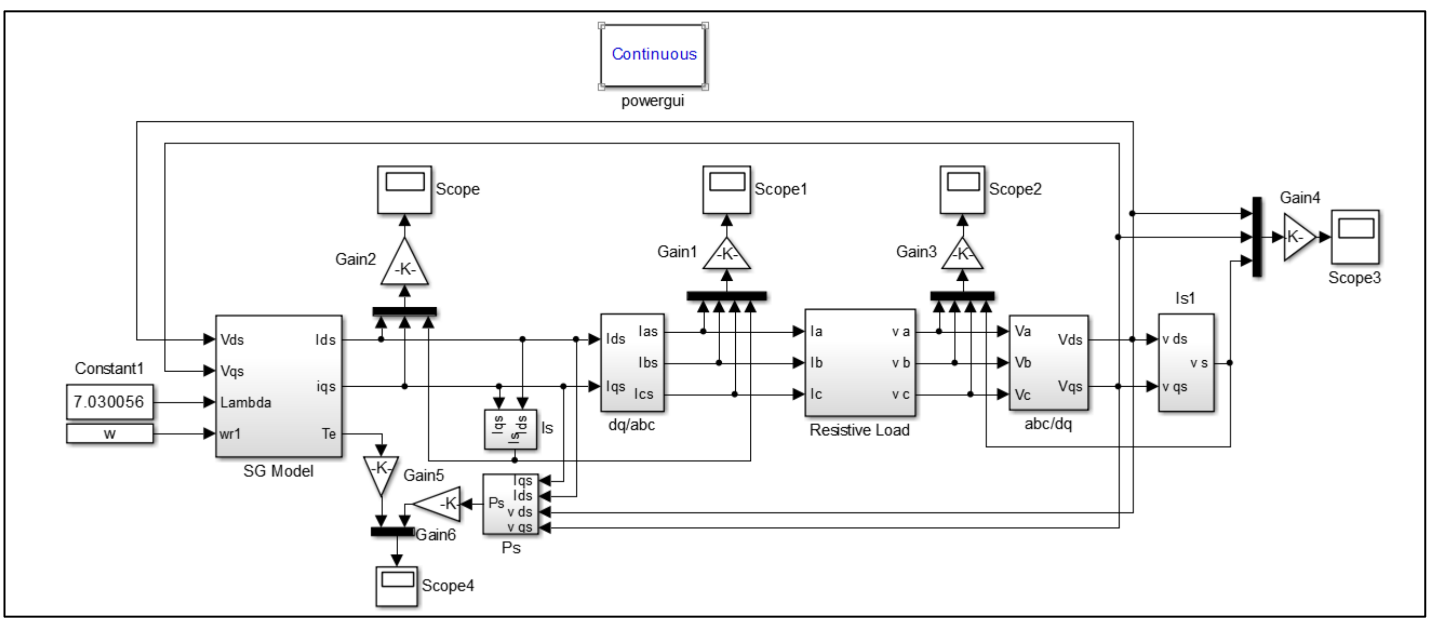
$$R_L = \frac{v_{ds}}{i_{ds}} = \frac{v_{qs}}{i_{qs}} = 1.25\ p.u. = 6\ \Omega$$

The Load Resistance is halved at t=0.015s by closing a switch and adding an equal resistance in parallel.

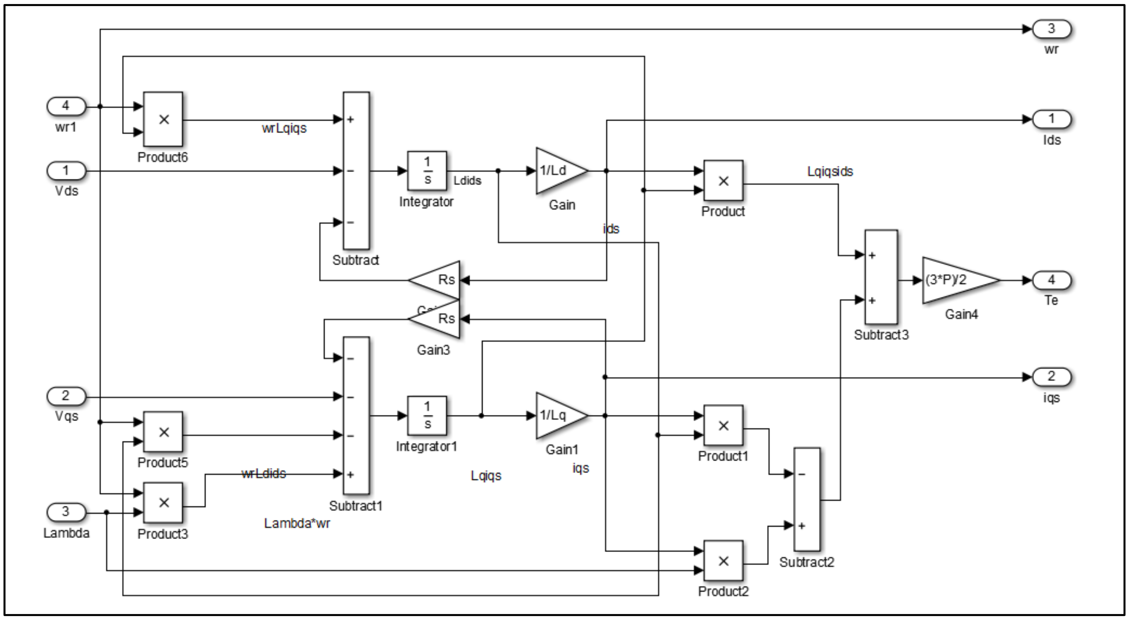
Simulink Model

The input variables of the model include the dq-axis stator voltages vds and vqs, rotor voltages vdr and vqr, the mechanical torque Tm, and the speed of the arbitrary reference frame w. The output variables are dq-axis stator currents, ids and iqs, the electromagnetic torque Te, and the mechanical speed wm of the generator.

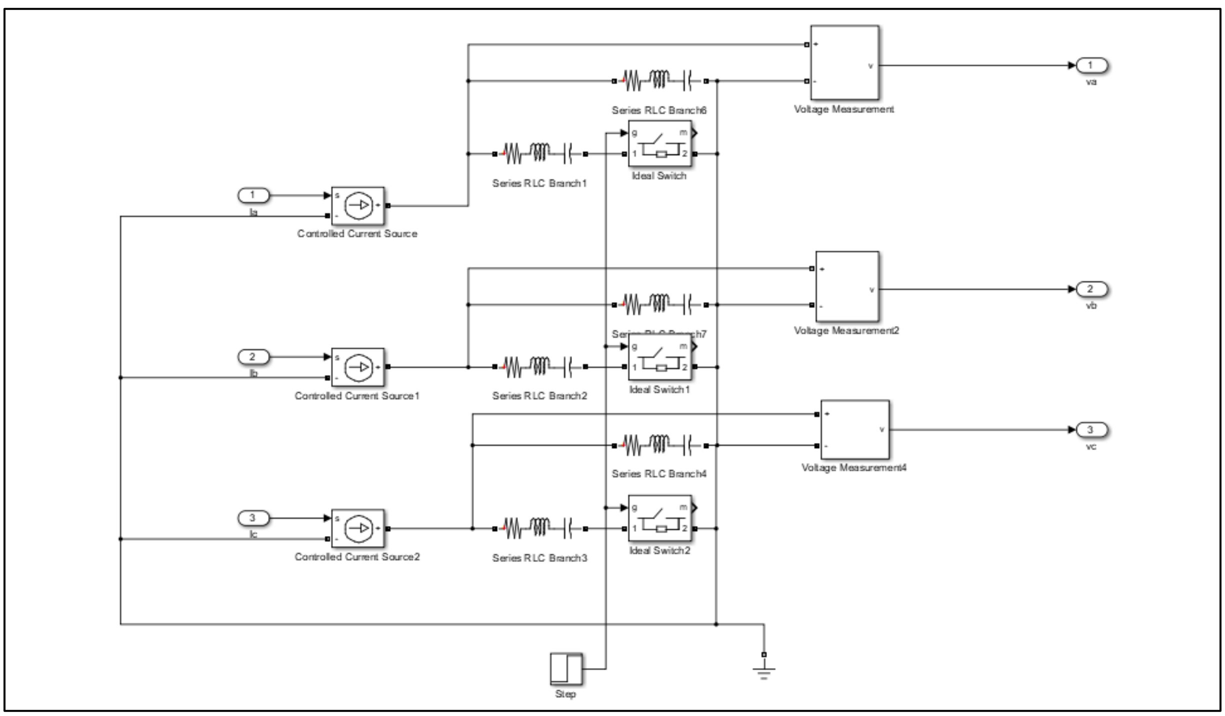
1. Block diagram for dynamic simulation of PMSG for standalone operation.



2. PMSG System



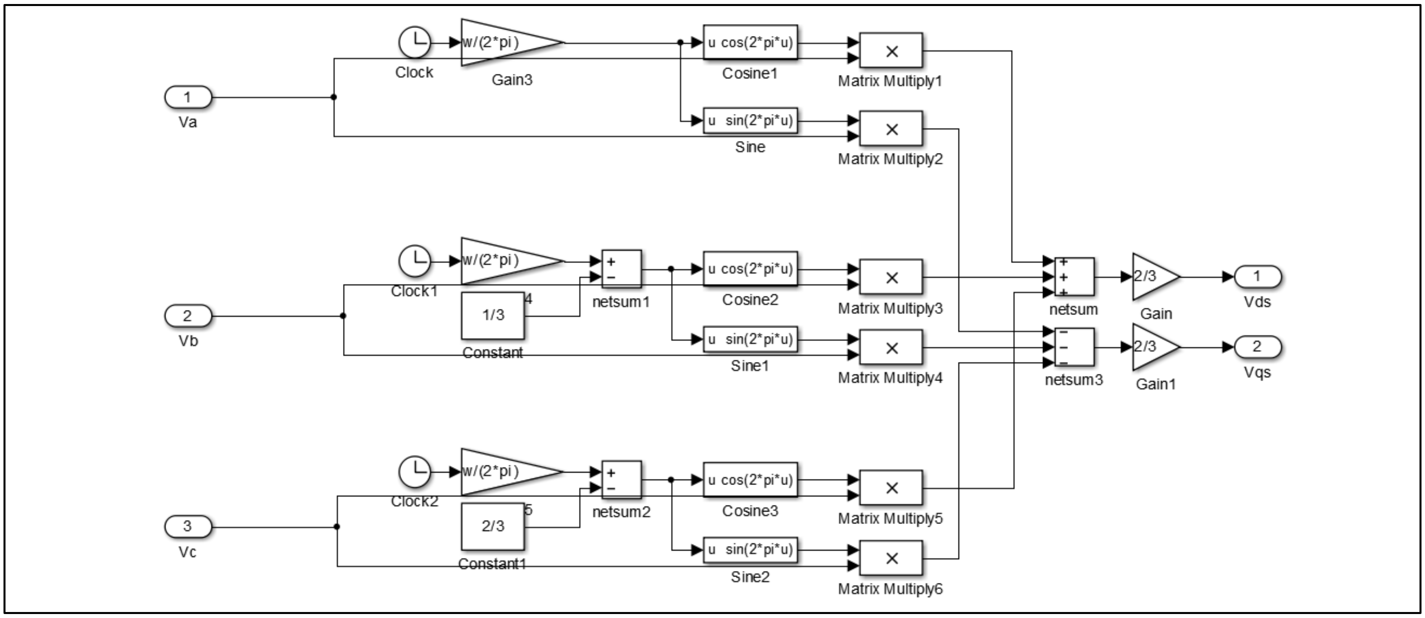
3. Block diagram for Three Phase Resistive Load controlled with ideal switches.



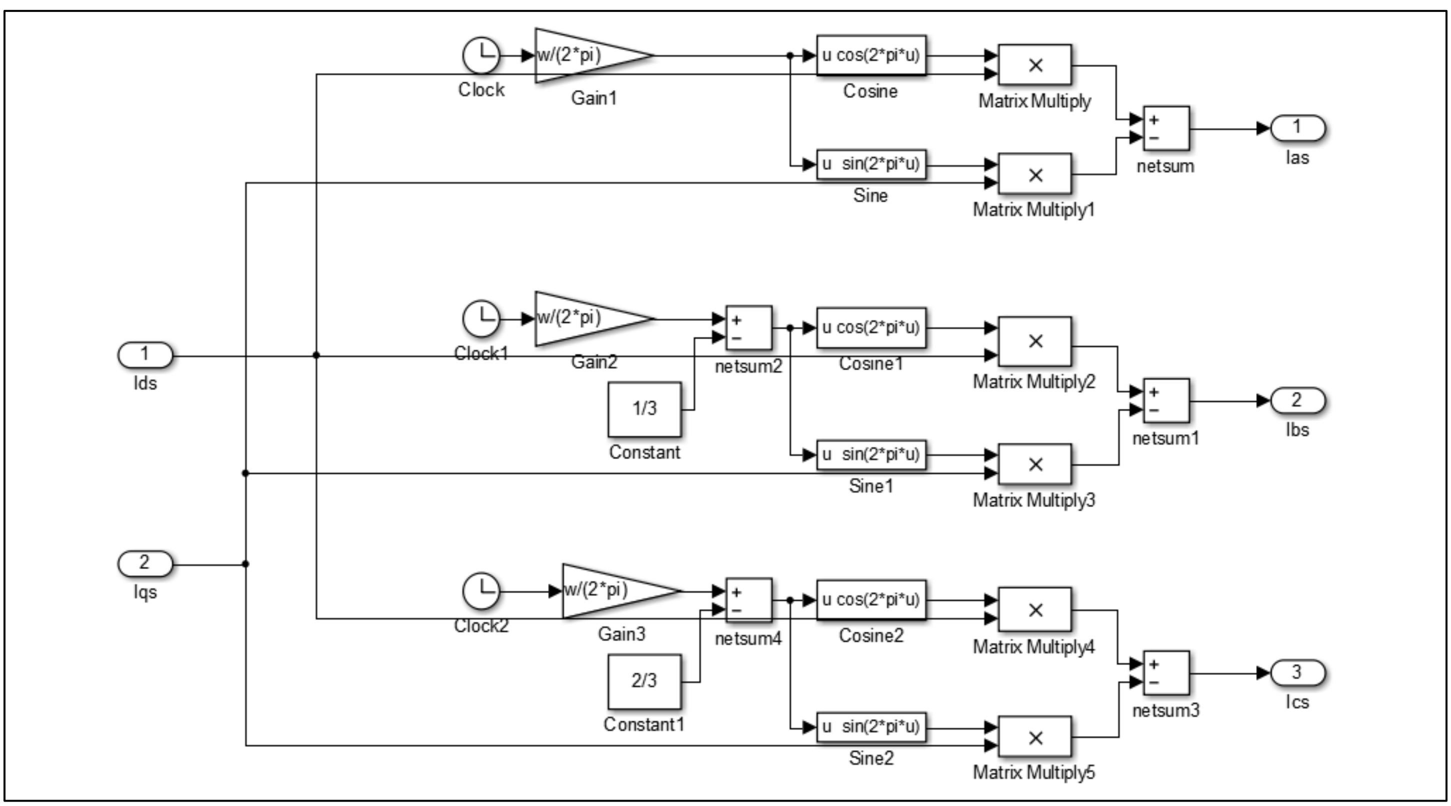
4. Reference Frame Transformations

Assuming a three-phase balanced grid, the grid voltages vas, vbs, and vcs in the stationary frame are transformed to the two-phase voltages vd and vq in the dq synchronous frame through the abc/dq transformation. The simulated dq-axis stator currents ids and iqs are also in the synchronous frame, which are transformed to the three-phase currents ias, ibs, and ics by the dq/abc transformation. The three-phase stator voltages are transformed to the two-phase voltages via the abc/dq transformation and the calculated two-phase stator currents are transformed back to the three-phase stator currents via the dq/abc transformation.

abc/dq Transformation



dq/abc Transformation

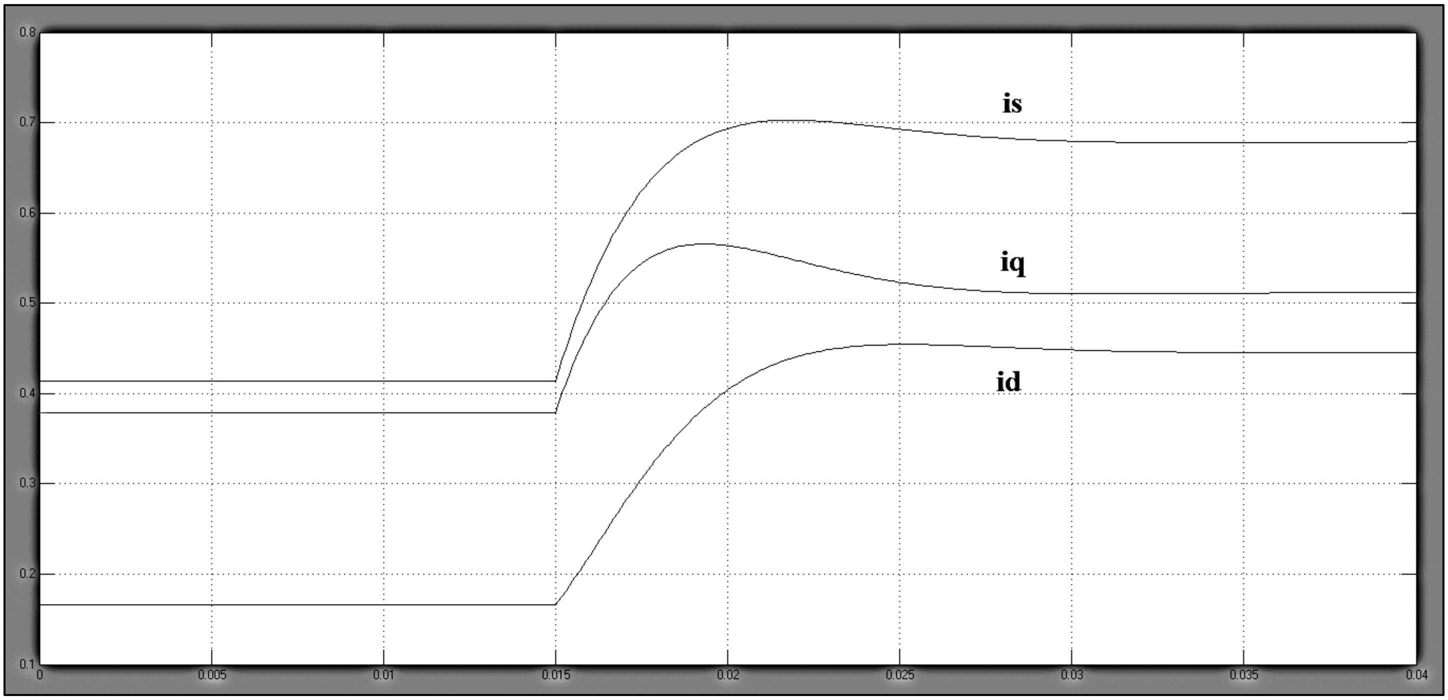


5. synch2.m

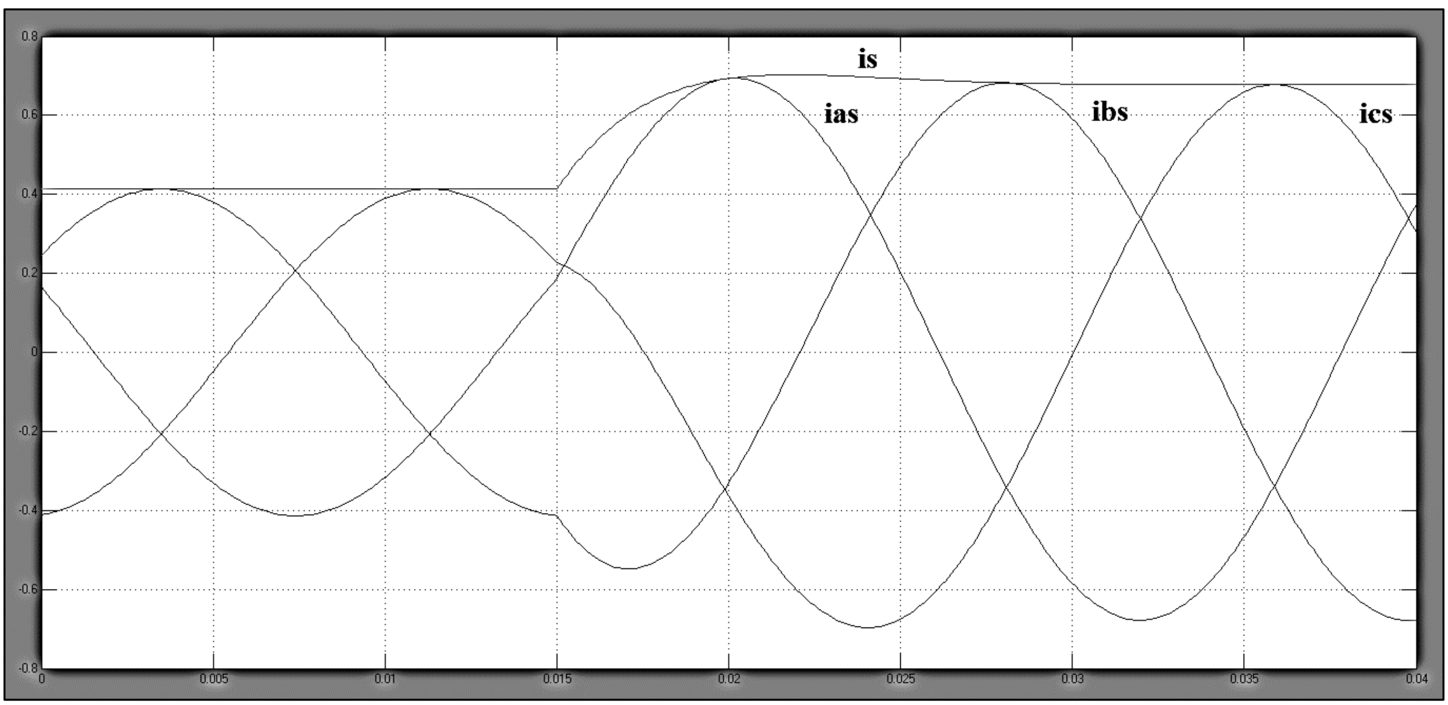
```
clc;clearvars;close all; %to clear all the variables from workspace

f=53.33;
P=8;
nr=400;                    %speed in rpm
w=0.8*nr*P*2*(pi/60);    %working speed (0.8per unit)in radian per second
T=1/f;
Ld=9.816e-3;
Lq=9.816e-3;
Rs=24.21e-3;
RL=6;
%%dt=1e-4;                 %step size (0.0001second)
%%t=0;
%for t=0:dt:1
%update the values of time systematically to be used in sine & cosine(w*t)
%end
```

Results

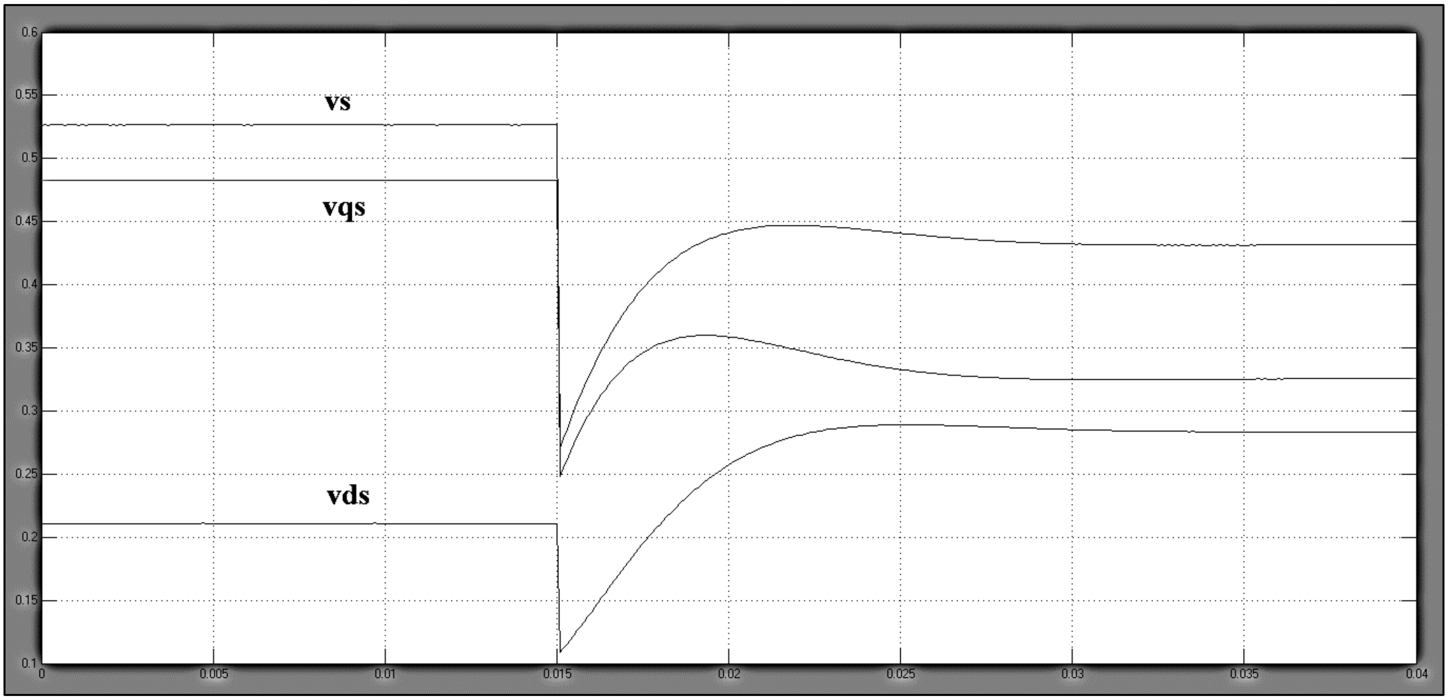
1. Currents (ids, iqs, is)



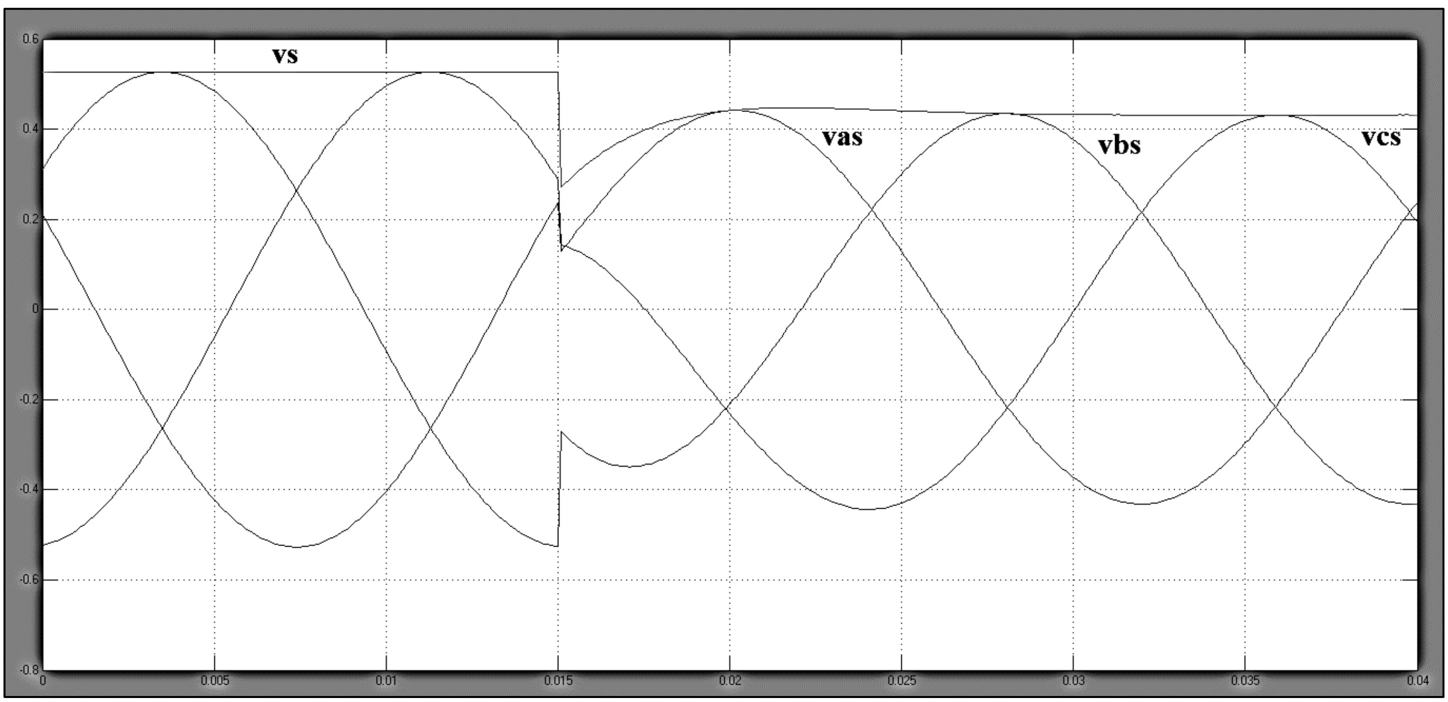
2. Currents (ias, ibs, ics, is)



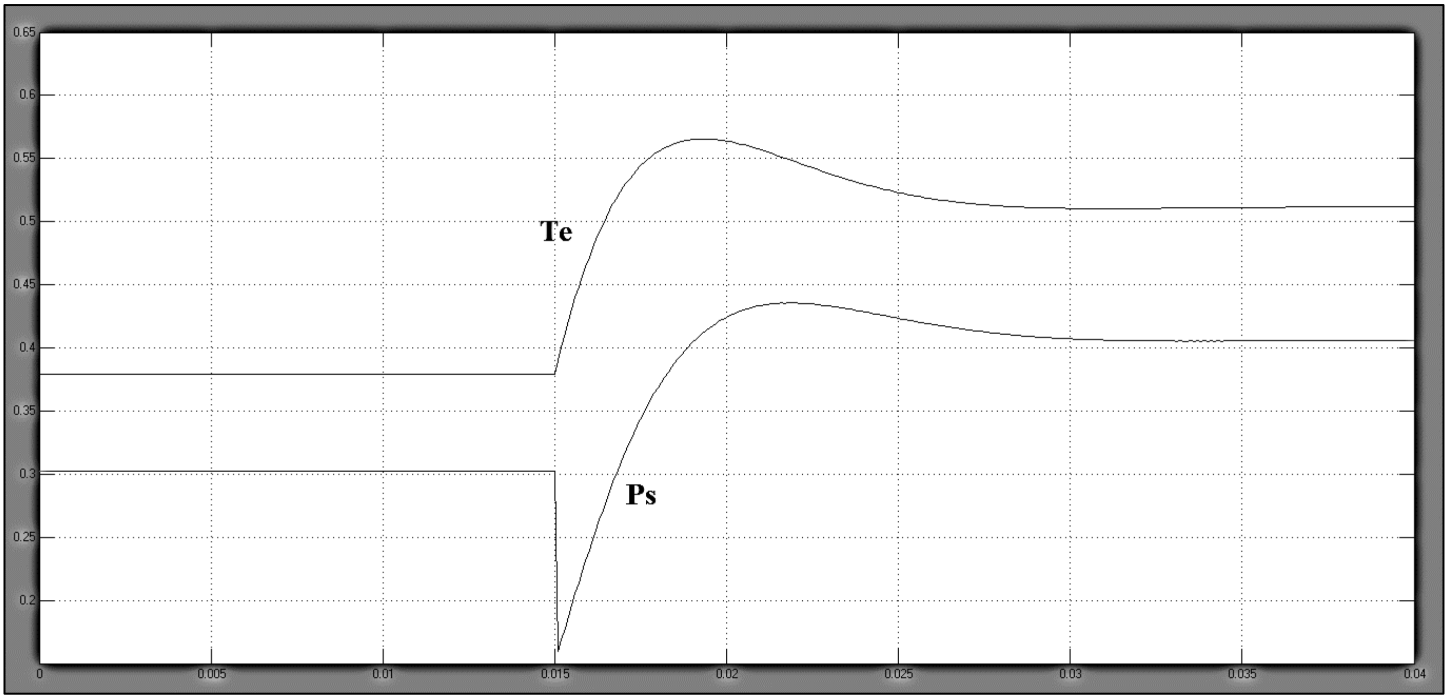
3. Voltages (vds, vqs, vs)



4. Voltages (vas, vbs, vcs, vs)



5. Electromagnetic Torque and Stator Active Power



The generator initially operates in steady state with a resistive load of RL. The load resistance is reduced to RL/2 by closing switches at t = 0.015 sec. After a short transient period, the system reaches a new steady-state operating point. The dq-axis stator currents, ids and iqs, in the synchronous frame are DC variables, whereas the abc-axis stator currents, ias, ibs, and ics, in the stationary frame are sinusoids in steady state. The magnitude of the stator current is, represents the peak value of ias, ibs and ics. A similar phenomenon can be observed for the stator voltages. A decrease in the load resistance results in an increase in the stator currents (is increases from 0.4139 p.u. to 0.6738 p.u.), but the stator voltages are reduced (vs reduces from 0.5266 p.u. to 0.4316 p.u.) mainly due to the voltage drop across the stator inductances. The electromagnetic torque Te and stator active power Ps are increased (Te increases from 0.3792 p.u. to 0.5118 p.u., Ps increases from 0.3021 p.u. to 0.4061 p.u.) accordingly when the system operates at the new operating point.