Analysis of Wind Turbine Driven Permanent Magnet Synchronous Generator under Different Loading Conditions

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Abstract

This paper proposes the configuration of a Wind Turbine generating system equipped with Permanent Magnet Synchronous Generator (PMSG). There are different types of synchronous generators, but the PMSG is chosen which has better performance due to higher efficiency and less maintenance. Since it can be used without a gearbox also implies a reduction of the weight of the nacelle and a reduction of costs. The model includes a wind turbine model, drive train model and PMSG model. The equations that explain their behavior have been introduced. The generator model is established in the d-q synchronous rotating reference frame. The proposed Wind Turbine Generator System (WTGS) has been implemented in MATLAB/SIMULINK software. The PMSG is operating in stand-alone which is loaded with different types of loads. The simulation results indicate the ability of wind driven PMSG to operate over wide range of operating conditions at different loading conditions and show effect of different load types in operation.

Keywords: Permanent Magnet Synchronous Generator (PMSG), Wind Turbine, Wind Energy and WTGS MATLAB/SIMULINK.

1. Introduction

During the last few decades, wind energy became the most competitive form of clean, non-polluting and renewable energy to provide a sustainable supply to the world development (Chen *et al.* 2012) which worldwide wind capacity doubled approximately every three years. Currently, five countries (Germany, USA, Denmark, India and Spain) concentrate more than 83% of worldwide wind energy capacity in their countries. The need for increased power production from the wind and economic reasons, when the rated power of today's wind turbines is still relatively small (2MW units are now typical), makes it necessary to group wind turbines into so-called wind farms(Rolan' *et al.* 2009).Wind farms are built on land, but in recent years there has been(and will be in the future) a strong trend towards locating them offshore this due to the lack of suitable wind turbine sites on land and the highest wind speeds located near the sea(and consequently higher energy can be extracted from the wind).

Both induction and synchronous generators can be used for wind turbine systems (Slootweg *et al.* 2003). Mainly, three types of induction generators are used in wind power conversion systems: cage rotor, wound rotor with slip control and doubly fed induction rotors .The last one is the most utilized in wind speed generation because it provides a wide range of speed variation. However, the variable speed directly driven multi-pole permanent magnet synchronous generator (PMSG) wind architecture is chosen for this purpose and it is going to be modelled: it offers better performance due to higher efficiency, simple structure, reliable operation, low noise and less maintenance because it does not have rotor current. What is more, PMSG can be used without a gearbox, which implies a reduction of the weight of the nacelle and reduction of costs and so on (Rolan' *et al.* 2009).This investigation presents the model of a PMSG WT able to work under low and fast wind speed conditions and during wind gusts (López-Ortiz *et al.* 2012).

The general goal of this paper is to model the electromechanical energy conversion system of Standalone wind turbine driven with PMSG. Optimum wind energy extraction is achieved by running the Wind Turbine Generator (WTG) invariable speed because of the higher energy gain and the reduced stresses with using the (PMSG) the design can be even more simplified.

Simulations have been implemented with the software MATLAB/ SIMULINK to validate the model.

2. System structure and analysis

A typical structure of wind energy conversion system with PMSG consists of a wind turbine, drive train and PMSG.

2.1. Wind Energy Conversation

The kinetic energy of the wind is given by the following equation (S.VIJAYALAKSHMI *et al.* 2011):

$$Ec = \frac{1}{2mv^2} \tag{1}$$

$$m = \rho v A \Delta t \tag{2}$$

Where: m is the air mass, v is the wind speed, A is the covered surface of the turbine and ρ is the air density.

The wind power Pw has the following expression:

$$Pw = \frac{d}{dt} Ec = \frac{1}{2} \rho A v^3 \tag{3}$$

The power coefficient of the turbine Cp can be defined by following equation:

$$Cp = \frac{Pm}{Pw} ; \quad CP < 1 \tag{4}$$

So the extracted power is given by:

$$Pm = \frac{1}{2} Cp \, \rho \pi R^2 v^3 \tag{5}$$

Where: A is area swept by the rotor ($A = \pi R^2$), R is radius of the turbine rotor and Pm is the mechanical power that extracts from the wind.

The power coefficient Cp (betz coefficient) reaches maximum value =0.593. In practice, values of obtainable power coefficient's are in the range of 45 percent which depends of the tip speed ratio ʎ of the wind turbine and angle of the blades ß.

$$Cp = Cp(ʎ, ß) \tag{6}$$

The amount of aerodynamic torque is obtained from the power:

$$T_m = \frac{Pm}{w} = \frac{1}{2} \, Cp \, \rho \pi R^2 \frac{v^3}{w} \tag{7}$$

Substitute from $\quad ʎ = \frac{Rw}{v} \tag{8}$

$$T_m = \frac{1}{2} \, \rho \pi R^3 v^2 \frac{Cp}{ʎ} \tag{9}$$

Often the torque coefficient $\quad C_T = \frac{C_P}{ʎ} \tag{10}$

So, $\qquad\qquad\qquad Tm = \frac{1}{2} C_T \rho \pi R^3 v^2 \tag{11}$

2.2 The power coefficient of the turbine

The power coefficient can be utilized in the form of look-up tables or in form of a function. The second approach is presented below (Slootweg *et al.* 2003), where the power coefficient is defining as a function of the tip-speed ratio ʎ and the blade pitch angle ß as

$$C_p(ʎ, ß) = 0.5 \left(\frac{116}{Q} - 0.4ß - 5\right) e^{-\frac{21}{Q}} \tag{12}$$

Where Q is represented as

$$Q = \frac{1}{\frac{1}{ʎ+0.08ß} - \frac{0.035}{1+ß^3}} \tag{13}$$

2.3 The variation of Cp

The simulation model is shown in Figure 1 which the variation of Cp with tip speed ratio ʎ at different values of pitch angle ß, also the variation of Cp with pitch angle ß at different values of ʎ are obtained.
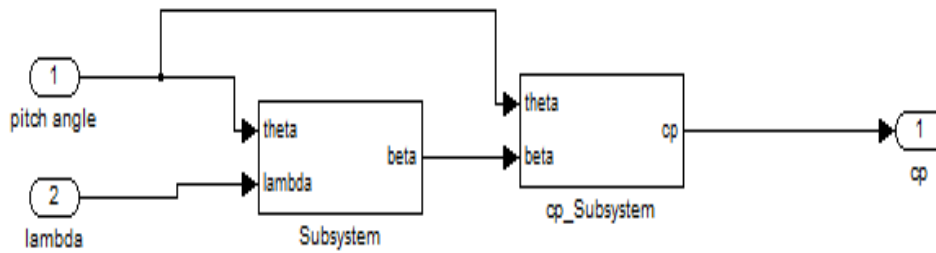
Figure 1. Power Coefficient cp

2.3.1   *The variation of CP with the tip speed ratio ʎ for various values of the pitch angle β*

The variation of CP with the tip speed ratio ʎ for various values of the pitch angle β is depicted in Figure 2. Thus, by varying the pitch angle ß, the power coefficient can be changed and the power captured by the turbine can be controlled.
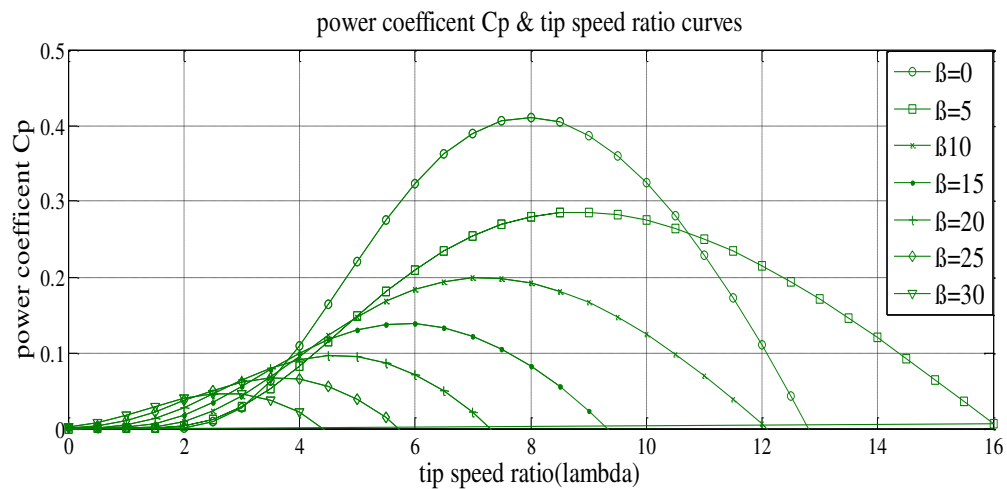

Figure 2. Analytical Approximation of Cp (ʎ, ß) Curves

2.3.2   The variation of CP with pitch angle ß at different values of ʎ

The variation of CP with the pitch angle β for various values of the tip speed ratio ʎ is depicted in Figure 3. Thus, by varying the tip speed ratio ʎ, the power coefficient can be changed and the power captured by the turbine can be controlled.

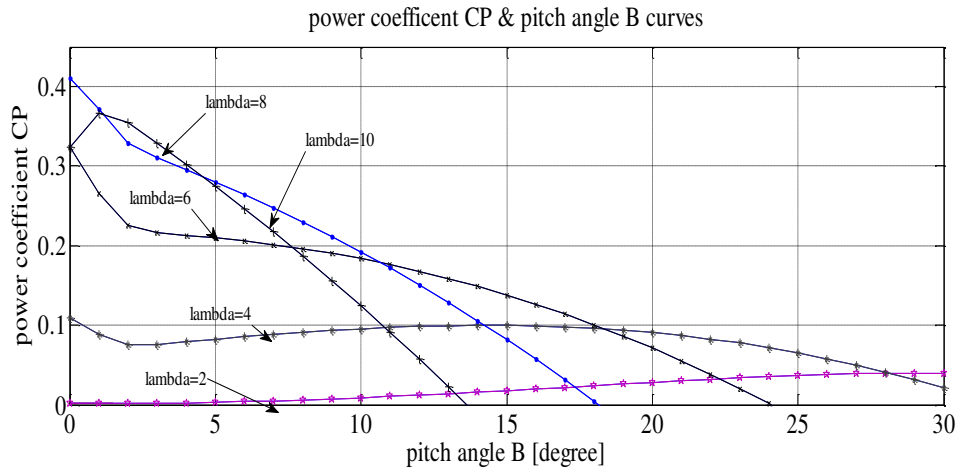power coefficent CP & pitch angle B curves

Figure 3. Power Coefficient of Cp (Ʌ, ß) with Pitch Angle ß Curves

3. Drive Train Model

The rotational speed is expressed by the following equation (Slootweg *et al.* 2003):

$$\frac{dwg}{dt} = \frac{(Te - Tw_g - Bm.wg)}{Jeq} \tag{14}$$

Where Sub-index g represents the parameters of the generator side, wg is the mechanical angular speed [rad/s] of the generator, Bm is the damping coefficient [N.m/s], Te is the electromagnetic torque[N.m], Twg is the aerodynamic torque that has been transferred to the generator side which (Twg=Tw/ng)[N.m], Jeq is the equivalent rotational inertia of the generator [Kg.m^2].The equivalent rotational inertia of the generator is calculated from this equation:

$$Jeq = J_{g+}\frac{Jw}{n^2\,g} \tag{15}$$

Where Jg and Jw are the generator and rotor rotational inertia respectively , ng is the gear ratio (ng=1 , no gear box).

The parameters used in simulation models are shown in the table (1) :

Table 1: Drive Train Parameters

Parameter	Symbol	Value
Gear Ratio	Ng	1
Rotational Damping Coefficient	Bm	0
Equivalent Inertia	Jeq	0.3kg.m2

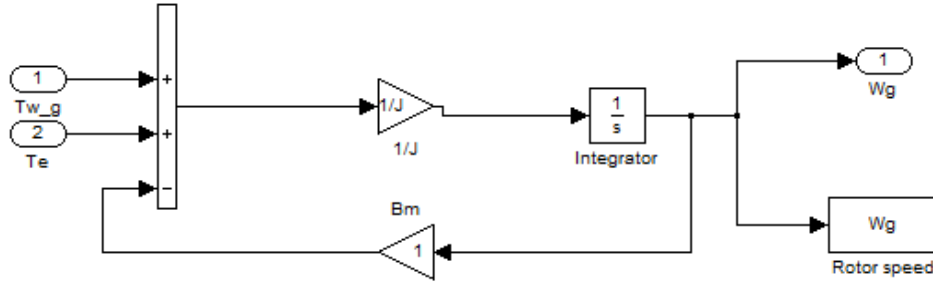The block diagram of drive train model is shown in Figure 4.

Figure 4.   Drive Train Model

4. Generator Model

The PMSG is used to produce electricity from the mechanical energy obtained from the wind Turbine. In the PMSG, the rotor magnetic flux is generated by permanent magnets which are placed on the rotor surface (a non-salient-pole PMSG)(Wu et al. 2011; Yin *et al.* 2007).

The main purpose of this case study is to modelling of PMSG from its equations. To simplify the analysis, The PMSG is normally modeled in the rotor field (dq-axis) synchronous reference Frame, which the q-axis is 90o ahead of the d-axis with respect to the direction of rotation. The rotor has two axes which the axis that is aligned with the rotor and flux is called d-axis and the perpendicular axis to d-axis called q-axis (Abedini 2008).

The flux caused by PM is in the direction of d-axis, the angle between stator axis and d-axis is called Θ_e as shown in Figure 5.
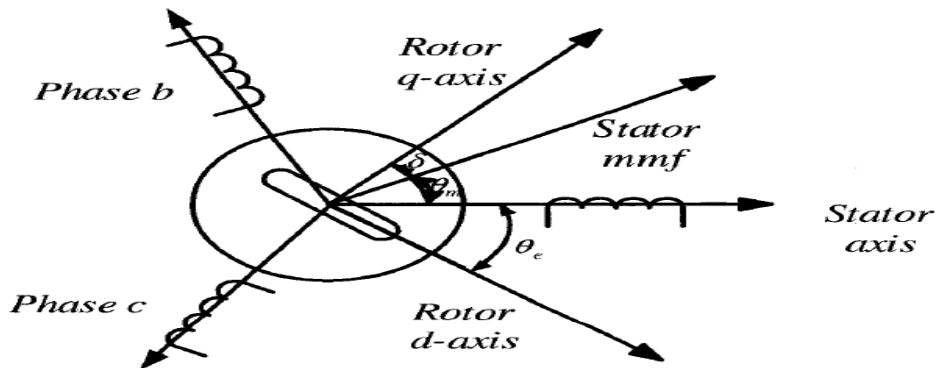

Figure 5. The Configuration of The Winding and PM in The PMSG

The synchronization between the d-q rotating reference frame and the abc-three phase frame is maintained by utilizing a phase locked loop .To simplify the SG model of Figure 5, the following mathematical manipulations can be performed.

The voltage equations for the synchronous generator are given by (16) and (17):

$$v_{ds} = -R_s \, i_{ds} - w_r \Lambda_{qs} + p\Lambda_{ds} \tag{16}$$

$$v_{qs} = -R_s i_{qs} + w_r \Lambda_{ds} + p\Lambda_{qs} \tag{17}$$

Where

$$\Lambda_{ds} = -L_d i_{ds} + \Lambda_r \tag{18}$$

$$\Lambda_{qs} = -L_q i_{qs} \tag{19}$$

Where Λ_r is the rotor flux which is constant in the PMSG so, $\dfrac{d\Lambda_r}{dt} = 0$; Ld and Lq are the stator dq-axis self-inductances .

Substitute from equations (18) and (19) in (16) and (17) yield

$$v_{ds} = -R_s \, i_{ds} + w_r L_q i_{qs} - L_d p i_{ds} \tag{20}$$

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$$v_{qs} = -R_s i_{qs} - w_r L_d i_{ds} + w_r \Lambda_r - L_q p i_{qs} \tag{21}$$

A simplified dq-axis model of the PMSG in the rotor-field synchronous reference frame is shown in figure 6.

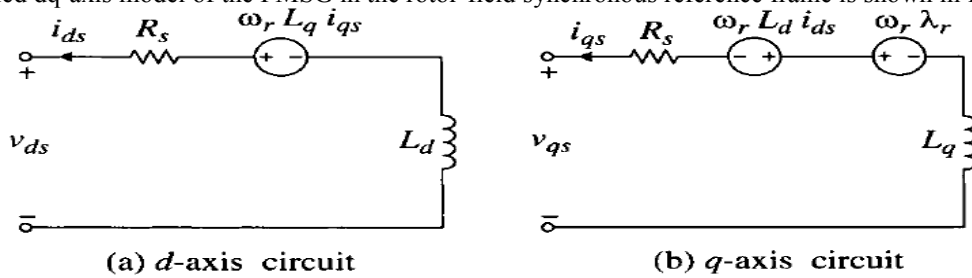(a) d-axis circuit   (b) q-axis circuit

Figure 6. Equivalent Circuit of The PMSG in The Synchronous Frame.

The electromagnetic torque produced by the PMSG can be calculated from the following equations:

$$T_e = \frac{3P}{2}\left(i_{qs}\Lambda_{ds} - i_{ds}\Lambda_{qs}\right) \tag{22}$$

$$= \frac{3P}{2}\left([i_{qs}\Lambda_r - \left(L_d - L_q\right)i_{ds}i_{qs}\right] \tag{23}$$

The rotor speed w_r is governed by motion equation given by:

$$w_r = \frac{P}{JS}(T_e - T_m) \tag{24}$$

To derive the PMSG model for dynamic simulation of synchronous generators equations are rearranged as:

$$i_{ds} = \frac{1}{S}\left(-v_{ds} - R_s\ i_{ds} + w_r L_q i_{qs}\right)/L_d \tag{25}$$

$$i_{qs} = \frac{1}{S}\left(-v_{qs} - R_s i_{qs} - w_r L_d i_{ds} + w_r \Lambda_r\right)/L_q \tag{26}$$

The active power delivered to the load is given by:

$$Ps = Pm - Pcus = Tm * wm = Te * \frac{wr}{P} - 3Is^2 Rs \tag{27}$$

Where v_{ds}, v_{qs} are the dq-axis stator voltages, R_s is the stator resistance , Λ_r is the rotor flux linkage, T_m is the mechanical torque , i_{ds} , i_{qs} are the dq-axis stator currents , w_r is the rotor mechanical speed and T_e is the electromagnetic torque (Krause 2002 ; Boldea 2006) .

5. Simulation results

The main purpose of this case study is to investigate the operation of a stand-alone PMSG wind energy system feeding different types of loads .The generator used in the study is a 2.45MW, 4000V, 53.33 HZ,400 rpm non salient pole PMSG. The parameters of the PMSG used in this paper are shown in table 2.

Table2: The Parameters of The PMSG used in This Paper are listed below:

2.45 MW,4000V,53.33HZ, non-salient pole PMSG Parameters		
Parameter	Values and units	Values in Pu
Rated power	2.4487MW	1.0 pu
Rated Apparent power	3.419 MVA	1.0 pu
Rated Line voltage	4000 V (rms)	1.0 pu
Rated stator current	490 A (rms)	1.0 pu
Rated rotor speed	400 rpm	1.0 pu
Rated Stator Frequency	53.33 Hz	1.0 pu
Number of pole pairs (p)	8	
Rated mechanical torque	58.4585 KN.m	
Rated Rotor Flux Linkage (Λ_r)	4.971Wb (rms)	0.7213 pu
Stator resistance(Rs)	24.21 mΩ	0.00517 pu
Stator d-axis inductance(Ld)	9.816mH	0.7029 pu
Stator q-axis inductance(Lq)	9.816mH	0.7029 pu

5. 1   Loading of PMSG with Resistive Load

5.1.1 Loading PMSG with Fixed Resistive Load

The PMSG is loading with a three-phase resistive load $R_{L=}$ 5.5Ω, the block diagram and matlab simulation for the model is shown in Figures. 7 and 8 respectively.
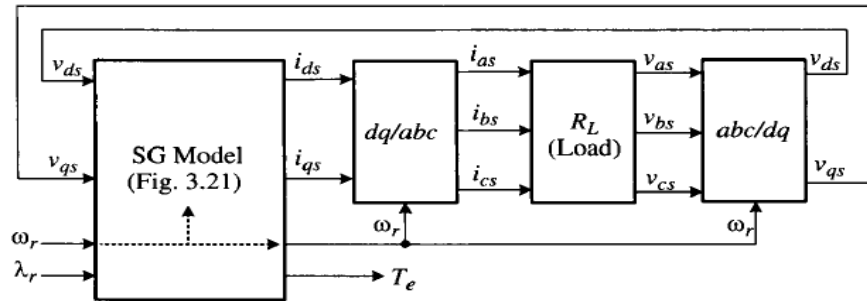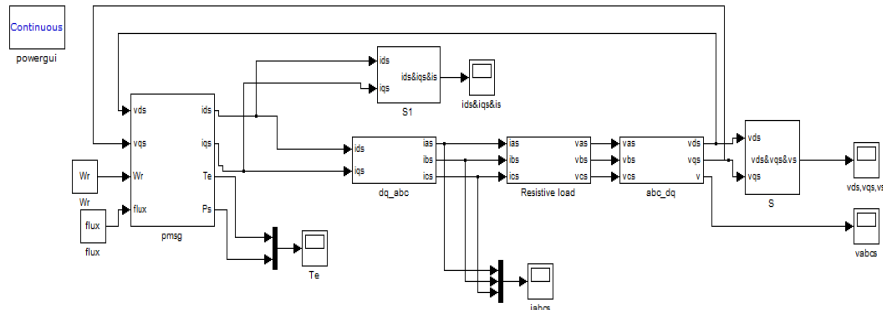
Figure 7. Block Diagram for Simulation

Figure 8.   Matlab Simulink Model

The dq-axis stator currents, ids and iqs in the synchronous frame rotating at the synchronous speed of w_r are calculated by the SG model.   They are then transformed into the abc -axis stator currents ias, ibs, and ics in the stationary frame through the dq/abc transformation. The calculated load voltages vas, vbs and vcs which are also the stator voltages are transformed to the dq-axis voltages vds and vqs in the synchronous frame .These voltages are then fed back to the SG model.

First , the PMSG is loaded with a three phase balanced resistive load Rl and operates at 320 rpm(.8 pu)at a given wind speed (the rotor speed is kept constant at 320 rpm due to assumption that the combined moments of inertia is very large) .

The following Figure 9. Shows the currents and voltages at PMSG terminals.
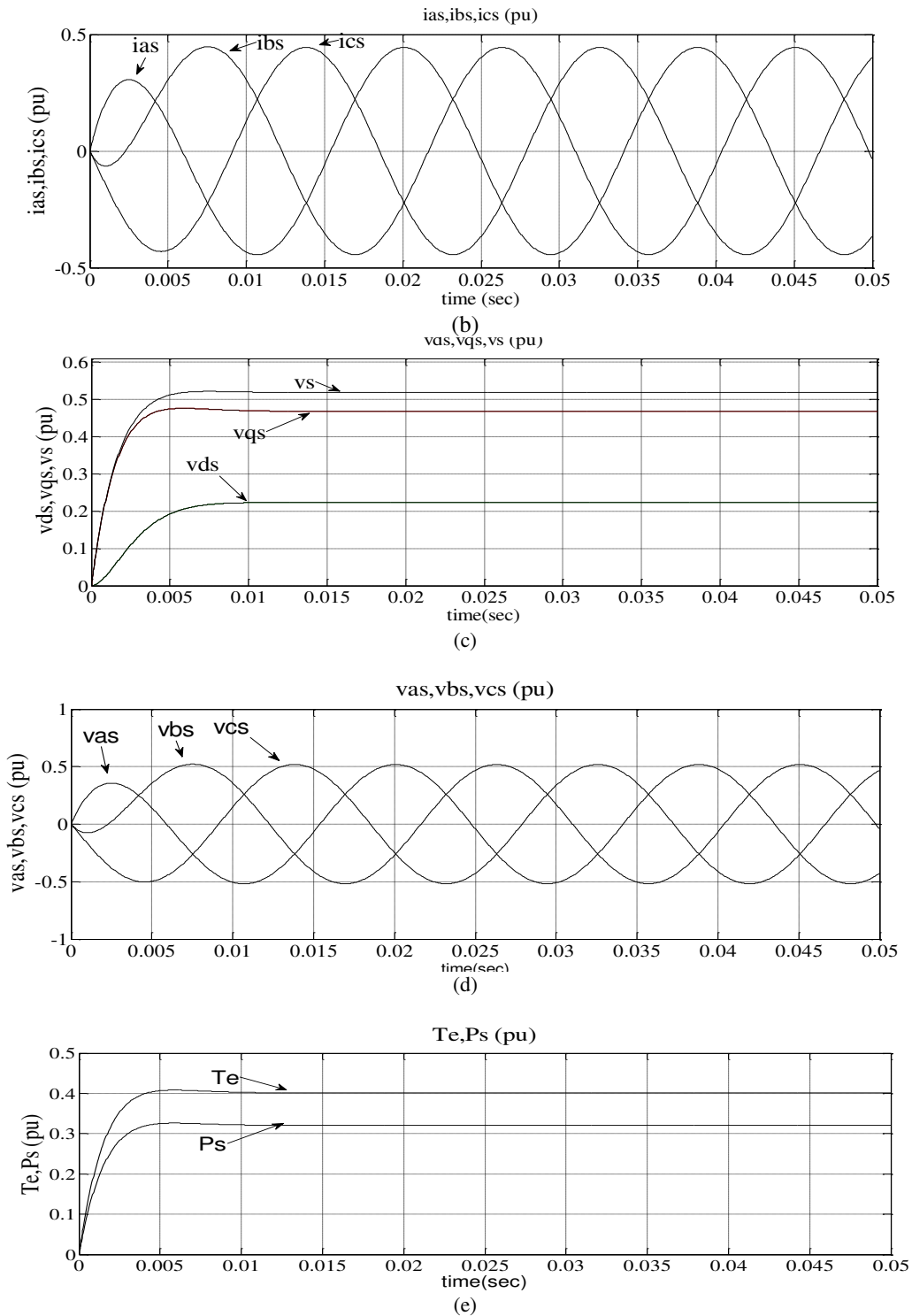
(a)
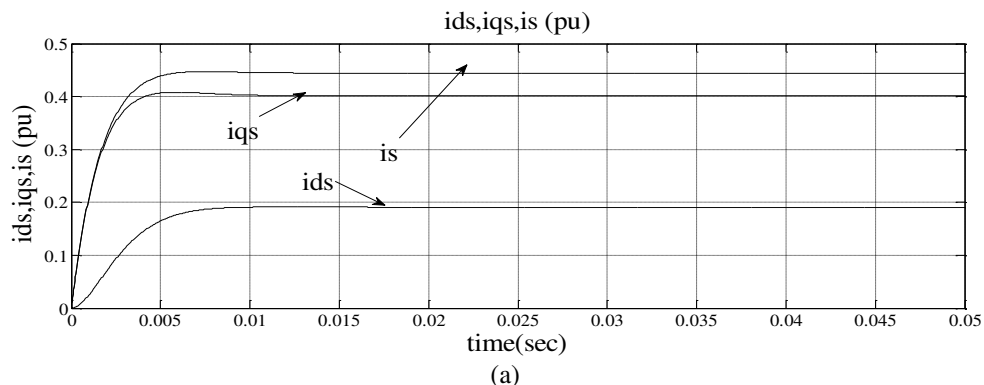
Figure 9. (a) dq-axis currents, (b)abc-currents,(c)dq-axis voltages,(d) abc voltages, (e)Torque and Power in case of Resistive Load

From figure 9, 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 is given by equation (28):

$$is = \sqrt{(iqs^2 + ids^2)} \qquad (28)$$

A similar phenomenon can be observed for the stator voltages.

5.1.2   *Decreasing The Load by Half*

The generator initially operates in steady state with a resistive load of R_l. The load resistance is reduced to $R_l/2$ by closing switch S at t = 0.0234 sec as shown in figure 10.
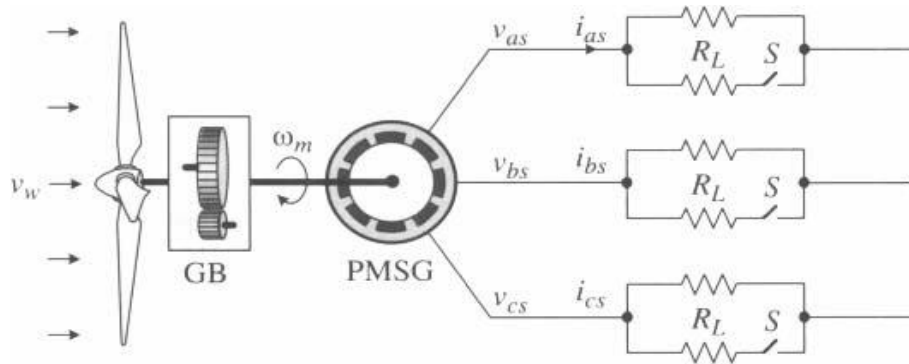

Figure 10.   SG with a Three-Phase Resistive Load

After a short transient period, the system reaches a new steady-state operating point as shown in Figure 11. From figures, a decrease in the load resistance results in an increase in the stator currents, but the stator voltages are reduced mainly due to the voltage drop across the stator inductances. The electromagnetic torque Te and stator active power Ps are increased accordingly when the system operates at the new operating point.
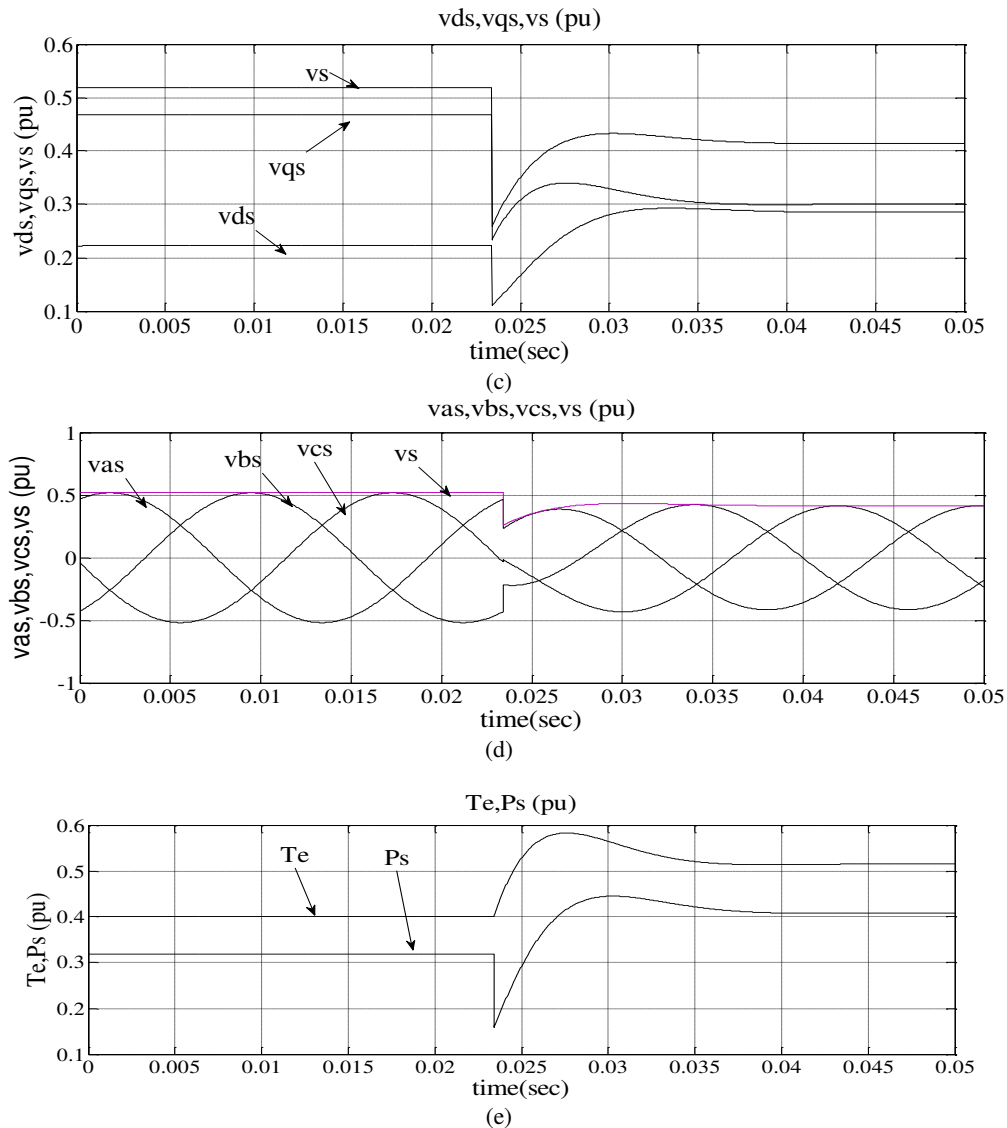

(a)

(b)
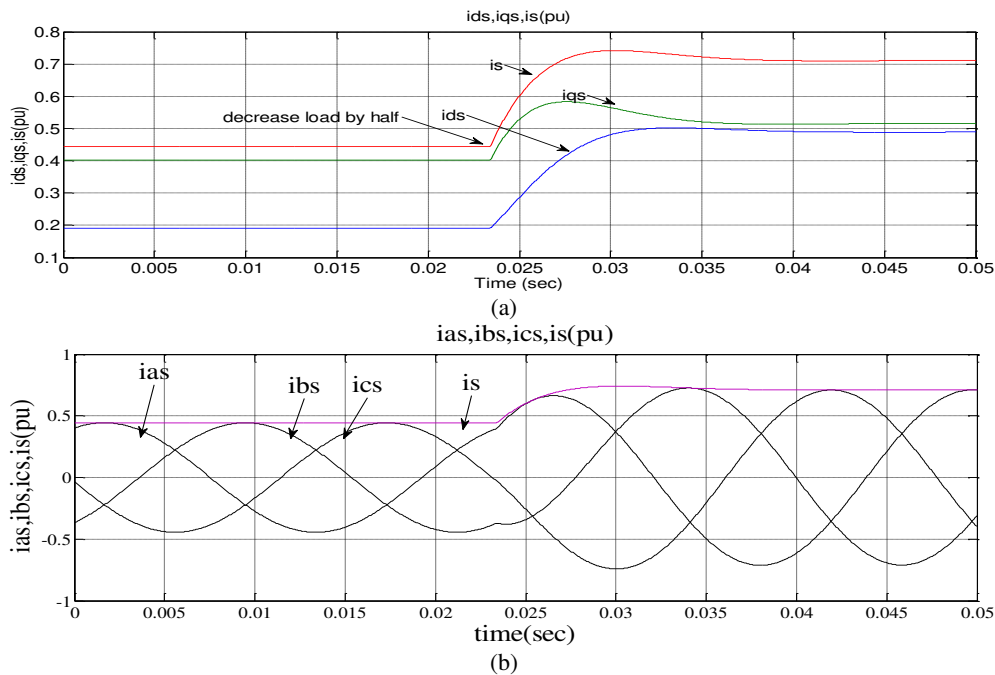
Figure 11. (a) dq-axis currents, (b)abc-currents,(c)dq-axis voltages,(d)abc voltages, (e)Torque and Power in Case of Decreasing to the Half of The Resistive Load

5.2 PMSG Loaded with (R-L) Load:

The steady-state performance of a stand-alone salient-pole PMSG with an inductive load is analyzed using the dq-axis steady-state equivalent circuit (Wu et al. 2011 ; Krause 2002).The generator operates at the rotor speed of 320 rpm and supplies a three-phase RL load of $R_L = 4.6797\Omega$ and   L = 13.966 mH, Since the q-axis leads the d-axis by 90°, The generator dq-axis stator voltages which are also the load voltages can be calculated by following equations:

$$v_{ds} + jv_{qs} = (i_{ds} + ji_{qs})(R_l + jw_rL_l)$$
$$= (R_li_{ds} - w_rL_li_{qs}) + j(R_li_{qs} + w_rL_li_{ds}) \qquad (29)$$

Where w_r is the rotor electrical speed which is also the speed of the dq synchronous reference frame.
Equation (29) can be arranged as

$$v_{ds} = R_li_{ds} - w_rL_li_{qs} = R_li_{ds} - X_Li_{qs} \qquad (30)$$

$$v_{qs} = R_l i_{qs} + w_r L_l i_{ds} = R_l i_{qs} + X_l i_{ds} \qquad (31)$$

Where $X_L i_{qs} = w_r L_l i_{qs}, X_l i_{ds} = w_r L_l i_{ds}$ are referred to speed voltages due to the transformation of the load inductance from abc-stationary frame to the dq-synchronous frame. A model for RL load is simulating which dq-axis equivalent circuits of inductive load are shown in Figures. 12 and .The results are shown in Figure 13.
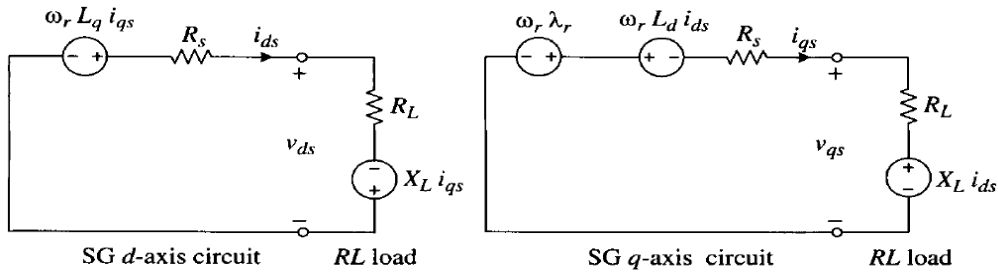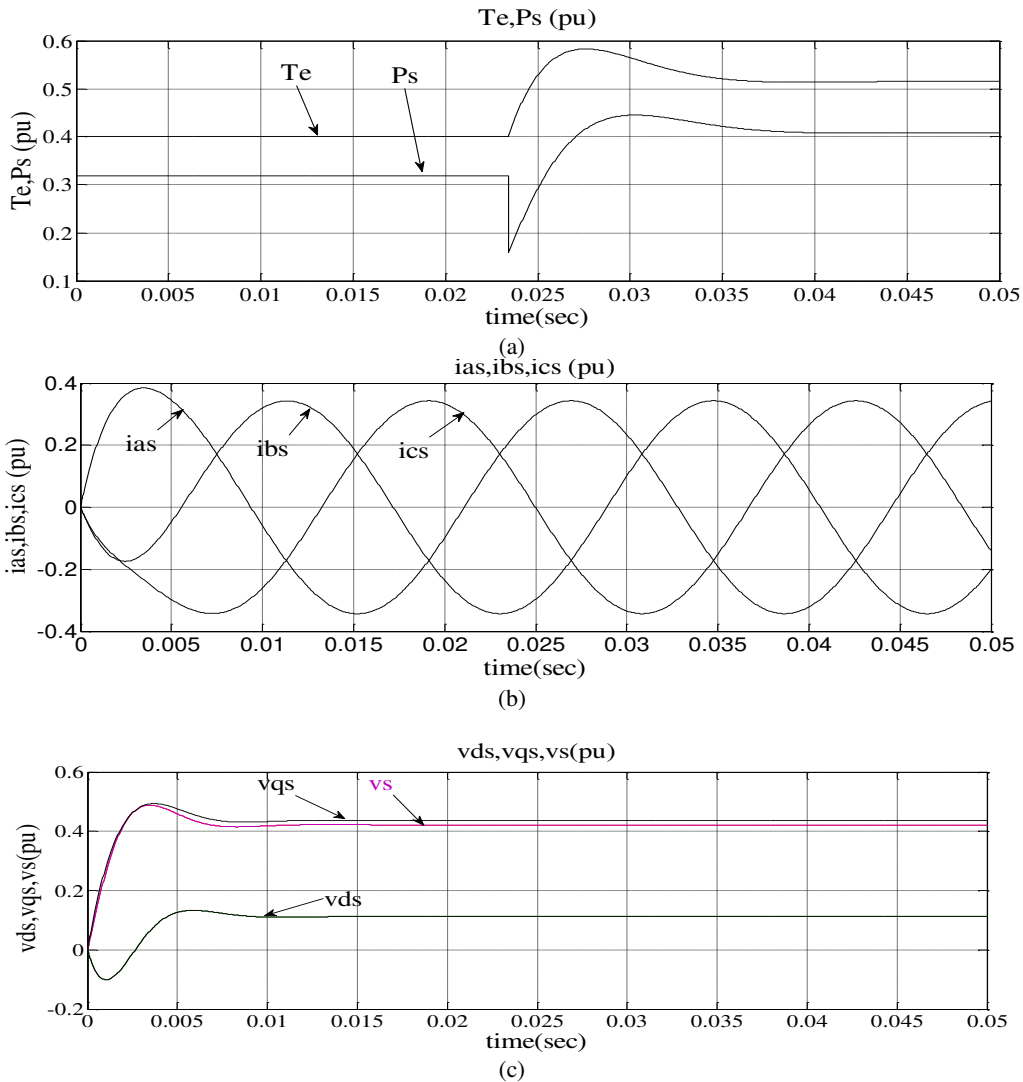
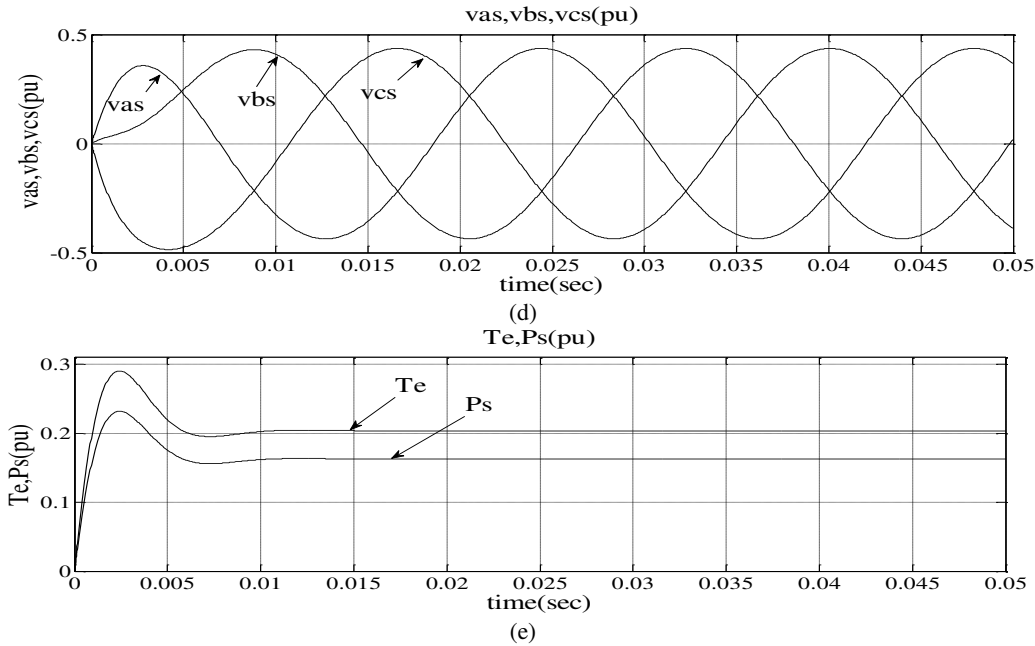Figure 12. dq-axis Equivalent Circuits

(a)

(b)

(c)

Figure 13. (a) dq-axis currents, (b)abc-currents,(c)dq-axis voltages,(d)abc voltages, (e)Torque and Power in Case of the Inductive Load

5.3 PMSG Loaded with RC Load

The steady state performance of a stand-alone salient-pole PMSG with a capacitive (RC) load is developed as inductive (RL) load which is analyzed using the dq-axis steady-state equivalent circuit .The generator operates at the rotor speed of 320 rpm and supplies a three-phase RC load of $R_l = 5.5\ \Omega$ and C = 637.72 µF. Since the q-axis leads the d-axis by 90° so the generator dq-axis stator voltages which are also the load voltages can be calculated by following equations:
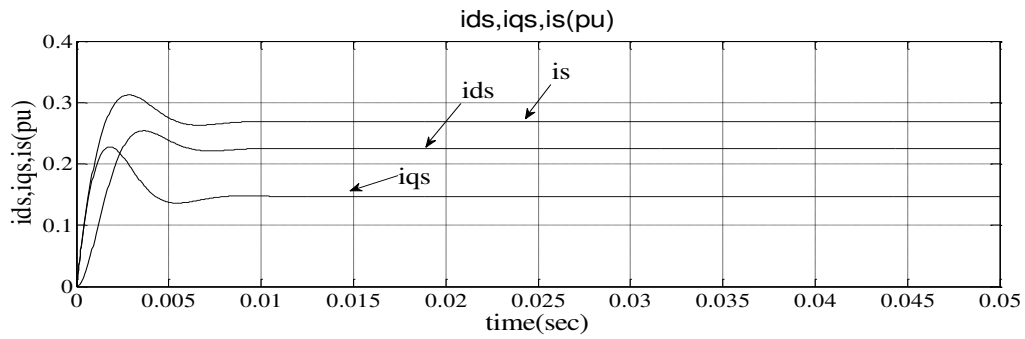
$$v_{ds} + jv_{qs} = (i_{ds} + ji_{qs})(R_l - j/w_r C_l)$$

$$= \left(R_l i_{ds} + \frac{i_{qs}}{w_r C_l}\right) + j\left(R_l i_{qs} - i_{ds}/w_r C_l\right) \tag{32}$$
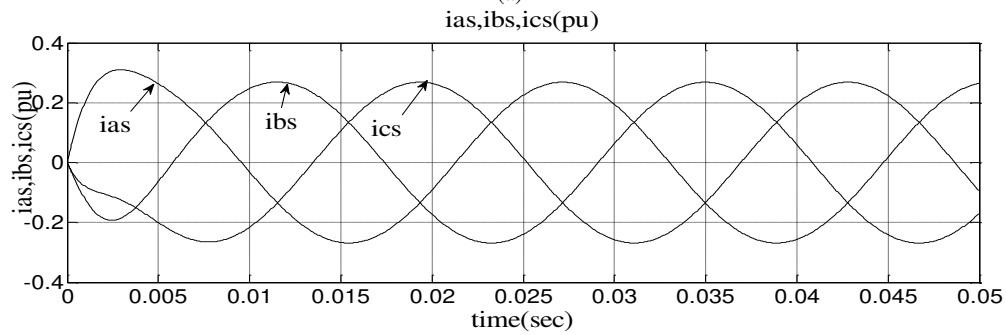
So,

$$v_{ds} = R_l i_{ds} - \frac{i_{qs}}{w_r C_l} = R_l i_{ds} + X_c i_{qs} \tag{33}$$

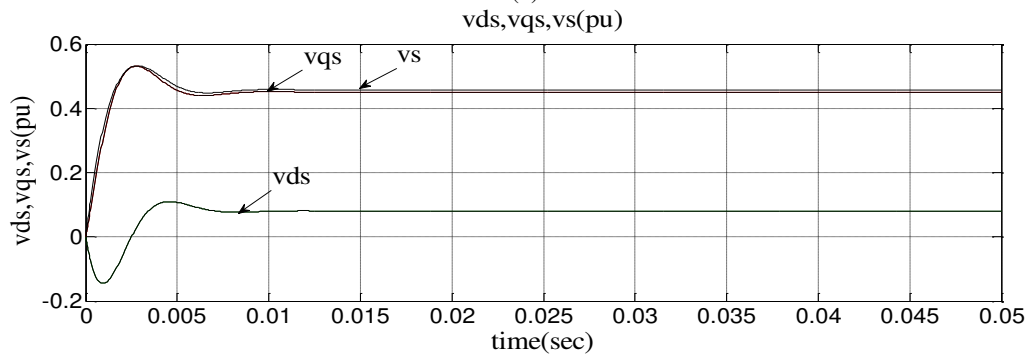$$v_{qs} = R_l i_{qs} - \frac{i_{ds}}{w_r C_l} = R_l i_{qs} - X_c i_{ds} \tag{34}$$

Where $X_c i_{qs} = i_{qs}/w_r C_l$, $X_c i_{ds} = i_{ds}/w_r C_l$ are referred to speed voltages due to the transformation of the load inductance from abc-stationary frame to the dq-synchronous frame.The simulation results are shown in Figure 14.
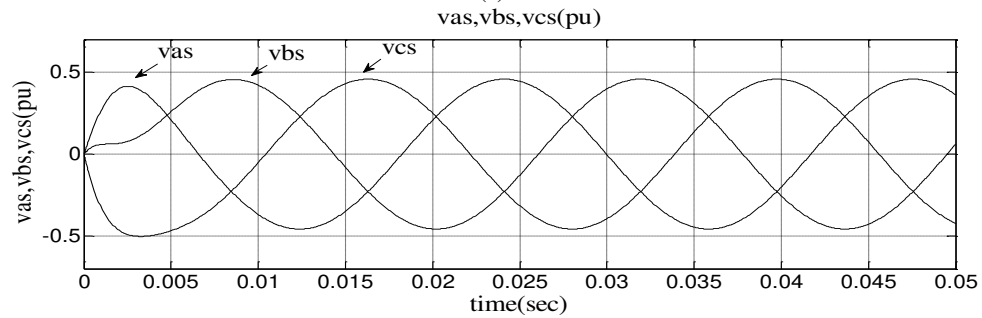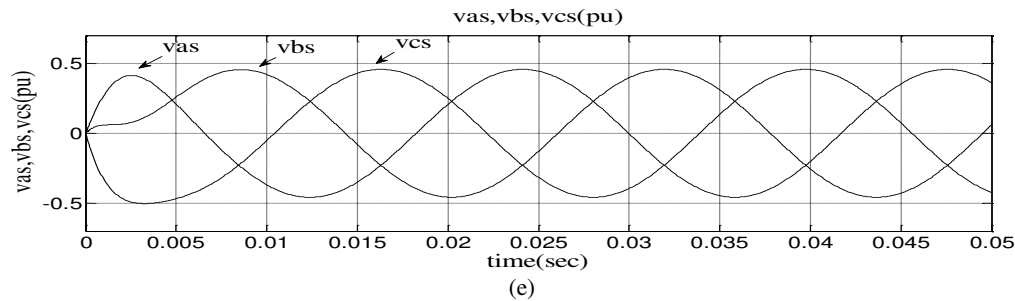
(a)

(b)

(c)

(d)

Figure 14. (a) dq-axis currents, (b)abc-currents,(c)dq-axis voltages,(d) abc voltages, (e)Torque and Power in case of capacitive load

6. Conclusion

- This paper presents the model of stand-alone wind turbine driven permanent magnet synchronous generator (PMSG) which the model has been implemented in MATLAB / SIMULINK.

- The power coefficient (Cp) curves have been developed and drawn with both tip speed ratio ʎ and pitch angle ß. These curves show that with varying of the pitch angle ß or tip speed ratio ʎ, the power coefficient can be changed and the power captured by the turbine also can be controlled.

- The PMSG has been modeled in the d-q synchronous rotating reference frame.

- The wind driven PMSG is operating stand alone at resistive load firstly where The values of currents, voltages, torque and Power are obtained. 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.

- Then decreasing the load by half, the values of currents, voltages, torque and Power obtained. Due to a decrease in the load resistance results in an increase in the stator currents, but the stator voltages are reduced mainly due to the voltage drop across the stator inductances. The electromagnetic torque Te and stator active power Ps are increased accordingly when the system operates at the new operating point.

- Moreover, wind driven PMSG is loaded with inductive and capacitive loads also.

- The results show that the ability of wind driven PMSG to operate over wide range of operating conditions and at different load changing. Show effect of load type in operation.

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