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Performance analysis of transient behaviour of *PMSG* model with sudden load variations part-1

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***Abstract*—as the demand of electricity is ever increasing the need for electricity from alternative energy sources which is cheap is increasing year after year. One of the best among the alternative energy source is wind energy. The permanent magnet synchronous generator is gaining more importance in this field of producing electricity from wind because of its inherent properties like simple in structure suitable for direct drive wind energy conversion etc. In this work the dynamic model of permanent magnet synchronous generator is considered and the performance is analyzed for sudden variations in loading conditions. Salient pole machine is considered and the results are analyzed. For the analysis purpose the input speed is kept constant. The same is verified with step response of transfer function model of the machine.**

Keywords*— *dynamic model; permanent magnet synchronous generator; step response

I. INTRODUCTION

The wind energy conversion is increasing day by day owing to the continuous increase of demand for the electricity in domestic and industrial purposes. It increased from 1456 MW installed capacity in 2001 to 9655 MW by 2008 to 28,700 MW by 2016 in India [1]. This is a tremendous raise of 663 percent from 2001 to 2008 and 297 percent from 2008 to 2016. It is heading forward with a target of 60,000 MW by the end of 2022 [2]. If this continues with this steady growth in installed capacity year after year the day on which one can receive electricity with nominal price may be with no-price also may come in the next decade itself. Only china has cumulative installed capacity of 1, 68,732 MW with a share of 34.7 percentage and USA has 82,184 MW with 16.9 percentage followed by Germany 50,018 MW with a share of 10.8 percentage in the global scenario by the end of 2016. India has 28,700 MW cumulative installed capacity and shares 5.9 percentage [3]. In the process of wind energy conversion for better conversion efficiency wind turbine, generator and gear box are the key role players.

Control of turbine falls into mechanical whereas generator control into electrical side. Generator control can be done in various ways. As the permanent magnets are used in the rotor of PMSG there is no scope for control from rotor side. Therefore back-to-back converter system is used on stator side to connect the wind system to the grid. The back-to-back converter is generally used with one of the dc-dc converters to stabilize the dc link voltage and to rectify associated issues. Control of the generator can be done from rectifier side. Usually the wind speed is continuously changing in nature. This causes the fluctuations in the output power from the generator. For this reason to extract the energy from the wind and feed into the grid or a local load in standalone operation different control techniques are used. Using these control strategies the maximum possible power can also be extracted simultaneously. In this work permanent magnet synchronous generator is considered for analysis with sudden load variations on it. For the sake of analysis the speed input of the machine is kept constant. The remaining part of the paper is organized as follows. In section II modeling of the PMSG is presented. Section III describes the analysis section IV presents results. Section V is conclusions from the results.

II. MACHINE MODEL

A. dq model of the machine

Induction generators were used widely for wind energy conversion particularly squirrel cage machines later Doubly fed induction generators came in to picture giving room for control from both stator and rotor side as well as bidirectional power flow. Presently with the development of full rated power electronic converters synchronous generators gaining importance for direct drive application. Also the non salient pole machine offers smooth electromagnetic torque [4]. Salient and non-salient pole synchronous machines are considered in this work. Salient pole PMSG usually is suitable for slow speed application and non salient pole for moderate to high speed. The former is bigger in size for the same rating.

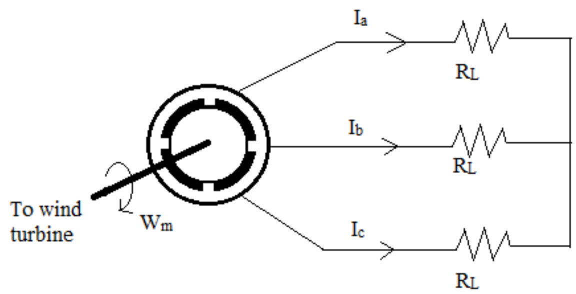


Figure 1: *pmsg* feeding a resistive load

The figure 1 shows a pmsg feeding a 3-phase resistive load. The following model of the machine is considered here for analysis [5].

$$v_d = -R_s i_d + \omega_r L_q i_q - L_d p i_d \quad (1)$$

$$v_q = -R_s i_q - \omega_r L_d i_d + \omega_r \lambda_r - L_q p i_q \quad (2)$$

Where p stands for the $\frac{d}{dt}$ operator. λ_r stands for permanent magnet flux linkages. i_d is the direct axis stator current and i_q the quadrature axis stator current. L_d and L_q are d-axis and q-axis stator inductances. ω_r is electrical angular speed of the generator. Equations (1) and (2) when solved using a numerical method give the short circuit currents of the stator. The corresponding waveforms of i_d and i_q are shown in the Fig.2.

From the Fig.2 it is clear that the current i_d is going above 2 kilo amperes exceeding the rated value of the machine.

The equation (3) gives the model of the machine with the load impedance included.

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{-(R_s + R_L)}{L_d} & \frac{\omega_r L_q}{L_d} \\ \frac{-\omega_r L_d}{L_q} & \frac{-(R_s + R_L)}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\omega_r \lambda_r}{L_q} \end{bmatrix} \quad (3)$$

The model is again solved using numerical methods. For this to solve the initial conditions of i_d and i_q can be used. These values can be obtained by solving the equation (3) by letting the changes in i_d and i_q equal to zero. The load resistance and the machine inductance caused the response to raise like the response of first order RL series circuit. The response is shown in Fig.3.

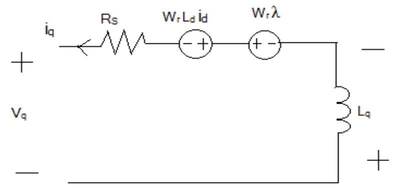


Figure 2: q-axis equivalent circuit of *pmsg*

$$\frac{d}{dt} i_d = \frac{-R_s}{L_d} i_d + \frac{\omega_r L_q i_q}{L_d} - \frac{v_d}{L_d} \quad (4)$$

$$\frac{d}{dt} i_q = \frac{\omega_r L_d i_d}{L_q} - \frac{R_s}{L_q} i_q + -\frac{v_q}{L_q} + \frac{\omega_r \lambda_r}{L_q} \quad (5)$$

The mathematical model given in equation (3) of the generator when feeding a 3-phase RL load will become

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{-(R_s + R_L)}{(L_L+L_d)} & \frac{\omega_r L_q}{(L_L+L_d)} \\ \frac{-\omega_r L_d}{(L_L+L_q)} & \frac{-(R_s + R_L)}{(L_L+L_q)} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\omega_r \lambda_r}{(L_L+L_q)} \end{bmatrix} \quad (6)$$

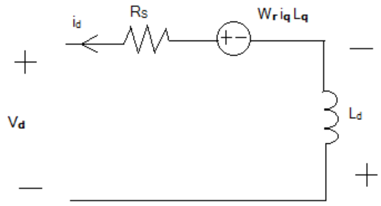


Figure 3: d-axis equivalent circuit of PMSG

Equation (6) can also be solved using initial values of both d-axis and q-axis currents similar to equation (3). The difference here is that because of the presence of the inductance in the load impedance the response i.e. the solution of the equation (6) will be somewhat different. This analysis is presented in next section.

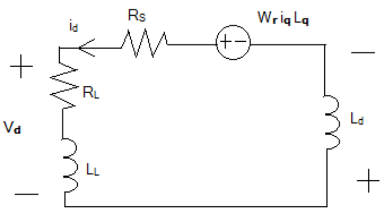


Figure 4: d-axis equivalent circuit of PMSG with RL load

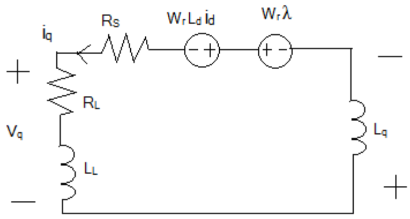


Figure 5: q-axis equivalent circuit of PMSG with RL load

III. ANALYSIS OF THE MODEL

A. *without any load impedance*

The initial values of the model given in equation (6) can be obtained by equating the differential terms to zero i.e.

$$\frac{-(R_s + R_L)}{(L_L+L_d)} i_d + \frac{\omega_r L_q}{(L_L+L_d)} i_q = 0$$

From this the value of i_d can be obtained as

$$i_d = \frac{\omega_r L_q}{(R_s + R_L)} i_q \quad (7)$$

Also from (6)

$$\frac{-\omega_r^2 L_d L_q}{(R_s + R_L)} i_d - (R_s + R_L) i_q + \omega_r \lambda_r = 0$$

Using the above two equations,

$$i_d = \frac{\omega_r \lambda_r (R_s + R_L)}{\omega_r^2 L_d L_q + (R_s + R_L)^2} \qquad (8)$$

Using the equations (7) and (8) the initial conditions can be calculated for any given load impedance and speed of the machine. The machine considered in this paper is 3.383MVA 4000 volts rms and 40Hz whose details are given in table-I.

IV. RESULTS

The mathematical model presented in (1)-(2) is solved using numerical solvers of matlab. This model is without any load resistance. As the pmsg is nothing but can be considered as an alternator with fixed magnitude of field flux, solution of (1) – (2) gives the symmetrical short circuit current with a dc off-set voltage included.

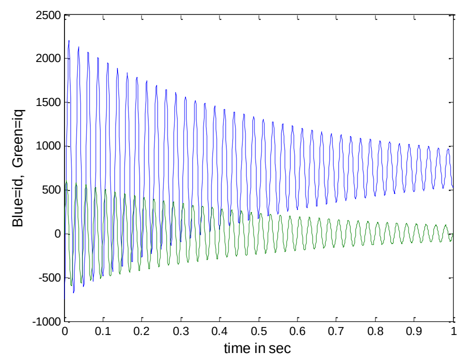


Figure 6: Id and Iq with zero load resistance

This is evident from the figure. 6 which shows the symmetrical short circuit current in terms of d-axis and q-axis currents of the stator. The currents go beyond the normal rated currents as much as 5 times the full load current in the sub-transient period.

A. *With Resistive load*

- Next the mathematical model presented in (3) is also solved using numerical solver in matlab. The plots of i_d and i_q are given in figure.7 the load inclusion has introduced a good damping to the machine that the currents have raised from their initial values and straightaway settled to final value of 270 amperes and 516 amperes for d-axis and q-axis respectively. In figure. 8 the corresponding electromagnet torque is also shown which exhibits similar characteristic as the q-axis current for the torque of the pmsg is given by (9).[8]

$$T_e = \frac{3}{2} n_p \left[\lambda_r i_q - (L_d - L_q) i_q i_d\right] \qquad (9)$$

- With the equality of L_d and L_q for the salient pole machine the torque produced becomes proportional to i_d. This is given by (10).

$$T_e = \frac{3}{2} n_p \lambda_r i_q \qquad (10)$$

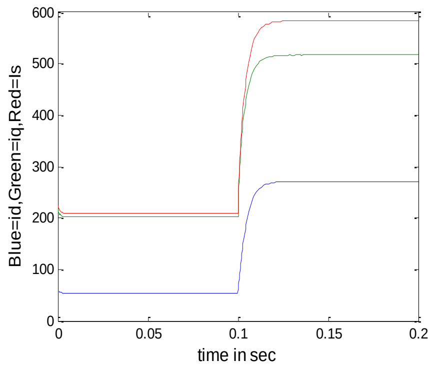
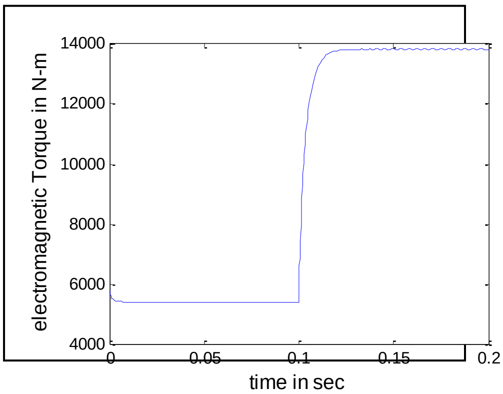


Figure 7: Id Iq and Is with load included.



B. *With R-L laod*

R-L load is applied on the machine. Equation (6) gives the dynamic model of this case. Addition of inductance in the load caused the overshoot in the currents. This can be seen in both figure.9 and 10 as well. But the currents remained in the range of the rating of the machine here.

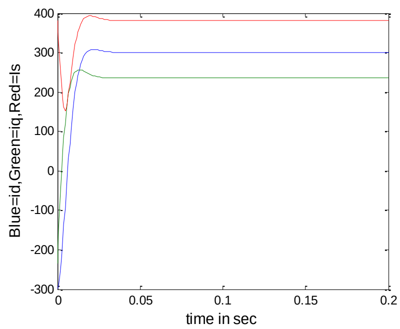


Figure 9: I_d & Iq with a load of R=4.3Ohm L=8.3mH

C. Changing the load

On the same machine when the load is changed suddenly from one value to another the transients in currents are observed with overshoots every time. The red colored curve in the figures.7 9 and 10 is the stator current I_s. This is given by (11).

$$I_s = \sqrt{i_d^2 + i_q^2} \quad (11)$$

The stator currents variation is shown in figure. 11. The three phases undergone changes when loads are suddenly varied.

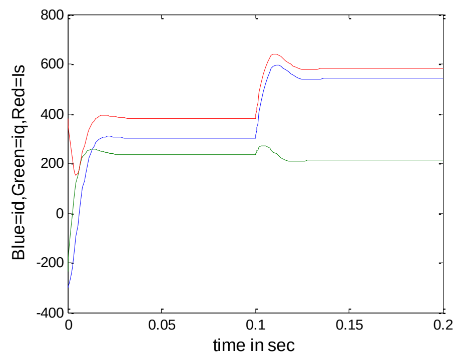


Figure 10: Change of RL load from 50% to 100%

The figure.11 shows the same thing of RL load from 50 to 100 percent.

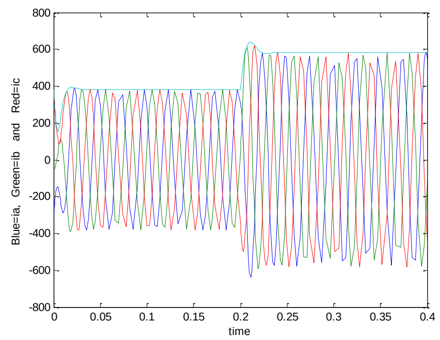


Figure 11: Stator currents and Is with load variation-50 to 100%.

The transfer function model of the machine is considered for check with step response. The step input is the change in the load. In this work both case with resistive load and RL load are given a step input.

$$tf2 = \frac{2.717ecp7}{s^2 + 248.2s + 5.007exp4} \quad (12)$$

$$tf1 = \frac{56100s + 1.398exp7}{s^2 + 392.1s + 5.943exp4} \quad (13)$$

The transfer function of equation (12) is of the machine with 100 percent load whereas that of (13) is of 50 percent load. For the first system the output is q-axis current and for the later one d-axis current. The step responses confirm with the magnitudes of currents simulated using matlab solvers. The responses are shown in figure. 12.

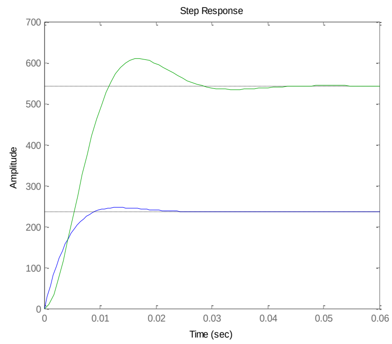


Figure 12: step response with 100% and 50% load variations.

D. Machine details

Table. 1[5]

Quantity	Value
Rated Mechanical	2.5 MW
Rated Apparent	3.383 MVA
Rated Line-to-line	4000 V (rms)
Rated Stator Current	485 A (rms)
Rated Stator Frequency	40 Hz
Rated Rotor Speed	400 rpm
Number of Pole Pairs	6
Rated Mechanical	59.6831 kN-m
Rated Rotor Flux	4.759 Wb (rms)
Stator Resistance, *Rs*	24.25 *mil*
Ld	8.9995 mH
Lq	21.8463 mH

V. CONCLUSIONS

In this work the dynamic model of the permanent magnet synchronous generator is considered for the examination of the response for the sudden variation of loads on it. The response of the machine beginning from the short circuit condition to full load is observed. Sudden change of loads is also applied from 50 percent full load to 100 percent. The transfer function model is considered for the same machine with load change as the input and stator current as output. The step response also confirms the changes in stator currents for the considered load change with the same magnitude.

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ANNEXURE

Matlab code for the simulation of pmsg

```
function []= mct_pmsg()
close all
clc
[ax bx int_c1 ay by int_c2 wr]=mct_gen_cal();
[t1 y1]=ode45(@mct_1,[0 0.1],int_c1);
[t2 y2]=ode45 (@mct_2,[0.1 0.2],int_c2);

    function [di]= mct_1(~,i)
        di = zeros(2,1);     % a column vector
        di(1) = ax(1,1)*i(1)+ax(1,2)*i(2)+bx(1);
        di(2) = ax(2,1)*i(1)+ax(2,2)*i(2)+bx(2);
    end
        function [di]=mct_2(~,i)
            di=zeros(2,1);
            di(1) = ay(1,1)*i(1)+ay(1,2)*i(2)+by(1);
            di(2) = ay(2,1)*i(1)+ay(2,2)*i(2)+by(2);
        end

id=[y1(:,1);y2(:,1)];
iq=[y1(:,2);y2(:,2)];
% Stator currents calculation
txy=[t1;t2];
theta=wr.*txy;

ia=id.*cos(theta)-iq.*sin(theta);
ib=id.*cos(theta-2*pi/3)-iq.*sin(theta-2*pi/3);
ic=id.*cos(theta-4*pi/3)-iq.*sin(theta-4*pi/3);

plot(txy,ia,txy,ib,txy,ic);
xlabel ('time','Fontsize',15)
ylabel ('Blue=id,  Green=iq   and
Red=Wr','Fontsize',15)
end
function [ax bx int_c1 ay by int_c2 wr]=
RL_load_cal()
clc
% Data of Salient pole PMSG for the calculations

p=2.5e6; % rated mechanical power and rated apparent
power %
rated_Vph=2309.4;rated_iph=485;
rated_VL=sqrt(3)*rated_Vph;
rpm=400;
Rs=0.0243;
```

```
Lds=0.0089995;
Lqs=0.0218493;
pole_pairs=6; %input('enter the number of poles of
PMSG  =  ');
lambda=4.759;%wb(rms)
max_lambda=sqrt(2)*lambda;
load_R=4.2855;
load_L=8.258e-3;
wr=2*pi*rpm*pole_pairs/60;
J=1.3131e6; %inertia
 % Calculations
iq=wr*max_lambda*(load_R+Rs)/((load_R+Rs)^2+(Lds*Lqs
*wr^2));
id=wr*Lqs*iq/(load_R+Rs);
is=sqrt(id^2+iq^2);
vd=-Rs*id+wr*Lqs*iq;
vq=-Rs*iq-wr*Lds*id+wr*max_lambda;
Te=3*pole_pairs/2*(iq*max_lambda-(Lds-Lqs)*id*iq);
 [ax bx int_c1]= r100();
[ay by int_c2]=r50();
    function [ax bx int_c1]= r100()
    x=1;% fraction of Load
    a1=-(Rs+x*load_R)/(x*load_L+Lds);
b1=wr*Lqs/(x*load_L+Lds);       c1=0;
    a2=-wr*Lds/(x*load_L+Lqs);      b2=-
(Rs+x*load_R)/(x*load_L+Lqs);
c2=wr*max_lambda/(x*load_L+Lqs);


    ax=[a1 b1;a2 b2;];
    bx=[c1;c2;];
    int_c1=linsolve(ax,bx);
    end

    function [ay by int_c2]=r50()
        y=0.5;% fraction of Load
        a1=-(Rs+y*load_R)/(y*load_L+Lds);
b1=wr*Lqs/(y*load_L+Lds);       c1=0;
        a2=-wr*Lds/(y*load_L+Lqs);      b2=-
(Rs+y*load_R)/(y*load_L+Lqs);
c2=wr*max_lambda/(y*load_L+Lqs);


        ay=[a1 b1;a2 b2;];
        by=[c1;c2;];
        int_c2=linsolve(ay,by);
    end
end
```