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Analysis of Steady State Stability of a Csi Fed Synchronous Motor Drive System with Damper Windings Included

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ABSTRACT

Steady state stability criteria of A.C. drives play a dominant role for making the drive system practically successful. Generally such analysis is done using small perturbation model. But the complexity of the mathematical formulation depends on the nature of the drive system used. This study presents a detailed analysis of steady state stability criterion based on small perturbation model of a current source inverter fed synchronous motor drive system taking d-axis and q-axis damper winding into account using generalized theory of electrical machines. The modeling also clearly shows that even at no load the system satisfies steady state stability criterion. Routh-Herwitz criterion is used to finalize the result. The methodology of the proposed research work can be stated as follows: The synchronous motor has been treated as a five coil primitive machine model using the concept of generalized theory of electrical machines. Using the concept of Park's transformation the armature current in d-q model has been represented by suitable equations as a function of armature current magnitude in phase model (I_S) and the field angle (β). As the system under consideration is basically a current source inverter fed system, I_S has been considered as a constant and as a consequence the field angle (β) finally appears as a control variable. Furthermore voltage balance equations of the five coils have been expressed in time domain and those equations has been transformed accordingly after applying Laplace transform technique and then small perturbation technique is applied on the transformed equations. Finally the transfer function $\Delta\beta$ (s)/ΔT_L(s) have been formulated; where $\Delta\beta$ (s) and ΔT_L (s) represent small change in transformed field angle and load torque, respectively. The analysis concludes that the absence of damper winding leads to instability of the machine system.

Key words: Equivalent circuit, current source inverter, small perturbation model, routh-herwitz criterion

INTRODUCTION

For achieving flexibility in operation, the traditional method of feeding direct supply to the major components of an A.C. drive system i.e. synchronous machine or induction machine are avoided and the void is filled up by the use of power electronic converters. In this study, A.C. motor drives using inverter-fed synchronous machines are used in some specific application areas, certain features that make them preferable to induction motor drives (Marx *et al*., 2008). One of those specific examples is the accurate simultaneous speed control of a number of motors by using synchronous motors.

There are companion studies (Das and Chattopadhyay, 2004; Yan *et al.*, 2008) in the direction of power electronic control of synchronous motor drive systems. Das and Chattopadhyay (2004) basically deals with the analysis of control mechanism of a synchronous motor drive system with the help of a cycloconvertor: direct torque control. Sayeef *et al.* (2008) explained the direct torque control of Permanent Magnet Synchronous Machine Motors (PMSM). Yan *et al.* (2008) discussed the direct torque control of PMSM taking the effect of saturation saliency into account.

Chan *et al.* (2008) introduced a flux-observer method to estimate the rotor speed of a PMSM. Fabijanski and Lagoda (2008) has been reported anthor study in 2008. This study deals in fuzzy logic control of inverter fed synchronous motor of inverter fed synchronous motor based on a simply mathematical model, algorithmic investigations of stability criteria.

Using fuzzy logic algorithm, similar work on PMSM (Uddin and Rahman, 2007) has been reported and the controller was found to robust for high-speed applications. Though most of the inverters used in A.C. drive are voltage source inverters, current source inverters are also being recognized due to simplicity, greater controllability and ease of protection. This study examines steady state stability aspects of a C.S.I. fed synchronous machine drive system considering the presence of damper winding on both direct and quadrature axis. There is a necessity of providing a damper winding in the q-axis to assure the steady-state stability at no-load. The present study also confirms the above said statement by presenting a rigorous analysis based on generalized theory of electrical machines by Adkins (1957). Furthermore, there exists an interesting research study (Al-Ohaly *et al.*, 1997) in connection to the dynamics of a three phase synchronous motor being fed from a single phase supply, using state space model. Korshunov (2009) explained an interesting study in the area of stability analysis of a synchronous motor with permanent magnets by using small perturbation model. Even though the authors of the present study have used the axis model of synchronous motor for analysis of steady state stability, the reference (Korshunov,2009) has drawn the attention because such work relates with the state variable model.

Chattopadhyay *et al.* (2011) does not involve synchronous motor as a topic of research but the main similarity lies in the fact that this study, also uses Laplace transforms as a tool for mathematical modeling using state variable approach applied to solar array power system. The study by Zayandehroodi *et al.* (2010) is basically a research work related to the fault location in a power system. This study uses neural network technique for the problem formulation but it can be linked up with the proposed research work involving synchronous motor in the sense that the same power system can consist of the synchronous motor drive system as a load. Ghorab *et al.* (2007) basically deals with the simulation of a power system consisting of a turbo generator using matlab. The points of similarity with the present study are:

- It is also a stability problem even though different technique like Lyaponov technique has been used
- Laplace transform has been used to carry out the block diagram approach
- Torque angle and power balance equations under dynamics have been used. It may be noted that the term torque angle (Ghorab *et al.*, 2007) corresponds to the term field angle referred in the present study

Jazaeri *et al.* (2011) basically deals with the distance relay protection scheme implemented on a transmission line in presence of Unified Power Flow Controller (UPFC).The UPFC is a member of the FACTS family with attractive features. The present study involving synchronous motor drive system can be easily linked up with the findings of Jazaer *et al.* (2011). According to him synchronous motor can be included playing the role of the symbol of the motor shown in the Fig. 1 and 2. Babainejad and Keypour (2010) analysed the effect of electrical parameters of an Induction Generator on the transient voltage stability of a variable speed wind turbine system. The similarity of this study with the present study lies in the fact that the Induction generator also has been modeled in d-q frame through voltage balance and flux linkage equations. Furthermore this study uses the torque balance equations in the phase model which can be converted to d-q model using the well known torque balance equation i.e., $T_e = i_d \Psi_{q-} \Psi_d i_q$.

There are many representative form of transfer function in association with the steady state stability analysis of a Current Source Inverter fed synchronous motor drive system. Taking the practical aspect into account, the present study targets to derive an expression in a suitable form for transfer function which is the ratio of the Laplace transfer of the small signal version of the change in angle (β) between the field (rotor) m.m.f. axis and armature (stator) m.m.f. axis to the Laplace transform of the small signal version of change in load torque (T_L). The mathematical analysis in the said direction is presented in the subsequent section. The objective of the study is to diagnose the fact whether the synchronous motor with damper winding and fed through a current source inverter can sustain small perturbation in load torque or not. This analysis has been carried out from the view point of the concept of steady state stability criteria of an electrical drive system.

MATERIALS AND METHODS

The basic block diagram of the proposed scheme is shown in Fig. 1

To have a better feeling of the method of analysis, the primitive machine model of the synchronous motor is drawn and it is shown in Fig. 2

In the following analysis, saturation is ignored but provision is made for inclusion of saliency and one number of damper winding on each axis. Following Park's transform, a constant stator current of value is at a field angle 'β' can be represented by direct and quadrature axis currents as:

$$i_d = i_s \cos \beta \tag{1}$$

$$i_q = -i_s \sin b\beta \tag{2}$$

Designating steady state value by the subscript '0' and small perturbation by Δ, the perturbation equations of the machines are:

$$\Delta i_d = -i_s \sin \beta_0 \Delta\beta \tag{3}$$

$$\Delta i_d = i_s \cos \beta_0 \Delta\beta \tag{4}$$

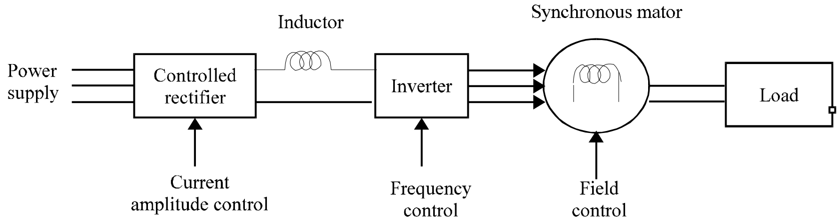

Fig. 1: Drive configuration for open-loop current-fed synchronous motor control

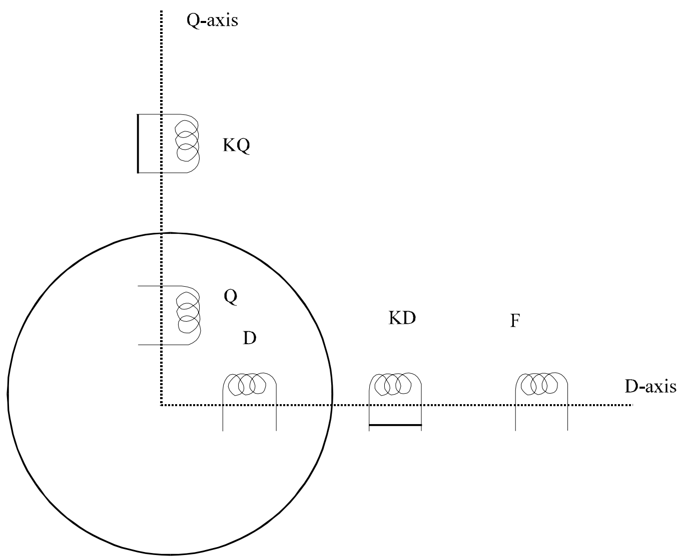

Fig. 2: Primitive machine model of a synchronous motor

The transformed version of Eq. 3 and 4 are:

$$\Delta I_d\,(s) = -i_s \sin \boldsymbol{\beta}_0 \Delta\boldsymbol{\beta}\,(s) \tag{5}$$

$$\Delta I_q\,(s) = i_s \cos \boldsymbol{\beta}_0 \Delta\boldsymbol{\beta}\,(s) \tag{6}$$

The generalized expression for electromagnetic torque of a primitive machine model is an established one and it is expressed as:

$$\begin{aligned} T_e &= \Psi_d i_q - i_d \Psi_q = \left(L_d i_d + L_{md} i_f + L_{md} i_{kd}\right) i_q - \left(L_q i_q + L_{mq} i_{kq}\right) i_d \\ &= \left(L_d - L_q\right) i_d i_q + L_{md} i_q i_f + L_{md} i_{kd} i_q - L_{mq} i_{kq} i_d \end{aligned} \tag{7}$$

Small signal version of torque equation in time domain is expressed as:

$$\begin{aligned} \Delta T_e = {} & \left(L_d - L_q\right) \Delta i_d i_{q0} + \left(L_d - L_q\right) \Delta i_q i_{d0} + L_{md} \Delta i_q i_{f0} + L_{md} \Delta i_f i_{q0} \\ & + L_{md} \Delta i_{kd} i_{q0} + L_{md} i_{kd0} \Delta i_q - L_{mq} \Delta i_{kq} i_{d0} - L_{mq} i_{kq0} \Delta i_d \end{aligned} \tag{8}$$

Equation 8 after being transformed takes the shape as given by:

$$\begin{aligned}
\Delta T_e(s) &= (L_d - L_q)\, i_{q0}\Delta I_d(s) + (L_d - L_q) i_{d0}\Delta I_q(s) + L_{md} i_{f0}\Delta I_q(s) + L_{md} i_{q0}\Delta I_f(s) \\
&+ L_{md} i_{q0}\Delta I_{kd}(s) + L_{md} i_{kd0}\Delta I_q(s) - L_{mq} i_{d0}\Delta I_{kq}(s) - L_{mq} i_{kq0}\Delta I_d(s) \\
&= [(L_d - L_q) i_{q0} - L_{mq} i_{kq0}]\Delta I_d(s) + \left[(L_d - L_q) i_{d0} + L_{md} i_{kd0} + L_{md} i_{f0}\right]\Delta I_q(s) \\
&+ L_{md} i_{q0}\Delta I_f(s) + L_{md} i_{q0}\Delta I_{kd}(s) - L_{mq} i_{d0}\Delta I_{kq}(s)
\end{aligned} \tag{9}$$

To tackle Eq. 9 in an easier form, it is expressed as:

$$\Delta T_e(s) = c_1\Delta I_d(s) + c_2\Delta I_q(s) + c_3\Delta I_f(s) + c_4\Delta I_{kd}(s) + c_5\Delta I_{kq}(s) \tag{10}$$

where,

$$c_1 = \left[(L_d - L_q) i_{q0} - L_{mq} i_{kq0}\right] \tag{11a}$$

$$c_2 = \left[(L_d - L_q) i_{d0} + L_{md} i_{kd0} + L_{md} i_{f0}\right] \tag{11b}$$

$$c_3 = L_{md} i_{q0} \tag{11c}$$

$$c_4 = L_{md} i_{q0} \tag{11d}$$

$$c_5 = -L_{mq} i_{d0} \tag{11e}$$

The small perturbation model of the transformed voltage balance equations of F-coil, KD-coil and KQ are expressed as:

$$0 = \Delta U_f(s) = R_f\Delta I_f(s) + sL_{ff}\Delta I_f(s) + sL_{md}\Delta I_d(s) + sL_{md}\Delta I_{kd}(s) \tag{12}$$

$$0 = \Delta U_{kd}(s) = R_{kd}\Delta I_{kd}(s) + sL_{kkd}\Delta I_{kd}(s) + sL_{md}\Delta I_d(s) + sL_{md}\Delta I_f(s) \tag{13}$$

$$0 = \Delta U_{kq}(s) = R_{kq}\Delta I_{kq}(s) + sL_{kkq}\Delta I_{kq}(s) + sL_{mq}\Delta I_q(s) \tag{14}$$

As the damper winding on d-axis and q-axis are short-circuited within themselves, ΔU_{kd}=0 and Δu_{kq} = 0. So in transformed version $\Delta u_{kd}(s)$ = 0 and $\Delta u_{kq}(s)$ = 0 as shown in Eq. 13 and 14. Furthermore in general, the voltage fed to the field winding is fixed. That is why Δu_f (s) = 0 as shown in Eq. 12.

From Eq. 12 and 13 it yields:

$$\Delta I_f(s)=\left(\frac{s^2(L_{md}{}^2-L_{md}L_{kkd})-sL_{md}R_{kd}}{s^2(L_{kkd}L_{ff}-L_{md}{}^2)+s\,(L_{kkd}R_f+R_{kd}L_{ff})+R_{kd}R_f}\right)\Delta I_d(s)$$
$$=\left(\frac{a_1s^2+a_2s}{D(s)}\right)\Delta I_d(s) \tag{15}$$

where,

$$a_1=L_{md}{}^2-L_{md}L_{kkd} \tag{16a}$$

$$a_2=-L_{md}R_{kd} \tag{16b}$$

$$D(s)=b_1s^2+b_2s+b_3 \tag{16c}$$

$$b_1=L_{kkd}L_{ff}-\ L_{md}{}^2 \tag{16d}$$

$$b_2=L_{kkd}R_f+\ R_{kd}L_{ff} \tag{16f}$$

$$b_3=R_{kd}R_f \tag{16g}$$

Similarly Eq. 12 and 13 yields:

$$\Delta I_{kd}(s)=\left(\frac{s^2(L_{md}{}^2-L_{md}L_{ff})-sL_{md}R_f}{s^2(L_{kkd}L_{ff}-L_{md}{}^2)+s\,(L_{kkd}R_f+R_{kd}L_{ff})+R_{kd}R_f}\right)\Delta I_d(s)$$
$$=\left(\frac{d_1s^2+d_2s}{D(s)}\right)\Delta I_d(s) \tag{17}$$

where,

$$d_1=(L_{md}{}^2-L_{md}\,L_{ff}) \tag{18a}$$

$$d_2=(L_{md}\,R_f-L_{md}\,R_f) \tag{18b}$$

From Eq. 14 it is obtained:

$$\Delta I_{kq}(s)=\left(\frac{-sL_{mq}}{R_{kq}+sL_{kkq}}\right)\Delta I_q(s)$$
$$=\left(\frac{e_1s}{Q(s)}\right)\Delta I_q(s) \tag{19}$$

where,

$$e_1 = -L_{mq} \tag{20a}$$

$$Q\ (S) = f_1 s + f_2 \tag{20b}$$

$$f_1 = L_{kkq} \tag{20c}$$

$$f_2 = R_{kq} \tag{20d}$$

Substituting Eq. 15, 17, 19 in Eq. 10, it yields:

$$\begin{aligned}\Delta T_e(s) &= c_1\Delta I_d(s) + c_2\Delta I_q(s) + c_3\left[\frac{a_1 s^2 + a_2 s}{D(s)}\right]\Delta I_d(s) + c_4\left[\frac{d_1 s^2 + d_2 s}{D(s)}\right]\Delta I_d(s) + c_5\left[\frac{e_1 s}{Q(s)}\right]\Delta I_q(s) \\ &= \left[c_1 + \frac{c_3 a_1 s^2 + c_3 a_2 s + c_4 d_1 s^2 + c_4 d_2 s}{D(s)}\right]\Delta I_d(s) + \left[c_2 + \frac{c_5 e_1 s}{Q(s)}\right]\Delta I_q(s)\end{aligned} \tag{21}$$

Equation 21 can be re expressed as:

$$\Delta T_e(s) = \left[\frac{(m_1 s^3 + m_2 s^2 + m_3 s + m_4)\Delta I_d(s) + (n_1 s^3 + n_2 s^2 + n_3 s + n_4)\Delta I_q(s)}{l_1 s^3 + l_2 s^2 + l_3 s + l_4}\right] \tag{22}$$

where,

$$m_1 = f_1 c_1 b_1 + c_3 a_1 f_1 + c_4 d_1 f_1 \tag{23a}$$

$$m_2 = c_1 f_1 b_2 + c_3 a_2 f_1 + c_4 d_2 f_1 + c_1 b_1 f_2 + c_3 a_1 f_2 + c_4 d_1 f_2 \tag{23b}$$

$$m_3 = c_1 b_2 f_2 + c_3 a_2 f_2 + c_4 d_2 f_2 + c_1 a_3 f_1 \tag{23c}$$

$$m_4 = c_1 b_3 f_2 \tag{23d}$$

$$n_1 = f_1 c_2 b_1 + c_5 e_1 b_1 \tag{23e}$$

$$n_2 = c_2 f_2 b_1 + c_2 f_1 b_2 + c_5 e_1 b_1 \tag{23f}$$

$$n_3 = c_2 f_2 b_2 + b_3 c_2 f_1 + b_3 c_5 e_1 \tag{23g}$$

$$n_4 = c_2 f_2 b_3 \tag{23h}$$

$$l_1 = b_1 f_1 \tag{23i}$$

$$l_2 = b_2 f_1 + b_1 f_2 \tag{23j}$$

$$l_3 = b_3f_1+b_2f_2 \tag{23k}$$

$$l_4 = b_3f_2 \tag{23l}$$

Substituting the expressions for Δi_d (s) and Δi_q (s) from Eq. 3 and 4 in Eq. 22 we have:

$$\Delta T_e\ (s) = \left[\frac{(m_1s^3+m_2s^2+m_3s+m_4)\ (-i_s \sin\beta_0\ (s)) + (n_1s^3+n_2s^2+n_3s+n_4)\ (i_s\cos\beta_0\ (s))}{l_1s^3+l_2s^2+l_3s+l_4}\right]\Delta\beta\ (s) \tag{24}$$

Equation 24 can be re-expressed as:

$$\Delta T_e\ (s) = \left[\frac{x_1s^3+x_2s^2+x_3s+x_4}{l_1s^3+l_2s^2+l_3s+l_4}\right]\Delta\beta\ (s) \tag{25}$$

where,

$$x_1 = n_1\ i_s \cos\ b_0 - m_1\ s_i \sin\ b_0 \tag{26a}$$

$$x_2 = n_2\ i_s \cos\ b_0 - m_2\ i_s \sin\ b_0 \tag{26b}$$

$$x_3 = n_3\ i_s \cos\ b_0 - m_3\ i_s \sin\ b_0 \tag{26c}$$

$$x_4 = n_4\ i_s \cos\ b_0 - m_4\ i_s \sin\ b_0 \tag{26d}$$

The torque dynamic equation of a synchronous motor can be written as:

$$T_e - T_L = J\frac{d\omega}{dt} \tag{27}$$

where, ω = motor speed in mechanical rad sec^{-1}. J = polar moment of inertia of motor and load (combined). The small change in speed 'ω' equal to $\Delta\omega$ can be related to small change in field angle, $\Delta\beta$ as given by:

$$\Delta\omega = -\frac{d\ (\Delta\beta)}{dt} \tag{28}$$

The negative sign in equation physically indicates a drop in speed (ω) due to increase in field angle (β).

Based on Eq. 28, the following expression can be written:

$$J\frac{d(\Delta\omega)}{dt} = J\frac{d}{dt}\left[-\frac{d}{dt}(\Delta\beta)\right] = -J\frac{d^2}{dt^2}(\Delta\beta) \tag{29}$$

The small-perturbation model of Eq. 27 can be written as:

$$\Delta T_e - \Delta T_L = J\frac{d\,(\Delta\omega)}{dt} \tag{30}$$

Combining Eq. 29 and 30, it yields:

$$\Delta T_e - \Delta T_L = -J\frac{d^2}{dt^2}(\Delta\beta) \tag{31}$$

The transformed version of Eq. 31 with initial condition relaxed, comes out to be:

$$T_e(s) - T_L(s) = -Js^2Db(s) \tag{32}$$

Substituting the expression for ΔT_e (s) from Eq. 25 in Eq. 32 we have:

$$\left[\frac{x_1s^3 + x_2s^2 + x_3s + x_4}{l_1s^3 + l_2s^2 + l_3s + l_4}\right]\Delta\beta\ (s) + Js^2\Delta\beta\ (s) = \Delta T_L\ (s) \tag{33}$$

Equation 33 gives, after manipulation, a transfer function T (s) expressed as:

$$T(s) = \frac{\Delta\beta\ (s)}{\Delta T_L(s)} = \frac{l_1s^3 + l_2s^2 + l_3s + l_4}{K_1s^5 + K_2s^4 + K_3s^3 + K_4s^2 + K_5s + K_6} \tag{34}$$

where,

$$K_1 = J\ l_1 \tag{35a}$$

$$K_2 = J\ l_2 \tag{35b}$$

$$K_3 = (J\ l_3 + x_1) \tag{35c}$$

$$K_4 = (J\ l_4 + x_2) \tag{35d}$$

$$K_5 = x_3 \tag{35e}$$

$$K_6 = x_4 \tag{35f}$$

The expression for:

$$\frac{\Delta\beta\ (s)}{\Delta T_L(s)}$$

in Eq. 34 gives a light in the direction of analysis of steady state stability criterion. In fact the denominator polynomial of right-hand side of Eq. 34, set to zero, becomes the characteristic equation. A Routh-Herwitz analysis of the characteristic equation will ultimately lead to the status of steady state stability. The detailed R-H analysis, considering a suitable example and the associated interpretation of the results are presented in the next section.

RESULTS

The denominator polynomial of the right hand side of Eq. 34 being set to zero, takes the form as given by:

$$K_1 s^5+K_2 s^4+K_3 s^3+K_4 s^2+K_5 s+K_6 = 0 \tag{36}$$

The Routh-Herwitz table for Eq. 36 is developed taking suitable values of the polynomial co-efficient (K_1 to K_6). The machine data based on which the K_1 to K_6 are calculated are presented in Appendix. The calculated values of K_1 to K_6 are as follows:

$$K_1 = 2.2871;\ K_2 = 0.3585;\ K_3 = 0.5577;\ K_4 = 0.0776;\ K_5 = 0.0023;\ K_6 = 2.419'10^{-6}$$

The coefficients of the first column of the R-H table do not show any change of sign. Therefore the steady state stability is assured.

Generally it is observed that at no-load, a synchronous motor without damper winding does not satisfy steady state stability criteria. At the no load condition with $\beta_0 = 0$, the transfer function expressed in Eq. 34 for a C.S.I. fed synchronous motor with damper winding is modified for the motor without damper winding as given by the expression:

$$\frac{\Delta\beta(s)}{\Delta T_L(s)} = \frac{1}{s^2 J + [L_{md} i_{f0} i_s + (L_{md} - L_{mq}) i_s^2]} \tag{37}$$

The denominator of the right hand side of the Eq. 37, being set to zero leads to a characteristic equation expressed as:

$$Js^2+C = 0 \tag{38}$$

where,

$$C = L_{md}\, i_{f0}\, i_s+(L_{md}-L_{mq})\, i_s^2 \tag{39}$$

Equation 39 clearly shows that the pair of roots of the characteristic equation are pure imaginary and complex conjugate. Such roots lead to a marginally stable or undamped system which does not clearly indicate the steady state stability criteria.

However, with damper winding considered and at no load ($\beta_0 = 0$), the denominator polynomial of the right hand side of the Eq. 34 being set to zero is made subjected to R-H. analysis. With the R-H table formed the 1st column coefficient of that table do not show any change in sign. This assures that at no load also, the motor satisfies the steady state stability criterion. The values of the coefficient K_1 to K_6 for no load condition are calculated based on the machine data which are also present in the Appendix. The calculated values of K_1 to K_6 for no load condition are as follows:

$$K_1 = 2.2871;\ K_2 = 0.3585;\ K_3 = 0.0421;\ K_4 = 0.0045;\ K_5 = 1.567'10^{-1};\ K_6 = 1.7'10^{-7}$$

DISCUSSION

From the study (Sergelen, 2007) we can observe that the study deals with the mathematical model of a synchronous motor energized through a power electronic converter and ultimately develops simulation results of time response of phase currents/phase voltages and motor speed. (This results are not in line with the results submitted in the present study because the objectives are different. However, a very good similarity is observed involving the fact that the study uses u-i relations and generalized torque equations in the primitive machine model and the same type of equations have also been used as a part of problem formulation in the present study.

Another comparison of the present study has been carried with Najafi and Kar (2007). In this study the main similarity lies in the method of modeling using voltage balance equations in the d-q model. As such there is no similarity in the results presented in the study, "Effect of Short-Circuit Voltage Profile on the Transient Performance of Saturated Permanent Magnet Synchronous Motors" and the present study. However, a minute observation on the literature on that study clearly indicates that the transient response on the performance figure takes torque angle, phase currents etc can lead to specific inference on stability criteria. Though the present study deals with the steady state stability analysis of a three phase synchronous motor the said similarity appears to be important as it falls in the broad category of stability studies on synchronous motors.

The results presented in the study, are similar as by the study of Kondo and Matsuoka (2007) uses block diagram approach for stability analysis of a permanent magnet Synchronous Motors for Railway Vehicle Traction in the Sudden Line Voltage Change and the formulation presented in the present study can easily lead to block diagram modeling in 'S' domain. Secondly both the studies are ultimately interested in the stability analysis but have some dissimilarity existing because the motor used in their work is permanent magnet synchronous motor and the study presented here uses synchronous motor consisting of physical field winding system. As a third aspect it is observed that, the study uses the concept of real part of the Eigen values to be negative for the assessment of the stability and the study presented here uses the same concept for stability assessment but in a slightly different form, that is on relative stability criteria based on Routh-Herwitz array.

The well known research study by Siemon *et al.* (1974) clearly indicates that the small perturbation model can be applied to a synchronous motor drive with current source inverter (the motor being without damper winding) for determination of steady state stability criteria. This particular study is in contrast of the proposed study because the authors of the present study have considered a synchronous motor with damper winding.

Jong *et al.* (2004) had drawn the attention to the authors of the present study. This study involves the stability improvement of a V/f controlled PWM inverter fed Induction motor using a dynamic current compensator. This particular study has been considered in contrast of the proposed study because induction motor can be treated as a singly excited magnetic field system where as synchronous motor considered by the authors of the present study can be treated as a multiple excited magnetic field system. Hence the opposition in the research philosophy is clearly observed.

The study of Tanneru *et al.* (2007) is related to induction motor as a component of the power system and transient modeling for such motor leading to the assessment of transient stability has been considered as the objective of the above study. This literature review is in contrast of the study carried by Tanneru *et al.* (2007) does not involve any analysis related to steady state stability criteria but it is clear that the model associated with the dynamics of Induction motor can be easily modified to be used in determination of the steady state stability criteria of the system.

CONCLUSIONS

This study highlights the following salient concluding points:

- The transfer function expressed in Eq. 34 has been developed in more general form such that the transfer function for no load condition can be derived from Eq. 34 directly just by substituting suitable marginal condition
- Statements similar to above are generally valid for the case of derivation of transfer function for a C.S.I. fed synchronous motor without damper winding

APPENDIX

List of symbols:

i_d = Current in the D coil in p.u.
i_q = Current in the Q coil in p.u.
i_f = Current in the F coil in p.u.
i_{kd} = Current in the d axis damper coil (KD) in p.u.
i_{kq} = Current in the q axis damper coil (KQ) in p.u.
L_d = Self-inductance of D coil in p.u.
L_q = Self-inductance of Q coil in p.u.
L_{md} = Mutual inductance along d axis in p.u.
L_{mq} = Mutual inductance along q axis in p.u.
L_{ff} = Self-inductance of F (field) coil in p.u
R_f = Resistance of the F (field) coil in p.u.
L_{kd} = Self-inductance of the KD coil in p.u.
R_{kd} = Resistance of the KD coil in p.u
L_{kq} = Self-inductance of the KQ coil in p.u.
R_{kq} = Resistance of the KQ coil in p.u
β = Angle between the field (rotor) m.m.f. axis and armature (stator) m.m.f. axis

The machine data:

J = 8 p.u.
L_d = 1.17 p.u.
L_{md} = 1.03 p.u.
L_q = 0.75 p.u.
L_{mq} = 0.61 p.u.
L_{kkd} = 1.122 p.u.
L_{kkq} = 0.725 p.u.
L_{ff} = 1.297 p.u.
R_{kd} = 0.03 p.u.
R_{kq} = 0.039 p.u.
R_f = 0.0015 p.u.

When machine is at load:

i_s = 1 p.u.
i_{f0} = 0.97 p.u.

i_{kd0} = 0 p.u.
i_{kq0} = 0 p.u.
β_0 = 10^0

When machine is at no load:

i_s = 0.1 p.u.
i_{f0} = 0.9 p.u.
i_{kd0} = 0 p.u.
i_{kq0} = 0 p.u.
β_0 = 0^0

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