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Performance Analysis of Hydro-generator Operating at Synchronous Mode

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Abstract: This paper presents the analysis of hydro-generator (synchronous machine). The dynamic and steady state equations of synchronous machines were analyzed. Synchronous machine operates with speed above synchronous speed. It was shown that as given in motoring convention, electromagnetic torque, T_{em} of synchronous machine is positive for motoring and negative for generating since the value of rotor angle, δ as defined, is positive for generating and negative for motoring. From the simulation results, it was shown that synchronous machines require excitation for its operation. Also, the simulation is used to determine the operational characteristics and parameter variation of a hydro-generator.

Keywords: Hydro-generator, excitation, operational characteristics, motoring convention, parameter variation.

1.0 Introduction

Synchronous machines operating on general power supply networks are hydro generators, turbo generators, engine driven generators, and motors.

The synchronous generators driven by water turbines are known as hydro-generator. The have ratings up to 750MH and are driven at speeds ranging from 100 to 1000 rpm [1-3].

The constructional features of hydro-generators are dependent upon the mechanical considerations which depend upon the speed of the machine. The hydro- generators are low speed machines, the speed depending upon the available head and the type of turbine used. The low speed demands a multi-polar construction and consequently a large diameter which may present transport problem[4,5]. The two major parts of synchronous machine are armature and field system. The stator core of synchronous generator is built up of laminations in order reduce eddy current iron loss. The loss in the laminated core is usually the largest singe loss in a hydro-generator and therefore the design of stator core particularly the choice of type and grade of steel is of utmost important. The stator winding of the entire synchronous generator is star connected with neutral earthed. This arrangement has the advantage that the winding has to be insulated to earth for the phase voltage and not the line voltage. Star connection also has the advantage that it eliminates all triple frequency harmonics from the line voltage. The salient poles are attached to the rotor body. The type of rotor used depends in general, on the peripheral speed. The body is machined with its shaft from a forging, built up from discs shrunk on a shaft, fabricated from a cast-steel spider mounted on the shaft and carrying laminar ring of segmental plates. The hydro-generator may have horizontal or vertical configuration. The alternators employed in conjunction with impulse turbines are usually of horizontal configuration while those employed with Francis and Kaplan turbines are of vertical configuration. Low speeds (about 50-100 rpm in case of vertical configuration and 100-1,000 rpm for the horizontal machines)[6]. The machines are usually of salient pole type and number of poles they consist of , varies from 6 – 120.

Synchronous machine can be operated by connecting exciter. The brushless excited synchronous motor is the most common type of exciter supplied today for use with synch ronous motors, requiring no brushes or collector ring maintenance[7,8].

The exciter is physically direct-connected to motor shaft. The brushless exciter has a three phase ac armature winding. The stationary field winding is on poles on the stator and is connected to an excitation supply source. The generated ac current is directly connected along the shaft to a rotating three-phase diode wheel, where ac is rectified to dc before going to the motor's main field. The magnitude of the motor field current is adjusted by changing the current to the stationary exciter field by a dc source.

By operating synchronous motor with leading power factor, the overall system power factor can be shifted towards unity. The power factor of a synchronous motor can be controlled by varying the amount of excitation current delivered to the motor field during operation [9]. As the dc field excitation is increased, the power factor of the motor load, as measured at motor terminal, becomes more leading as the over-excited synchronous motor produces vars. If the excitation is decreased, the power factor of the motor shifts toward lagging, and the motor will import var from the system.

To take full advantage of the synchronous motor, it is necessary to have an excitation system that will maintain constant power factor regardless of load and ac supply variation controller. Today's excitation systems are designed with features to help improve the quality of machine control. Some digital controller was specified by the engineering consultant with the following features: power-factor controller, under excitation limiting, overexcitation limiting, manual control[10].

The automatic control eliminates the concern with an ac supply variation to the excitation system that could otherwise result in pole slip due to too little excitation system for the motor field. Additionally, digital systems are equipped with safeguards to prevent pole slip from occurring. These include: field forcing margins, underexcitation limiting, overexcitation limiting.

Field forcing provides a means to maintain constant voltage into the field, even when the supply voltage drops as much 30-40%. Hence, if the field voltage required by motor were 100v dc at 0.9 power factor lead, and digital controller were selected to provide 150vdc maximum ceiling voltage, the digital controller would be able to 100 vdc to the field even if the supply voltage into the controller were to drop 50%. The additional margin could mean the difference between continue process control or a machine trip and plant outage.

Digital controllers also are equipped with unde-rexcitation limiters. These devices have always been popular for generators but also practical for synchronous motors using digital controllers. The underexcitation limiter monitors the kilowatts into the synchronous machine as compared to kilovars being supplied [11]. Should the kilovars drops below acceptable levels needed to maintain synchronism, the uderexcitation limiter will cause increase in excitation to prevent a machine trip.

2.1 Mathematical Model of Synchronous Machine

Before we derive the mathematical equations of the circuit model shown in Figure 3.10 let's take a brief look at the variation of inductances with rotor positions. In general, the permeances along the d- and q-axes are the same. Whereas the mmfs of the rotor windings are always directed along the d- or q-axes, the direction of the resultant mmf of the stator windings relative to these two axes will vary with the power factor. A common approach to handling the magne tic effect of the stator's resultant mmf is to resolve it along the d- and q-axes, where it could be dealt with systematically[12-16]. For example, let's consider the magnetic effect of just the a-phase current flowing in the stator. As shown in Figure 3.11, the resolved components of the a-phase mmf, F_a, produce the flux components, $\varphi_d = P_d F_a \sin e\theta_r \; and \; \emptyset_q = P_q F_a \cos\theta_r$ along the d- and q-axes, respectively.

The linkage of these resolve flux components with a $a - phase$ winding is

$$\lambda_{aa} = N_s(\phi_d \sin\theta_r + P_q \cos\theta_r) \qquad Wb.turn$$

$$= N_s F_a (P_d \sin^2\theta_r + P_q \cos^2\theta_r)$$

$$= N_s F_a \left(\frac{P_d + P_q}{2} - \frac{P_d - P_q}{2} \cos 2\theta_r \right) \qquad (1)$$

The above expression of λ_{aa} is of the form A – B $\cos 2\theta_r$.

Similarly, the linkage of the flux components, $\phi_d \; and \; \phi_q$, by the b-phase winding that is $2\pi/3$ ahead may be written as

$$\lambda_{aa} \; N_s F_a \left\{ P_d \sin\theta_r \sin\left(\theta_r - \frac{2\pi}{3}\right) + P_q \cos\theta_r \cos\left(\theta_r - \frac{2\pi}{3}\right) \right\} \quad Wb.turn$$

The expression of the mutual flux linkage, λ_{ba} , is of the

$$= N_s F \left\{ -\frac{P_d + P_q}{4} - \frac{P_d - P_q}{2} \cos 2\left(\theta_r - \frac{\pi}{3}\right) \right\} \qquad (2)$$

form

$$-(A/2) - B\cos 2\left(\theta_r - \frac{\pi}{3}\right).$$

The magnitude of its second harmonic component in θ_r is the same as that of λ_{aa}, but the constant part is half that of λ_{aa}.

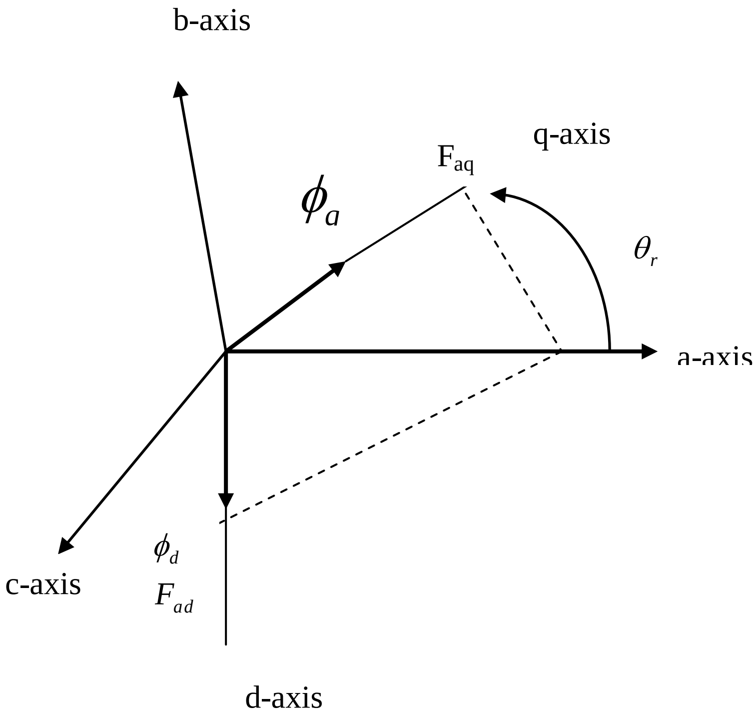

Figure 1: Mmf components along dq axes

Based on the functional relationship of λ_{aa} with the rotor angle, θ_r, we can deduce that the self-inductance of the stator $a - phase$ winding, excluding the leakage, has the form

$$L_{ab} = L_o - L_{ms} \cos 2\theta_r \qquad H \qquad (3)$$

Those of the b- and c-phases, L_{bb} and L_{cc}, are similar to that of L_{aa} but with θ_r replaced by $\left(\theta_r - \frac{2\pi}{3}\right)$ *and* $\left(\theta_r - \frac{4\pi}{3}\right)$, respectively.

$$L_{ab} = L_{ba} = -\frac{L_0}{2} - L_{ms} \cos 2\left(\theta_r - \frac{\pi}{3}\right) \quad H \qquad (4)$$

Similarly, we can deduce from equation 42 that the mutual inductance between the a and b-phases of the stator is of the form.

$$L_{ab} = L_{ba} = -\frac{L_0}{2} - L_{ms} \cos 2(\theta_r) \quad H \qquad (4)$$

Similar expressions for L_{bc} *and* L_{cc} can be obtained by replacing θ_r in equation 5 with $(\theta_r - \frac{2\pi}{3})$ *and* $(\theta_r - \frac{4\pi}{3})$, respectively.

The voltage equation for the stator and rotor windings can be arranged into the form.

$$\begin{bmatrix} v_s \\ v_r \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_r \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix} \qquad v \qquad (4)$$

Where

$$v_s = (v_a, v_b, v_c)^t$$
$$v_r = (v_f, v_{kd}, v_g, v_{kq})^t$$
$$i_s = (i_a \ i_b \ i_c)^t$$
$$i_r = (i_f \ i_{kd} \ i_g \ i_{kq})^t$$
$$r_s = diag \ (r_a \ r_b \ r_c)$$
$$r_r = dia\,g \ (r_f \ r_{kd} \ i_g \ r_{kq})$$
$$\lambda_s = (\lambda_a, \lambda_b, \lambda_c)^t$$
$$\lambda_r = (\lambda_f, \lambda_{kd}, \lambda_g, \lambda_{kq})^t$$

The symbols of the per phase parameters are as follows:

r_s	armature of stator winding resistance
r_f	d-axis field winding resistance
r_g	q-axis field winding resistance
r_{kd}	d-axis damper winding resistance
r_{kq}	q-axis damper winding resistance
L_{ls}	armature or stator winding leakage inductance
L_{lf}	d-axis field winding leakage inductance
L_{lp}	q-axis field winding leakage inductance
L_{lkd}	d-axis damper winding leakage inductance
L_{lkq}	q-axis damper winding leakage inductance
L_{md}	d-axis stator magnetizing inductance
L_{mq}	q-axis stator magnetizing inductance
L_{mf}	d-axis field winding magnetizing inductance
L_{mg}	q-axis field winding magnetizing inductance
L_{mkd}	d-axis damper winding magnetizing inductance
L_{mkq}	q-axis damper winding magnetizing inductance

The equations for the flux linkages of the stator and rotor windings can be expressed as

$$\lambda_s = L_{ss} i_s + L_{sr} i_r \qquad Wb.turn$$
$$\lambda_r = [L_{sr}]^t i_s + L_r i_r \tag{7}$$

Where

$$L_{ss} = \begin{bmatrix} L_{ls} + L_0 - L_{ms}\cos 2\theta_r, & -\frac{1}{2}L_0 - L_{ms}\cos 2\left(\theta_r - \frac{\pi}{3}\right) & -\frac{1}{2}L_0 - L_{ms}\cos 2\left(\theta_r + \frac{\pi}{3}\right) \\ -\frac{1}{2}L_0 - L_{ms}\cos 2\left(\theta_r - \frac{\pi}{3}\right) & L_{ls} - L_0 - L_{ms}\cos 2\left(\theta_r - \frac{2\pi}{3}\right) & -\frac{1}{2}L_0 - L_{ms}\cos 2(\theta_r - \pi) \\ -\frac{1}{2}L_0 L_{ms}\cos 2\left(\theta_r + \frac{\pi}{3}\right) & -\frac{1}{2}L_0 - L_{ms}\cos 2(\theta_r + \pi) & L_{ls} + L_0 - L_{ms}\cos 2\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \tag{8}$$

$$L_{rr} = \begin{bmatrix} L_{lf} + L_{mf} & L_{f\,kd} & 0 & 0 \\ L_{kdf} & L_{l\,kd} + L_{mkd} & 0 & 0 \\ 0 & 0 & L_{lg} + L_{mg} & L_{gkq} \\ 0 & 0 & L_{kqg} & L_{kqg} + L_{mkq} \end{bmatrix} \tag{9}$$

$$L_{sr} = \begin{bmatrix} L_{sf}\sin\theta_r & L_{skd}\sin\theta_r & L_{sg}\cos\theta_r & L_{skq}\cos\theta_r \\ L_s\sin\left(\theta_r-\frac{2\pi}{3}\right) & L_{skd}\cos\left(\theta_r-\frac{2\pi}{3}\right) & L_{sg}\cos\left(\theta_r-\frac{2\pi}{3}\right) & L_{skq}\left(\theta_r-\frac{2\pi}{3}\right) \\ L_{sf}\sin\left(\theta_r-\frac{2\pi}{3}\right) & L_{skd}\sin\left(\theta_r+\frac{2\pi}{3}\right) & L_{sg}\cos\left(\theta_r+\frac{2\pi}{3}\right) & L_{skq}\cos\left(\theta_r+\frac{2\pi}{3}\right) \end{bmatrix} \quad (10)$$

2.2 Transformation to the Rotor's *qd0* Reference Frame

When the stator quantities are transformed to a *qd0* reference frame it is attached to the machine's rotor, the resulting voltage equation has time-invariant coefficients. In the idealized machine, the axes of the rotor windings are already along the q- and d-axis, and the qd0 transformation need only be applied to the stator winding quantities. In vector notation, we define the augmented transformation matrix:

$$C = \begin{bmatrix} T_{qd0}(\theta_r) & 0 \\ 0 & U \end{bmatrix} \quad (11)$$

Where U is a unit matrix and

$$T_{qd}0(\theta_r) = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos\left(\theta_r-\frac{2\pi}{3}\right) & \cos\left(\theta_r+\frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r-\frac{2\pi}{3}\right) & \sin\left(\theta_r+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (12)$$

For convenience, we will denote the transformed *qd0* voltages, and flux linkages of the stator, that are

$$\left.\begin{aligned} v_{qd0} &= T_{qd0}(\theta_r)v_s \\ i_{qd0} &= T_{qd0}(\theta_r)i_s \\ \lambda_{qd0} &= T_{qd0}(\theta_r)\lambda_s \end{aligned}\right\} \quad (13)$$

$$\left.\begin{aligned} v_{qd0} &= \left[v_q, v_d, v_0\right]^t \\ i_{qd0} &= \left[i_q, i_d, i_0\right]^t \\ \lambda_{qd0} &= \left[\lambda_q, \lambda_d, \lambda_0\right]^t \end{aligned}\right\} \quad (14)$$

Applying the transformation $T_{qd0}(\theta_r)$ to only the stator quantities in equation 46, the stator voltage equations become

$$V_{qd0} = T_{qd0}r_sT_{qd0}^{-1}i_{qd0} + T_{qd0}\frac{d}{dt}T_{qd0}^{-1}\lambda_{qd0} \quad (15)$$

If $r_a = r_b = r_c = r_s$, the resistive drop term in the above equation reduces to

$$T_{qd0}r_sT_{qd0}^{-1}i_{qd0} = r_si_{qd0} \quad (16)$$

The second term on the right side of equation. 15 can be expanded as follows:

$$T_{qd0}\frac{d}{dt}T_{qd0}^{-1}\lambda_{qd0} = T_{qd0}\left[\left(\frac{d}{dt}T_{qd0}^{-1}\right)\lambda_{qd0} + T_{qd0}^{-1}\frac{d}{dt}\lambda_{qd0}\right] \quad (17)$$

Substituting in the transformation matrix from equation 12 and simplifying, we can show that

$$\frac{d}{dt}T_{qd0}^{-1}\lambda_{qd0} = \omega_r\begin{bmatrix} -\sin & \cos\theta_r & 0 \\ -\sin\left(\theta_r-\frac{2\pi}{3}\right) & \cos\left(\theta_r-\frac{2\pi}{3}\right) & 0 \\ -\sin\left(\theta_r+\frac{2\pi}{3}\right) & \cos\left(\theta_r+\frac{2\pi}{3}\right) & 0 \end{bmatrix}\lambda_{qd0}$$

and that

$$T_{qd0}\left[\frac{d}{dt}T_{qd0}^{-1}\right]\lambda_{qd0}=\omega_r\begin{bmatrix}0 & 1 & 0\\ -1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\lambda_{qd0}$$

Where ω_r denotes $d\theta_r / dt$ in electrical radians/sec.
Also,

$$T_{qd0}T_{qd0}^{-1}\frac{d}{dt}\lambda_{qd0}=\frac{d}{dt}\lambda_{qd0}$$

Back-substituting these results into equation 11 the stator voltage equations of the idealized synchronous machine in its own rotor dq reference frame simplifies to

$$v_{qd0}=r_s i_{qd0}+\omega_r\begin{bmatrix}0 & 1 & 0\\ -1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\lambda_{qd0}+\frac{d}{dt}\lambda_{qd0}$$

3.10.2 Flux Linkages in Terms of Winding Currents

The corresponding relationship between flux linkage λ_{qd0} and qd0 current can be obtained by transforming only the stator quantities, that is

$$\lambda_{qd0}=T_{qd0}L_{ss}T_{qd0}^{-1}i_{qd0}+T_{qd0}L_{sr}i_r \quad Wb.\ turn \qquad (18)$$

Equation 18 yields the following expressions for the stator $qd0$ flux linkages in which all the inductances shown are independent of the rotor angle, θ_r :

$$\left.\begin{aligned}\lambda_q &= \left\{L_{ls}+\frac{3}{2}(L_0-L_{ms})\right\}i_q+L_{sg}i_g+L_{skq}ikg\\ \lambda_d &= \left\{L_{ls}+\frac{3}{2}(L_0+L_{ms})\right\}i_d+Ls_{fd}+L_{skd}i_{kd}\\ \lambda_0 &= L_{1s}1\end{aligned}\right\} \qquad (19)$$

With the chosen rotor dq reference frame, the rotor winding variables need no rotational transformation. The expression for the flux linkages of the rotor winding are

$$\left.\begin{aligned}\lambda_f &= \frac{3}{2}L_{sf}i_d+L_{ff}i_f+L_{fkd}i_{kd}\\ \lambda_{kd} &= \frac{3}{2}L_{skd}i_q+L_{fkd}i_f+L_{kdkd}i_{kd}\\ \lambda_g &= \frac{3}{2}L_{sg}i_q+L_{gg}i_g+L_{gkq}i_{kq}\\ \lambda_{kd} &= \frac{3}{2}L_{skq}i_q+L_{gkq}i_g+L_{kqkq}i_{kq}\end{aligned}\right\} \qquad (2)$$

2.3 Referring Rotor Quantities to the Stator

Observe that the terms in equation 20 associated with the stator current components, i_d *and* i_q, have a 3/2 factor which will render the inductance coefficient matrices for the d- and q-axis windings non-symmetric when equations of equation 20 are combined with those of equation 19. Replacing the actual currents of the rotor windings by the following equivalent rotor currents will result in flux linkage equations with symmetric inductance coefficient matrices:

$$\left.\begin{aligned}i_f &= \frac{2}{3}i_f\\ i_{kd} &= \frac{2}{3}i_{kd}\\ i_g &= \frac{2}{3}i_g\\ i_{kq} &= \frac{2}{3}i_{kq}\end{aligned}\right\} \qquad (21)$$

Denoting the equivalent magnetizing inductances of the d- and q-axes stator windings in equation 20 by L_{md} *and* L_{mq} *that is*

$$L_{md} = \frac{3}{2}(L_0 + L_{ms}) = \frac{3}{2}\left\{N_5^2 \frac{P_d + P_q}{2} - N_5^2 \frac{P_d - P_q}{2}\right\} = \frac{3}{2} N_5^2 P_d \qquad (22)$$

and

$$L_{mq} = \frac{3}{2}(L_0 - L_{ms}) = \frac{3}{2} N_s^2 P_q \qquad (23)$$

Expressing the stator and rotor flux linkages in terms of the equivalent rotor currents and magnetizing inductances given by equations 60 through

$$\left.\begin{aligned}
\lambda_q &= (L_{1s} + L_{mq})i_q + \frac{3}{2}L_{sg}i_g + \frac{3}{2}L_{skq}i_{kq} \\
\lambda_d &= (L_{ls} + L_{md})i_d + \frac{3}{2}L_{sf}i_f + \frac{3}{2}L_{sk}i_{kd} \\
\lambda_0 &= L_{ls}i_0 \\
\lambda_f &= \frac{3}{2}L_{sf}i_d + \frac{3}{2}(L_{lf} + L_{mf})i_f + \frac{3}{2}L_{fkd}i_{kd} \\
\lambda_{kd} &= \frac{3}{2}L_{skd}i_d + \frac{3}{2}L_{fkd}i_f + \frac{3}{2}(L_{lkd} + L_{mkd})i_{kd} \\
\lambda_g &= \frac{3}{2}L_{sg}i_q + \frac{3}{2}(L_{lg} + L_{mg})i_g + \frac{3}{2}L_{gkq}i_{kq} \\
\lambda_{kq} &= \frac{3}{2}L_{skq}i_q + \frac{3}{2}L_{gkq}i_g + \frac{3}{2}(L_{lkq} + L_{mkq})i_{kq}
\end{aligned}\right\} \qquad (24)$$

Referring the rotor quantities to the stator using the appropriate turns ratios, denoting the equivalent rotor currents referred to the stator by a prime superscript:

$$\left.\begin{aligned}
i_f' &= \frac{N_f}{N_s}i_f = \frac{2}{3}\frac{N_f}{N_s}i_f \\
i_{kd}' &= \frac{N_{kd}}{N_s}i_{kd} = \frac{2}{3}\frac{N_{kd}}{N_s}i_{kd} \\
i_{kq}' &= \frac{N_{kq}}{N_s}i_{kq} = \frac{2}{3}\frac{N_{kq}}{N_s}i_{kq}
\end{aligned}\right\} \qquad (25)$$

$$v_f' = \frac{N_s}{N_f} v_f \qquad v_{kd}' = \frac{N_s}{N_{kd}} v_{kd}$$

$$v_g' = \frac{N_s}{N_f} v_g \qquad v_{kq}' = \frac{N_s}{N_{kq}} v_{kq} \qquad (26)$$

$$\lambda_f' = \frac{N_s}{N_f} \lambda_f \qquad \lambda_{kd}' = \frac{N_s}{N_{kd}} \lambda_{kd}$$

$$\lambda_g' = \frac{N_s}{N_g} \lambda_g \qquad \lambda_{kd}' = \frac{N_s}{N_{kq}} \lambda_{kd} \qquad (27)$$

$$r_f' = \frac{3}{2}\left(\frac{N_s}{N_f}\right)^2 rf \qquad r_{kq}' = \frac{3}{2}\left(\frac{N_s}{N_{kd}}\right)^2 r_{kd}$$

$$r_g' = \frac{3}{2}\left(\frac{N_s}{N_g}\right)^2 r_g \qquad r_{kq}' = \frac{3}{2}\left(\frac{N_s}{N_{kq}}\right)^2 r_{kq} \qquad (28)$$

The winding inductances can be expressed as

$$L_{sf} = N_s N_f P_d = \frac{2}{3}\frac{N_f}{N_s} L_{md} \qquad L_{skd} = N_s N_{kd} P_d = \frac{2}{3}\frac{N_{kd}}{N_s} L_{md}$$

$$L_{sg} = N_s N_g P_q = \frac{2}{3}\frac{N_g}{N_s} L_{mq} \qquad L_{skq} = N_s N_{kd} P_q = \frac{2}{3}\frac{N_{kq}}{N_s} L_{mq}$$

$$L_{ff}' = \frac{3}{2}\left(\frac{N_s}{N_f}\right)^2 L_{lf} + L_{md} \qquad L_{mf} = N_f^2 P_d = \frac{2}{3}\left(\frac{N_f}{N_s}\right)^2 L_{md}$$

$$L_{kdkd}' \frac{3}{2}\left(\frac{N_s}{N_{kd}}\right)^2 L_{lkd} + L_{md} \qquad L_{mkd} = N_{kd}^2 P_d = \frac{2}{3}\left(\frac{N_{kd}}{N_s}\right)^2 L_{md} \qquad (29)$$

$$L_{fkd} = N_f N_{kd} P_d = \frac{2}{3}\left(\frac{N_f N_{kd}}{N_s^2}\right) L_{md} \qquad L_{gkq} = N_g N_{kq} P_q = \frac{2}{3}\left(\frac{N_g N_{kq}}{N_s^2}\right) L_{mq}$$

$$L_{gg}' = \frac{3}{2}\left(\frac{N_s}{N_g}\right)^2 L_{lg} + L_{mq} \qquad L_{mg} = N_g^2 P_q = \frac{2}{3}\left(\frac{N_g}{N_s}\right)^2 L_{mq}$$

$$L_{kqkq}' = \frac{3}{2}\left(\frac{N_s}{N_{kq}}\right)^2 L_{lkq} + L_{mq} \qquad L_{mkq} = N_{kq}^2 P_q = \frac{2}{3}\left(\frac{N_{kq}}{N_s}\right)^2 L_m$$

In using the values of L_{md} *and* L_{mq} as the common mutual inductances on the d-axis and q-axis circuits, we have essentially defined their corresponding fluxes as the mutual fluxes in these axes; any additional flux linked by a current is considered a leakage component in the corresponding current path. Traditionally, the sums, $(L_{md} + L_{ls})$ *and* $(L_{mq} + L_{ls})$, are referred to the d-axis and q-axis synchronous inductance, respectively. That is

$$L_d = L_{md} + L_{ls}$$
$$L_q = L_{mq} + L_{ls} \qquad (30)$$

2.4 Voltage Equations in the Rotor's $qd0$ Reference Frame

A summary of the winding equations for the synchronous machine in the rotor's qd reference frame with all rotor quantities referred to the stator is given below:

$$
\left.
\begin{aligned}
v_q &= r_s i_q + \frac{d\lambda_q}{dt} + \lambda_d \frac{d\theta_r}{dt} \quad v \\
v_d &= r_s i_d + \frac{d\lambda_d}{dt} - \lambda_q \frac{d\theta_r}{dt} \\
v_0 &= r_s i_0 + \frac{d\lambda_0}{dt} \\
v_f^{'} &= r_f^{'} i_f^{'} + \frac{d\lambda_f^{'}}{dt} \\
v_{kd}^{'} &= r_{kd}^{'} i_{kd}^{'} + \frac{d\lambda_{kd}^{'}}{dt} \\
v_g^{'} &= r_g^{'} i_g^{'} + \frac{d\lambda_g^{'}}{dt} \\
v_{kq}^{'} &= r_{kq}^{'} i_{kq}^{'} + \frac{d\lambda_{kq}^{'}}{dt}
\end{aligned}
\right\} \quad (31)
$$

Where the flux linkages are given by

$$
\left.
\begin{aligned}
\lambda_q &= L_q i_q + L_{mq} i_g^{'} + L_{mq} i_{lq}^{'} \quad Wb.\ turn \\
\lambda_d &= L_d i_d + L_{md} i_f^{'} + L_{md} i_{kd}^{'} \\
\lambda_0 &= L_{ls} i_0 \\
\lambda_f^{'} &= L_{md} i_d + L_{md} i_{kd}^{'} + L_{ff}^{'} i_f^{'} \\
\lambda_{kd}^{'} &= L_{md} i_d + L_{md} i_f^{'} + L_{kdkd}^{'} i_{kd}^{'} \\
\lambda_g^{'} &= L_{mq} i_q = + L_{gg}^{'} i_g^{'} + L_{mq} i_{kq}^{'} \\
\lambda_{kq}^{'} &= L_{mq} i_q + L_{mq} i_g^{'} + L_{kqkq}^{'} i_{kq}^{'}
\end{aligned}
\right\} \quad (32)
$$

2.5 Steady-state Torque Expression

The total complex power into all three phases of the stator winding is given by

$$S = 3\left(\bar{V}_q - j\bar{V}_d\right)\left(\bar{I}_q - j\bar{I}_d\right)^{*} \quad VA \qquad (33)$$

The electromagnetic power developed by the machine is obtained by subtracting from the input real power the losses in the stator, which in this model is just the copper losses in the stator windings. Thus, subtracting $3\left(I_q^2 + I_d^2\right)r_s$ from the real part of the input power, the expression for electromagnetic power is

$$P_{em} = \Re\left[3\left(\omega_e L_d \bar{I}_d + \bar{E}_f + jw_e L_q \bar{I}_q\right)\left(\bar{I}_d + j\bar{I}_q\right)\right] \quad W$$

$$= 3\left\{E_f I_q + \omega_e\left(L_d - L_q\right) I_d I_q\right\} \qquad (34)$$

The expression for the electromagnetic torque developed by the machine is obtained by dividing the expression for the electromagnetic power by the actual rotor speed, that is

$$T_{em} = \frac{P_{em}}{\omega_{sm}} = \left(\frac{P}{2w_e}\right) \quad P_{em} \qquad N.m$$

$$= \ 3\left(\frac{P}{2w_e}\right) \ \left\{E_f I_q + \omega_e\left(L_d - L_q\right) I_d I_q\right\} \qquad (35)$$

The first torque component is the main torque component in a synchronous machine with field excitation. The second component is referred to as the reluctance torque component. It is present only when there is rotor saliency, that is $L_d \neq L_q$. Small three-phase reluctance motors are designed to operate on reluctance torque alone. They have simple and robust salient rotors that require no field excitation.

For large machines, where the resistive drop may be neglected such expressions for the electromagnetic power and torque can be reduce to

$$P_{em} = -3\left\{\frac{E_f V_a}{X_d}\sin\delta + \frac{V_a^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta\right\} \qquad W$$

$$T_{em} = -3\left(\frac{P}{2\omega_e}\right)\left\{\frac{E_f V_a}{X_d}\sin\delta + \frac{V_a^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta\right\} \quad N.m \qquad (36)$$

Where, V_a the rms value of the stator phase voltage, that is $V_m / \sqrt{2},\ \ X_d = \omega_e L_d$ is the $d-axis$ synchronous reactance and $X_q = \omega_e L_q$ is the q-axis synchronous reactance.

3.1 Equations for Simulation of Three-Phase Synchronous Machines

The winding equations of the synchronous machine model can be implemented in a simulation that uses voltages as input and currents as output. The main
inputs to the machine simulation are the stator *abc* phase voltages, the excitation voltage to the field windings, and the applied mechanical torque to the rotor.
The transformation from *abc* to *dq* rotor may be performed in a single step as shown below

$$v_q = \frac{2}{3}\left\{v_a\cos\theta_r(t) + v_b\cos\left(\theta_r(t) - \frac{2\pi}{3}\right) + \ v_c\cos\left(\theta_r(t) - \frac{4\pi}{3}\right)\right\}$$

$$v_q = \frac{2}{3}\left\{v_a\sin\theta_r(t) + \ v_b\sin\left(\theta_r(t) - \frac{2\pi}{3}\right) + v_c\sin\left(\theta_r(t) - \frac{4\pi}{3}\right)\right\} \qquad (37)$$

$$v_0 = \frac{1}{3}\left(v_a + v_b + v_c\right)$$

Expressing the *qd0* voltage equations as integral equations of the flux linkages of the windings, the above stator *qd0* voltages along with other inputs can then be used in the integral equations to solve for the flux linkages of the windings. For the case of a machine with only one field winding in the d-axis and a pair of damper windings in the d-and q-axis, the integral equations of the winding flux linkages are as follows:

$$\psi_q = \omega_b \int\left\{v_q - \frac{\omega_r}{\omega_b}\psi_d + \frac{r_s}{x_{ls}}\left(\psi_{mq} - \psi_q\right)\right\} dt \qquad Wb. \quad turn/s\ v$$

$$\psi_d = \omega_b \int\left\{v_d + \frac{\omega_r}{\omega_b}\psi_q + \frac{r_s}{x_{ls}}\left(\psi_{md} - \psi_d\right)\right\} dt$$

Where

$$\psi_0 = \omega_b \int\left(v_0 - \frac{r_s}{x_{ls}}\psi_0\right) dt \qquad (38)$$

$$\psi'_{kq} = \frac{\omega b r'_{kq}}{x'_{lkq}}\int\left(\psi_{mq} - \psi'_{kq}\right) dt$$

$$\psi'_{kq} = \frac{\omega b r'_{kd}}{x'_{lkd}}\int\left(\psi_{md} - \psi'_{kd}\right) dt$$

$$\left.\begin{aligned}
\psi_{mq} &= \omega_b L_{mq}\left(i_q + i_{kq}^{'}\right) \\
\psi_{md} &= \omega_b L_{md}\left(i_d + i_{kd}^{'} + i_f^{'}\right) \\
E_f &= x_{md}\frac{v_f^{'}}{r_f^{'}} \\
\psi_q &= x_{ls} i_q + \psi_{mq} \\
\psi_d &= x_{ls} i_d + \psi_{md} \\
\psi_0 &= x_{ls} i_0 \\
\psi_{kq}^{'} &= x_{lk}^{'} i_{kd}^{'} + \psi_{md} \\
\psi_{lq}^{'} &= x_{lkq}^{'} i_{kq}^{'} + \psi_{mq}
\end{aligned}\right\} \quad (39)$$

Note that the above equations are in motoring convention, that is with the currents, i_q and i_d, into the positive polarity of the stator windings' terminal voltages. As before, to handle the cut set of inductors in the q-axis circuits, we will express the mutual flux linkages terms of the total flux linkages of the windings as

$$\left.\begin{aligned}
\psi_{mq} &= xMQ\left(\frac{\psi_q}{x_{ls}} + \frac{\psi_{kq}^{'}}{x_{lkq}^{'}}\right) \\
\psi_{md} &= xMD\left(\frac{\psi_d}{x_{ls}} + \frac{\psi_{kd}^{'}}{x_{lkd}^{'}} + \frac{\psi_f^{'}}{x_{lf}^{'}}\right)
\end{aligned}\right\} \quad (40)$$

Where

$$\left.\begin{aligned}
\frac{1}{xMQ} &= \frac{1}{x_{mq}} + \frac{1}{x_{lkq}^{'}} + \frac{1}{x_{ls}} \\
\frac{1}{xMD} &= \frac{1}{x_{md}} + \frac{1}{x_{lkd}^{'}} + \frac{1}{x_{lf}^{'}} + \frac{1}{x_{ls}}
\end{aligned}\right\} (41)$$

Having the values of the flux linkages of the windings and those of the mutual flux linkages along the d- and q-axis, we can determine the winding currents using

$$\left.\begin{aligned}
i_q &= \frac{\psi_q - \psi_{mq}}{x_{ls}} \qquad A \\
i_d &= \frac{\psi_d - \psi_{md}}{x_{ls}} \\
i_{kd}^{'} &= \frac{\psi_{kd}^{'} - \psi_{md}}{x_{lkd}^{'}} \\
i_{kq}^{t} &= \frac{\psi_{kq}^{'} - \psi_{mq}}{x_{lf}^{'}} \\
i_f^{t} &= \frac{\psi_f^{'} - \psi_{md}}{x_{lf}^{'}}
\end{aligned}\right\} \quad (42)$$

The stator winding *qd* currents can be transformed back to *abc* winding currents using the following rotor to stationary *qd* and stationary *qd0* to *abc* transformations:

$$\left.\begin{aligned} i_q^s &= i_q \cos\theta_r(t) + i_d \sin\theta_r(t) \\ i_d^s &= -i_q \cos\theta_r(t) + i_d \sin\theta_r(t) \end{aligned}\right\} \quad (43)$$

$$\left.\begin{aligned} i_a &= i_q^s + i_0 \\ i_b &= -\frac{1}{2} i_q^s - \frac{1}{\sqrt{3}} i_d^s + i_0 \\ i_b &= -\frac{1}{2} i_q^s - \frac{1}{\sqrt{3}} i_d^s + i_0 \end{aligned}\right\} \quad (44)$$

3.2 Torque Expression

The electron mechanical torque developed by a machine with P-poles in motoring convention is

$$\left.\begin{aligned} T_{em} &= \frac{3}{2}\frac{p}{2}\left(\lambda_d i_q - \lambda_q i_d\right) \quad N.m \\ &= \frac{3}{2}\frac{p}{2w_b}\left(\psi_d i_q - \psi_q i_d\right) \quad N.m \end{aligned}\right\} \quad (45)$$

The value of T_{em} from the above expression is positive for motoring operation and negative for generating operation.

3.3 Equation of Motion of the Rotor Assembly

In motoring convention, the net acceleration torque, $T_{em} + T_{mech} – T_{damp}$, is in the direction of the rotor's rotation. Here, T_{em}, the torque developed by the machine, is positive when the machine is motoring and negative when the machine is generating; T_{mech}, the externally-applied mechanical torque in the direction of rotation, will be negative when the machine is motoring a load and will positive when the rotor is being driven by a prime mover as in generating; and, T_{damp}, the frictional torque, acts in a direction opposite to the rotor's rotation. Equating the net acceleration torque to the inertia torque, we have

$$T_{em} + T_{mech} - T_{damp} = J\frac{dw_{rm}(t)}{dt} = \frac{2J}{p}\frac{dw_r(t)}{dt} \quad N.m \quad (46)$$

The rotor angle, δ, is defined as the angle of the q_r-axis of the rotor with respect to the q_e-axis of the synchronously rotating reference frame, that is

$$\begin{aligned} \delta(t) &= \theta_r(t) - \theta_e(t \qquad elect.rad) \\ &= \int_0^t \left(w_r(t) - w_e\right)dt + \theta_r(0) - \theta_e(0) \quad (46) \end{aligned}$$

Since w_e is constant

$$\frac{d\{w_r(t) - w_e\}}{dt} = \frac{dw_r(t)}{dt} \quad (47)$$

Using equation 47 to replace $d\omega_r(t)/dt$ in equation 46, the slip speed can be determined from an integration of

$$w_r(t) - w_e = \frac{p}{2J}\int_0^t \left(T_{em} + T_{mech} - T_{damp}\right)dt \quad elect.rad/s \quad (48)$$

Note that $\theta_r(t)$ *and* $\theta_e(t)$ are the angles of the q_r – and q_e –axes of the rotor and synchronously rotating reference frame, respectively, measured with respect to the stationary axis of the $a - phase$ stator winding. The angle δ, will be equal to the conventional power angle defined as that between the q_r–axis of the rotor and the terminal voltage phasor if the phasor of v_a is aligned with the q_e-axis of the reference synchronously rotating frame, that is $v_a = V_m \cos(\omega_e t + \theta_e(0))$ *and* $\theta_e(0)$ *is zero. If* $\theta_e(0)$ is not zero, as with a sine wave excitation of $v_a = v_a = V_m \sin(\omega_e t) = V_m \cos(\omega_e t - \pi/2)$ *where* $\theta_e(0) = -\pi/2$, the no-load steady-state value aligned with the q_r=axis of the rotor at no-load, but both of them will be lagging $\pi/2$ behind the q_e-axis of the reference synchronously rotating frame. In a multi-machine system, the reference axis can be the q_r-axis of one of the generations in the system or the q_e-axis of an infinite bus voltage.

The initial values of $\theta_e(0)$ for the bus voltage, $\theta_r(0)$ for the variable frequency oscillator, and δ (0) for the rotor angle must be consistent if the machine's simulation is to begin with the desired operating condition.

3.4 Per-unit Expressions for Torque and the Equation of Motion

In the case of a study involving just one synchronous machine, the use of a per unit system offers no such advantage, other than perhaps the convenience of having the per unit parameters of the machine already available in terms of a set of base values that correspond to those of the rating of the machine. In such a situation, the base power, S_b, is the rated kVA of the machine.

For transient studies, the peak value rather than the rms value of the rated phase voltage is to be chosen as the base voltage, that is the base voltage, V_b, is $\left(\sqrt{2V_{line-to-line}/\sqrt{3}}\right)$.

Similarly, choosing the peak value of the rated current as the base current, I_b, that is $I_b = 2S_b/3V_b$, the base values for the stator impedance and torque are given by

$$\left.\begin{aligned} &\text{Base impedance: } Z_b = \frac{V_b}{I_b} \quad \Omega \\ &\text{Base to torque: } T_b = \frac{S_b}{\omega_{bm}} \quad N.m \end{aligned}\right\} \qquad (49)$$

The base mechanical angular frequency, ω_{bm}, *is* $2\omega_b/P$, where ω_b is the base electrical angular frequency and P is the number of poles. Using the second expression given in equation 45, the per unit electromagnetic torque develop is

$$T_{em} = \frac{T_{em}}{T_b} = \frac{\frac{3}{2}\frac{p}{2w_b}\left(\psi_d i_d - \psi_q i_d\right)}{\frac{3}{2}\left(\frac{v_b i_b}{\frac{2}{p}w_b}\right)} \quad pu \qquad (50)$$

Since the base for the flux linkages, ψ_q *and* ψ_d, is the same as V_b for the stator voltage, the above expression for the torque in per unit reduces to

$$T_{em} = \psi_d(pu)i_q(pu) - \psi_q(pu)i_d(pu) \qquad (51)$$

Equation for the motion of the rotor assembly, expressed in per unit, is

$$T_{em}(pu) + T_{emch}(pu) - T_{damp}(pu) = \left(\frac{1}{T_b}\right)\left(\frac{2J}{p}\right)\frac{dw_r}{dt} \quad pu \quad (52)$$

In terms of the inertia constant, H, that is defined as

H = $\frac{1}{2}J\omega_{bm}^2/S_b$ sec/. We have

$$T_{em}(pu) + T_{emch}(pu) - T_{damp}(pu) = 2H\frac{d(\omega_r/\omega_b)}{dt}$$

$$= 2H\frac{d\{(\omega_r - \omega_e/\omega_b\}}{dt} \qquad (53)$$

4.0 ANALYSIS OF RESULTS

4.5 Torque Angle Characteristics of Synchronous Generator

For a synchronous generator with parameters shown in table 1, the torque angle characteristics curve is plotted using equation 36 and is shown in figure (2).

Table 1: Hydro-generator generator parameters

Parameters	Value
Rated power, p	920.35MVA
Voltage	1800v
Rated p.f	0.9
Xls	0.215 pu
Rs	0.0048 pu
Xd	1.79 pu
Xq	1.66 pu
$x_d^{'}$	0.355 pu
$x_q^{'}$	0.57 pu
$x_d^{''}$	0.275
$x_q^{''}$	0.275
$T_{do}^{'}$	7.95sec
$T_{qo}^{'}$	0.415sec
$T_{do}^{''}$	0.032sec
$T_{qo}^{''}$	0.055sec
H	3.77sec
D_w	0
Frequency	50Hz

The values in the table 1 where obtained by substitution in the matlab environment until appropriate torque angle curve is obtained.

The torque angle characteristic of synchronous generator is shown in figure 2. I t is obtained by substituting the values of parameters in table 1 in equation 36

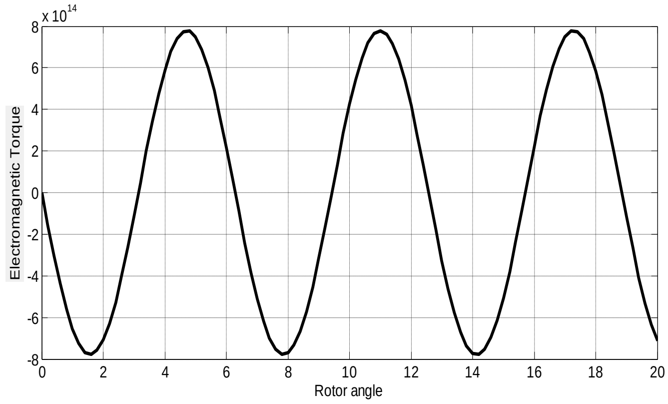

Figure 2: Torque-rotor angle characteristics of synchronous generator.

4.6 Simulation of the hydro-generator

Synchronous generator can be simulated using the values of the parameters shown in table 1 and the equations 40 through 53

4.6.1 Calculation of the Other Machine Parameters

$$x_{mq} = x_q - x_{ls}$$
$$= 1.66 - 0.215 = 1.445\, pu$$

$$x_{md} = x_d - x_{ls}$$
$$= 1.79 - 0.215 = 1.57\, pu$$

$$x'_{lkq} = \frac{x_{mq}\left(x''_q - x_{ls}\right)}{x_{mq} - \left(x''_q - x_{ls}\right)}$$
$$= \frac{0.76(0.275 - 0.215)}{0.76 - (0.275 - 0.215)} = 0.065\, pu$$

$$r'_f = \frac{1}{w_b T'_{do}}\left(x'_{lf}\right) + x_{md}$$

$$r'_{kd} = \frac{1}{w_b T''_{do}}\left(x'_{lkd} + x'_d - x_{ls}\right)$$
$$\frac{1}{100\pi\, x\, 0.032}(0.58 + 0.355 - 0.215) = 0.07159\, pu$$

$$r'_{kq} = \frac{1}{w_b T''_{qo}}\left(x'_{lkq} + x_{mq}\right)$$
$$\frac{1}{100\pi\, x\, 0.055}(0.065 + 1.445) = 0.08736\, pu$$

$$x'_{lkd} = \frac{\left(x''_q - x_{ls}\right)x_{md}\, x'_{lf}}{x'_{lf}\, x_{mq} - \left(x''_q - x_{ls}\right)\left(x_{md} + x'_{lf}\right)}$$

$$x'_{lkd} = \frac{(0.275 - 0.215)\, x\, 1.575\, x\, 0.15}{0.15\, x\, 1.575 - (0.275 - 0.215)(1.575 + 0.15)} = 0.58\, pu$$

$$\frac{1}{XMQ} = \frac{1}{xmq} + \frac{1}{x'_{lkq}} + \frac{1}{x_{ls}}$$
$$= \frac{1}{1..445} + \frac{1}{0.065} + \frac{1}{0.215}$$
$$\therefore$$
$$XMQ = 0.04991\, pu$$

$$\frac{1}{XMD} = \frac{1}{xmd} + \frac{1}{x'_{lkd}} + \frac{1}{x'_{lf}} + \frac{1}{x_{ls}}$$
$$= \frac{1}{1.575} + \frac{1}{0.58} + \frac{1}{0.15} + \frac{1}{0.215}$$
$$\therefore$$
$$XMD = 0.073116\, pu$$

Time Value =[0 0.5 0.5 0.5 3 3]
Mechanical torque = [1 10 0 -1 -1]

The figure 11 is the simulation result the synchronous generator.

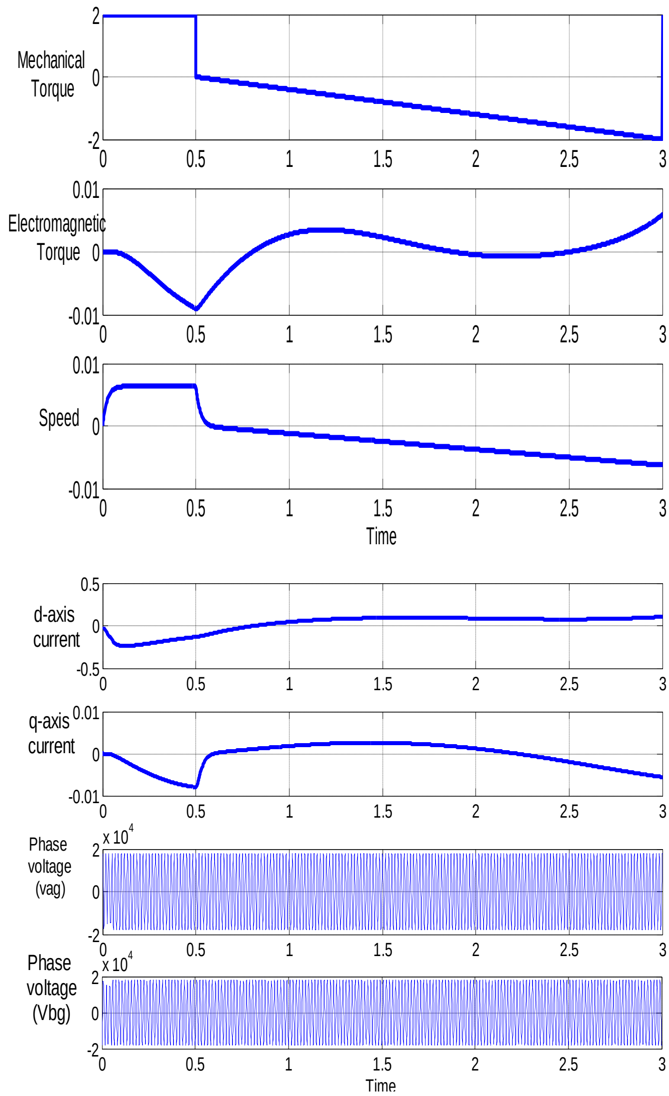

Figure 3: Simulation result of the synchronous generator

5.1 Conclusion

The synchronous machine has got no self starting torque and some external means is required for its starting. From the studies, its average speed is constant and independent of load. This machine can operate under a wide range of power factor both leading and lagging. From the simulation result, it has shown that synchronous machine requires dc excitation for its operation and so it is a doubly excited machine. Its torque is less sensitive to change in supply voltage. The breakdown torque of synchronous machine is proportional to the supply voltage.

From the simulation result, using the start time of 0 and stop time of 3 seconds, the machine will be generating at rated power at unity power factor. At time of 0.5 seconds, the externally applied mechanical torque is dropped from 2 per unit to zero for the next 2.5 seconds. At 3 seconds, the mechanical torque again changed from 0 to -2 per unit. The electromagnetic torque, speed and currents change with change in mechanical torque. The phase voltages are sinusoidal wave.

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