Efficiency Prediction of ESP through Mathematical Modeling for PV Applications

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Abstract— This project presents a generalized formulation for the computer-aided analysis of induction motor driving a submersible pump. In general Electric Submersible Pump [ESP] incorporates an induction motor and a pump, having centrifugal action. The pump is powered by the DC source especially by photovoltaic modules. In this case the insolation level of the sun is not constant at all time, it is necessary to predict the pump's performance. To do so, mathematical modeling and simulation of the electric submersible pump is proposed here. The dynamic model of the induction motor consists of an electrical sub-model to implement the three-phase to two-axis (3/2) d-q transformation of stator voltage and current calculation, a torque sub-model to calculate the developed electromagnetic torque, and a mechanical sub-model to yield the rotor speed. The submersible pump is modeled with the inputs as shaft speed, torque and head. The output variable is chosen to be discharge. With all these system modules, the electrical and mechanical condition of the pump under different operating condition is simulated with Matlab/Simulink model.

Keywords— ABC axis, Induction motor , Discharge, d-q axis, Steady state model, Submersible pump, System efficiency

INTRODUCTION

Solar submersible pumps are designed to move water by tapping on solar energy harnessed from the sun. These pumps can perform its functions well even when the sun is out. Pumps are primarily used to move water. The first designs of solar submersible pumps that came out were used to move water on a horizontal plane. Today, with the advanced solar panels and developments in the solar submersible pumps assembly, the pumps can now lift water for use in waterfalls, fountains or to move water to higher elevations than the actual source of the water.

Another feature of solar submersible pumps is that it is installed underwater. Placing the pump completely immersed in water has its advantages. It requires less cost in installation for one does not need another casing to hide the pump, like in the case when the pump is placed out in the open. Hiding the pump underwater also helps to muffle the sound of the pump. Thus the peace and tranquility of the surrounding area is maintained. The fact that the pump is underwater helps to maintain the even temperature of the pump. It helps in the cooling off process of the pump thus preventing overheating. This indirectly assists in prolonging the life of the pump assembly.

The feature that sets the solar submersible pumps apart from the rest of the pumps is that it is solar powered. These pumps are powered by harnessing the sun's rays. Using this as an energy source, the entire system depends on the solar panels that are placed high above the water. The solar panel does not necessarily have to be placed near the source of water. In fact, it is advised that it be placed in an area that is clear of shade so that it can get the most sunlight. The advancement in assembly now allows the solar panels to be mounted on a pivoting base that can move the panels to allow greater access to sunlight at all times of the day The greatest advantage of using solar submersible pumps is that the energy resource is free. There are no additional charges for the valuable energy obtained. The basic expenses incurred in setting up a system will be to purchase a solar panel motor, pump, and pipe.

This project lays emphasis on predicting the discharge of the over-all unit under different operating conditions using a commercially available software package, MATLAB.

ELECTRIC SUBMERSIBLE PUMP

The submersible pump unit consists of a pump powered by a three-phase squirrel cage induction motor. The induction motor and submersible pump are modeled mathematically using software package Matlab/Simulink [2] as shown in Fig 1

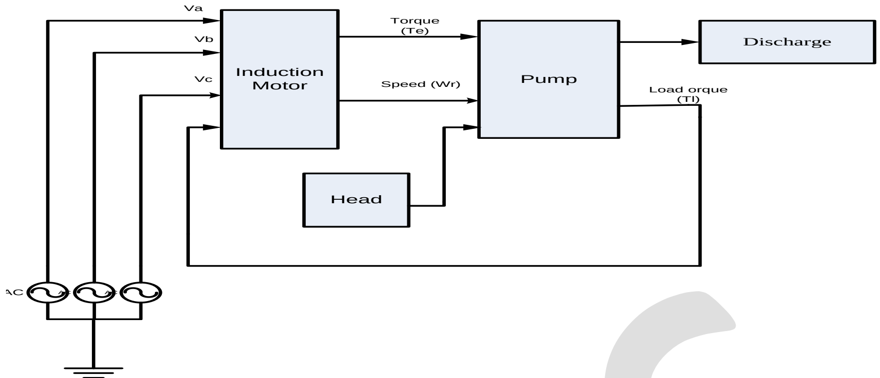

Fig.1 Block diagram of induction motor driven submersible pump

Matlab provides a powerful matrix environment for state space modeling, system design and algorithm development. Simulink is an extension to Matlab and allows graphical block modeling and simulation of the system. In the system design the entire system can be modeled using number of basic functional blocks to design and test each of them individually. The induction motor driven submersible pump consists of model of induction motor and pump.

INDUCTION MOTOR MODEL

Modeling is nothing but, the mathematical model of electrical machines, by using mathematical expressions and parameters. It is mainly done to know the performance of machine at different input and output conditions using simulation software. To find out time varying inductance and to simplify electrical and mechanical differential equations we go for reference frame

The primary function of the induction motor is to provide torque, which makes the shaft/loads to rotate at the required speed.

1. The “Torque” of an induction motor depends upon the flux in the air gap.
2. Further, flux is directly proportional to V/f, where V is supply voltage and f is the supply frequency. It can therefore be said that, the torque T is directly proportional to flux and flux is directly proportional to V/f.
3. Thus the torque producing capability of the motor at the rated/required speeds can be retained constants, by maintaining the voltage v/f frequency ratio constant.

However, the speed of the physical rotor must be less than the speed of the rotating magnetic field in the stator or else the magnetic field will not be moving relative to the rotor conductors and no currents will be induced. Fig.2 shows per phase equivalent circuit of the induction motor.

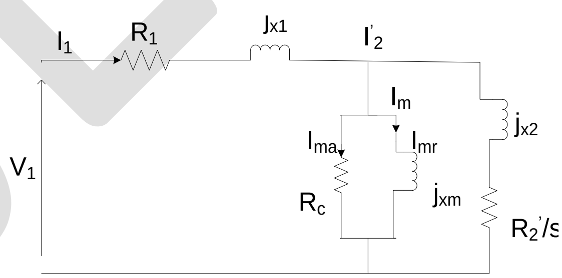

Fig.2 Per phase equivalent circuit of the induction motor

The starting step in the mathematical modeling of ac machines is to describe them as coupled stator and rotor polyphase circuits in terms of so-called phase variables, namely stator currents ias, ibs, ics; rotor currents iar, ibr, icr for an induction machine or if ikd, ikq for a synchronous machine; the rotor speed ω_r ; and the angular displacement θ between stator and rotor windings. The magnetic coupling is expressed in terms of an inductance matrix which is a function of position θ.

The next step is to transform the original stator and rotor abc frames of reference into a common k or d-q frame in which the new variables for voltages, currents, and fluxes can be viewed as 2-d space vectors. In this common frame the inductances become constant independent of position. The triplet [As Bs Cs] denotes a three-phase system attached to the stator while the pair [as bs] corresponds to an equivalent two-phase system (zero sequence components can be ignored in Y connected ac machines in which the neutral is normally isolated).

Among possible choices of d-q frames are the following:

a) Stator frame where $\omega_r = 0$

b) Rotor frame where $\omega_r = \omega m$

c) Synchronous frame associated with the frequency ω_s (possibly time varying) of the stator excitation.

d) Rotor flux frame in which the d-axis lines up with the direction of the rotor flux vector.

The choice of the common d-q frame is usually dictated by the symmetry constraints imposed by the construction and excitation of the machine. With the complete symmetry encountered in a three-phase induction machine with balanced sinusoidal excitation, any one of the five frames can be used, although the synchronous frame is more convenient in as much as all signals appear as constant dc in steady state.

ABC-SYN CONVERSION BLOCK

To convert three-phase voltages to voltages in the two- phase synchronously rotating frame, [3] they are first converted to two-phase stationary frame using (1) and then from the stationary frame to the synchronously rotating frame using (2)

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \quad (1)$$

$$\begin{Bmatrix} v_{qs} = v_{qs}^s \cos\theta_e - v_{ds}^s \sin\theta_e \\ v_{ds} = v_{qs}^s \sin\theta_e - v_{ds}^s \cos\theta_e \end{Bmatrix} \quad (2)$$

Where the superscript "s" refers to stationary frame.

Equation (1) is implemented in simple matrix transformation. Equation (2), however, contains the unit vectors; therefore, a simple matrix transformation cannot be used. Instead v_{qs} and v_{ds} are calculated using basic simulink "Sum" and "Product" blocks.

Unit vector calculation block

Unit vectors $\cos\theta_e$ and $\sin\theta_e$ are used in vector rotation blocks, "abc-syn conversion block" and "syn-abc conversion block"[4]. The angle, θe is calculated directly by integrating the frequency of the input three-phase voltages, ω_e

$$\theta_e = \int \omega_e dt \quad (3)$$

The unit vectors are obtained simply by taking the sine and cosine of θ_e. This block is needed where the initial rotor position can be inserted. If needed an initial condition to the Simulink "Integrator" block is added. Note that the result of the integration in (3) is reset to zero each time it reaches 2π radians so that the angle always varies between 0 and 2π.

syn-abc conversion block

This block does the opposite of the abc-syn conversion block for the current variables using (4) and (5) following the same implementation techniques as before.

$$\left\{\begin{matrix} i_{qs}^{s} = i_{qs}^{s}\cos\theta_e + i_{ds}^{s}\sin\theta_e \\ i_{ds}^{s} = -i_{qs}^{s}\sin\theta_e + i_{ds}^{s}\cos\theta_e \end{matrix}\right\} \quad (4)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{qs}^{s} \\ i_{ds}^{s} \end{bmatrix} \quad (5)$$

INDUCTION MACHINE d-q MODEL BLOCK

One of the most popular induction motor models derived from this equivalent circuit is Krause's model. When the reference frame is rotating at synchronous speed, both the stator and rotor are rotating at different speeds relative to it. However, with the reference frame rotating at the same speed as the stator and rotor space field MMF waves, the stator and rotor d,q variables are constant quantities, whereas the actual variables are at 50 Hz and slip frequencies respectively.

For any arbitrary value of θ, the transformation of stator ABC phase variables F [ABC] to d,q stator variables F [odq] is carried out through Park's transform.

The Flux linkage is a property of a coil of conducting wire and the magnetic field through which it passes. It is determined by the number of turns in the coil and the flux of the magnetic field. The definition of the flux linkage is the total flux passing through a surface (i.e. normal to that surface) formed by a closed conducting loop. The modeling equations in flux linkage form are as follows,

$$\frac{dF_{qs}}{dt} = \omega_b \left[v_{qs} - \frac{\omega_e}{\omega_b} F_{ds} + \frac{R_s}{x_{ls}} (F_{mq} + F_{qs}) \right] \quad (6)$$

$$\frac{dF_{ds}}{dt} = \omega_b \left[v_{ds} + \frac{\omega_e}{\omega_b} F_{qs} + \frac{R_s}{x_{ls}} (F_{md} + F_{ds}) \right] \quad (7)$$

$$\frac{dF_{qr}}{dt} = \omega_b \left[v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr} + \frac{R_r}{x_{lr}} (F_{mq} - F_{qr}) \right] \quad (8)$$

$$\frac{dF_{dr}}{dt} = \omega_b \left[v_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} + \frac{R_r}{x_{lr}} (F_{md} - F_{dr}) \right] \quad (9)$$

The magnetizing flux linkage along d-q axis is represented as,

$$F_{mq} = x_{ml}^{*} \left[\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}} \right] \quad (10)$$

$$F_{md} = x_{ml}^{*} \left[\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}} \right] \quad (11)$$

The stator and rotor current is mainly depend on the stator and rotor leakage reactance and flux linkages, which is mathematically represented as,

$$i_{qs} = \frac{1}{x_{ls}} \left(F_{qs} - F_{mq} \right) \quad (12)$$

$$i_{ds} = \frac{1}{x_{ls}}\left(F_{ds} - F_{md}\right) \tag{13}$$

$$i_{qr} = \frac{1}{x_{lr}}\left(F_{qr} - F_{mq}\right) \tag{14}$$

$$i_{dr} = \frac{1}{x_{lr}}\left(F_{dr} - F_{md}\right) \tag{15}$$

The electromagnetic (inner) torque of the machine is computed by

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_b}\left(F_{ds} i_{qs} - F_{qs} i_{ds}\right) \tag{16}$$

In the presented investigation neither friction nor ventilation losses nor stray load losses are taken into account. In order to obtain the dynamic characteristics, it is necessary to relate torque and speed [4]

$$T_e - T_l = J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} \tag{17}$$

Where T_l is the load torque and J is the total inertia.

For a squirrel cage induction machine as in the case of this paper, v_{qr} and v_{dr} in (14) and (15) are set to zero. An induction machine model can be represented with four differential equations as seen above. To solve these equations, they have to be rearranged in the state-space form. It can be achieved by inserting (10) and (11) in (6-9) and collecting the similar terms together. So that each state derivative is a function of only other state variables and model inputs. Then, the modeling equations (6-9 and 16) of a squirrel cage induction motor in state-space become,

$$\frac{dF_{qs}}{dt} = \omega_b\left[v_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{x_{ls}}\left(\frac{x^*_{ml}}{x_{lr}}F_{qr} + \left(\frac{x^*_{ml}}{x_{ls}} - 1\right)F_{qs}\right)\right] \tag{18}$$

$$\frac{dF_{ds}}{dt} = \omega_b\left[v_{ds} + \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{x_{ls}}\left(\frac{x^*_{ml}}{x_{lr}}F_{dr} + \left(\frac{x^*_{ml}}{x_{ls}} - 1\right)F_{ds}\right)\right] \tag{19}$$

$$\frac{dF_{qr}}{dt} = \omega_b\left[-\frac{(\omega_e - \omega_r)}{\omega_b}F_{dr} + \frac{R_r}{x_{lr}}\left(\frac{x^*_{ml}}{x_{ls}}F_{qs} + \left(\frac{x^*_{ml}}{x_{ls}} - 1\right)F_{qr}\right)\right] \tag{20}$$

$$\frac{dF_{dr}}{dt} = \omega_b\left[\frac{(\omega_e - \omega_r)}{\omega_b}F_{qr} + \frac{R_r}{x_{lr}}\left(\frac{x^*_{ml}}{x_{ls}}F_{ds} + \left(\frac{x^*_{ml}}{x_{lr}} - 1\right)F_{dr}\right)\right] \tag{21}$$

$$x^*_{ml} : \frac{1}{\left(\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}\right)} \tag{22}$$

$$\frac{d\omega_r}{dt} = \left(\frac{p}{2J}\right)\left(T_e - T_l\right) \quad (23)$$

PUMP MODEL :

The ESP is a multistage centrifugal pump. The performance or characteristic curve of the pump provides information on the relationship between total head and flow rate. There are three important points on this curve.

1. The shut-off head, this is the maximum head that the pump can achieve and occurs at zero flow. The pump will be noisy and vibrate excessively at this point. The pump will consume the least amount of power at this point.

2. The best efficiency point B.E.P. this is the point at which the pump is the most efficient and operates with the least vibration and noise. This is often the point for which pumps are rated and which is indicated on the nameplate. The pump will consume the power corresponding to its B.E.P. rating at this point.

3. The maximum flow point, the pump may not operate past this point. The pump will be noisy and vibrate excessively at this point. The pump will consume the maximum amount of power at this point

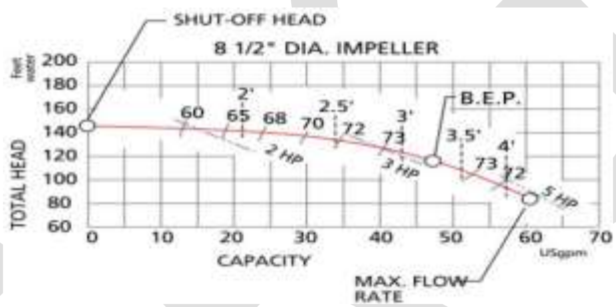

Fig.3 Pump characteristic curve

This curve is only valid for water, if the fluid has a different density than water you cannot use this curve. However you can use the total head vs. flow rate curve since this is independent of density.

MODELING EQUATIONS

The horsepower required at the pump shaft to pump a specified flow rate against a specified total dynamic head is the brake horse power and is given by [1]

$$BHP = \frac{100 * Q * H}{3960 * \eta} \quad (24)$$

The power added to water as it moves through a pump is the water horse power.

$$WHP = \frac{Q * h}{3960} \quad (25)$$

The efficiency of the pump is given by,

$$\eta = \frac{WHP}{BHP} \quad (26)$$

The pump discharge (Q) which mainly depends on the area and velocity of flow is given by [12],

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$$Q=A*V_{f1} \quad (27)$$

$$A=\pi*d*b \quad (28)$$

$$V_{f1}=u*\tan\theta \quad (29)$$

$$u=\frac{\pi*d*\omega_r}{60} \quad (30)$$

$$w=\rho*g*Q*H \quad (31)$$

Where,

Q - Flow rate or discharge
H - Total head
η - Pump efficiency
V_f – velocity of flow
g – Acceleration due to gravity
A – Area of flow
d – Diameter of the impeller
b – Width of the impeller
w – Weight of the water
u – Tangential flow of water
θ – Vane angle at the inlet or outlet

SIMULINK IMPLEMENTATION :

The inputs of a squirrel cage induction machine are the three-phase voltages, their fundamental frequency, and the load torque. The outputs, on the other hand, are the three- phase currents, the electrical torque, and the rotor speed. The induction machine model implemented is shown in Fig.5.2.

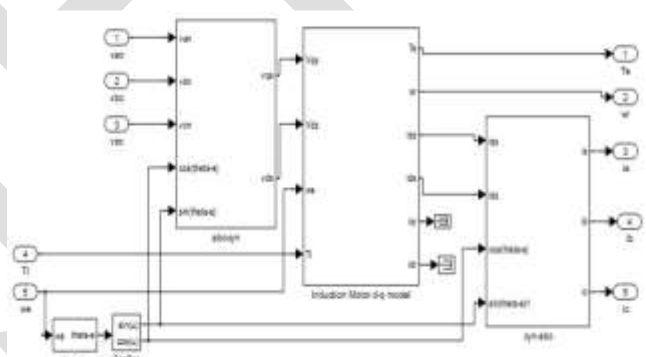

***Fig.4* Simulink model of three phase induction motor**

The d-q model requires that all the three-phase variables have to be transformed to the two-phase synchronously rotating frame. Consequently, the induction machine model will have blocks transforming the three-phase voltages to the d-q frame and the d-q currents back to three-phase. The rotor speed and torque sub model of IM is shown in Fig.5.3

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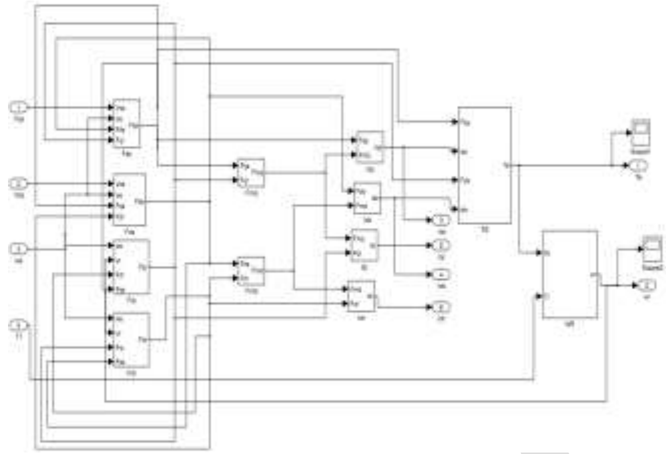

Fig.5 **Induction motor d-q model**

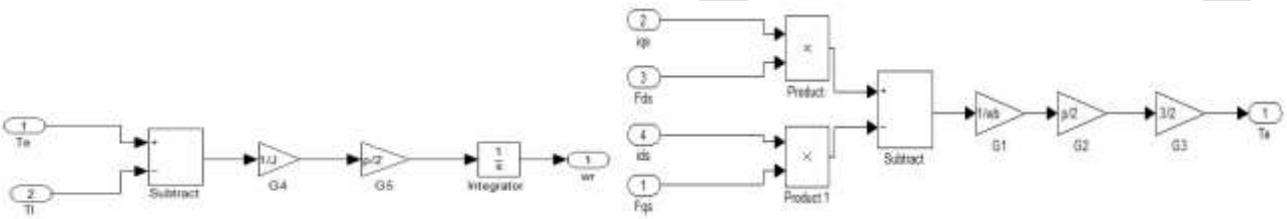

Fig.6 Rotor speed and torque sub model

The main inputs for the pump are electromagnetic torque, rotor speed and head. The discharge is mainly depends on impeller design and vane angle. The brake horse power and water horse power are used to calculate the efficiency of the pump. The torque applied to the pump is inversely related to the efficiency

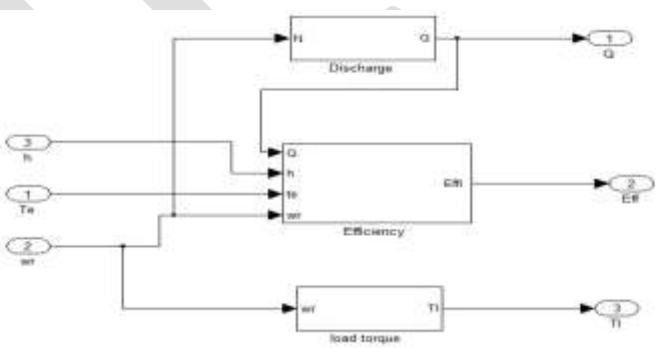

Fig.7 Simulink model of pump

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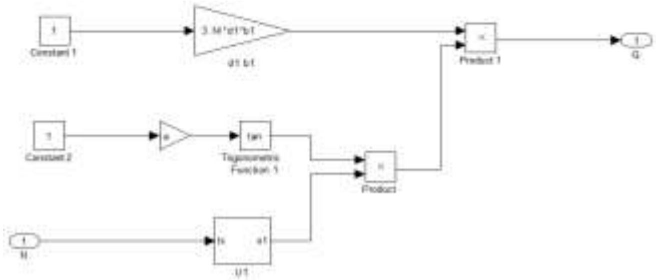

Fig.8 Discharge sub model

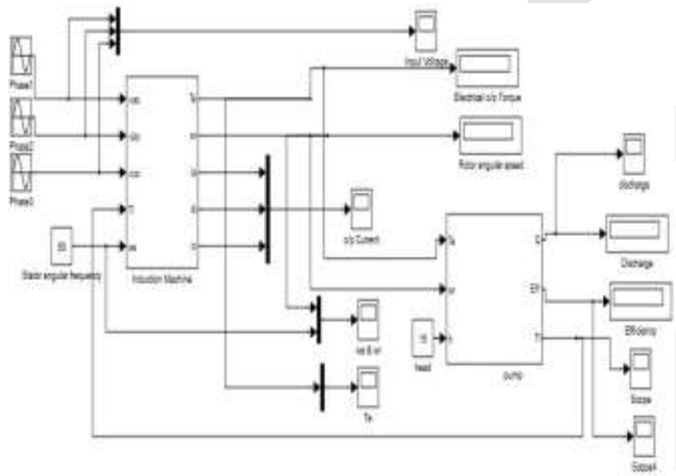

Fig.9 ESP Model

RESULTS AND DISCUSSION :

The rotor speed is mainly dependent on the number of poles being used at the stator. Here the number of poles being used is 4. So the synchronous speed is set as 1500rpm. Since rotor speed is also a function of moment of inertia, it takes certain time period to reaches the synchronous speed.

The following figure shows the output rotor speed ($\acute{\omega}_r$) of the three phase induction motor that gets increasing gradually and catch up the nearby synchronous speed after the time period of 0.25 seconds.

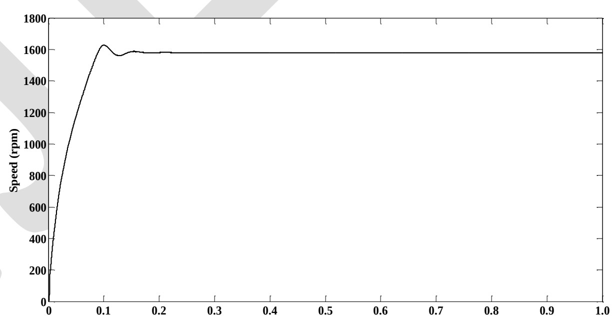

Fig.10 Output rotor speed waveform of three phase induction motor

The induction motor draws more current at the time of starting, and then it reaches the steady state. Fig shows the output current of the three phase induction motor, and it draws steady current after 0.25seconds

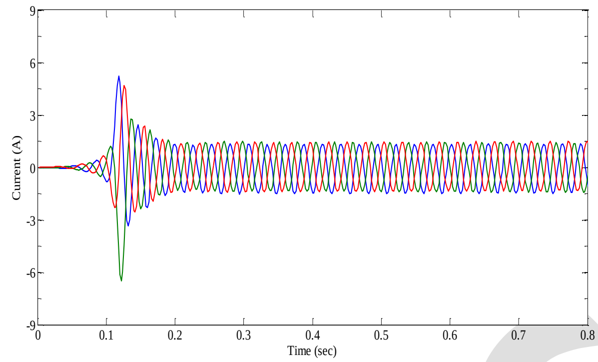

Fig.11 Output current waveform of three phase induction motor

The electromechanical torque developed depends on the stator and rotor flux linkages and the base angular frequency. Here the base frequency set at Indian standard of 50 hz. The machine accelerates at first and comes to steady state at 0.2 seconds with a small slip because of the inertia load. Fig clearly depicts it

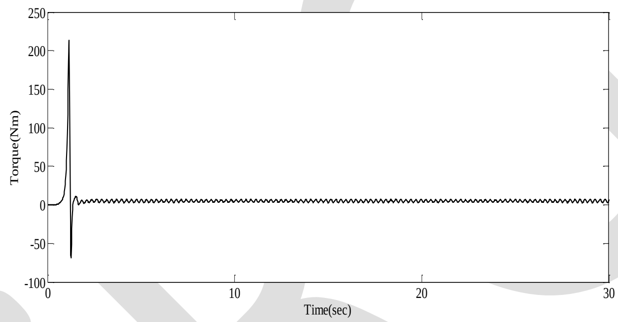

Fig.12 Output torque waveform of three phase induction motor

Table shows the variation of the efficiency under different heads, with almost constant discharge at rated voltage

Head (m)	**Discharge (m^3/Sec)**	**Efficiency (η)**	**Speed (rpm)**
5	0.00589	12.9	1450
15	0.00568	31.56	1410
25	0.00525	46.07	1380
35	0.00476	56.81	1350
45	0.00425	63.39	1330
55	0.00366	66.69	1310
65	0.00314	66.34	1295
75	0.00275	65.17	1268
80	0.00204	59.53	1240

CONCLUSION

The steady state model of submersible pump driven by induction motor is presented using MATLAB/SIMULINK. The variation of pump efficiency with head and magnetizing inductance with air gap voltage has been effectively included in the MATLAB model of pump-motor unit. The sun's insolation produces variation in input voltage to the pump. The discharge is almost constant for voltage variation between 380v to 440v for a given head, but its efficiency changes considerably. The simulink model of the submersible pump shows the variation of the efficiency under various heads. With this mathematical modeling, the efficiency and discharge under various input voltage level and head is predicted early.

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