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Improved Direct Torque Controller of Dual Inverter Fed Double Star Induction Motor

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Abstract*—this paper describes the improved direct torque controller of Double star induction motor. Double star induction motors are widely used in industrial applications where high reliability is required; there are many advantages of it compared to conventional method. It minimizes & reduces the torque pulsations and the current stress of each semiconductor power device by one half compared with the 3-phase conventional induction motor. The Concept of Direct torque control has opened up a new possibility that Induction motor can be controlled to obtain high Performance torque control as good as that of DC or brushless DC motors. A PID controller is used to avoid unwanted oscillations after applying the reference load. Finally, simulation results obtained from MATLAB/Simulink environment.

Keywords*— Direct torque control, Double star induction motor,Space vector pulse width modulation,three phase inverter,Controller.

I. INTRODUCTION

Now-a-days the induction machine[17] is most widely used in industrial drive systems because of its simple design, rugged, low-price, easy maintenance and its speed depends on number of poles and frequency of applied power supply. It is not easy to have variable speed control & requires a variable-frequency power-electronic drive for optimal speed control. In the industrial applications where high reliability is required, multi-phase induction machines are used instead of traditional three-phase machines.

The double star induction machine[1] is also known as six-phase induction machine or double stator induction machine needs a double three phase supply and is based on the principle of a double stators displaced by α=30° and rotor at the same time. The stators are similar to the stator of a simple induction machine and fed with a 3 phase alternating current and provide a rotating flux. Each star is composed by three identical windings with their axes spaced by $2\pi/3$. Compare to three phase machine double star induction machine has many advantages such as it minimizes the torque pulsations, total rating of system is multiplied, the torque pulsations will be smoothed, the rotor harmonic losses as well as the harmonics content of the DC link current will be reduced and the loss of one or more phases does not prevent the machine working, so improving the system reliability. High power drives employing multiphase machines are required in a lot of applications, such as traction, electric/hybrid vehicles and ship propulsion etc.

In the middle of 80s new strategies for the torque control of induction motor was presented by I. Takahashi and T. Noguchi as Direct Torque Control (DTC) and by M.Depenbrock as Direct Self Control. Recently, from the classical DTC methods new control techniques called Direct Torque Control–Space Vector Modulated (DTC-SVM) has been developed. In this new method disadvantages of the classical DTC are eliminated. Basically, the DTC-SVM strategies are the methods, which operate with constant switching frequency.

II. DOUBLE STAR INDUCTION MOTOR MODELLING

The Double-star induction motor consists of a standard simple squirrel-cage rotor and two separate three phase stator windings.

The following assumptions are made:

- Motor windings are sinusoidally distributed,
- The two star have same parameters,
- Flux path is linear.

The mathematical model is written in stationary reference frame. The machine is represented with two stars windings: As_1, Bs_1, Cs_1 and As_2, Bs_2, Cs_2 which are displaced by α = 30° and thee rotor phases Ar, Br, and Cr as shown in Fg.1.

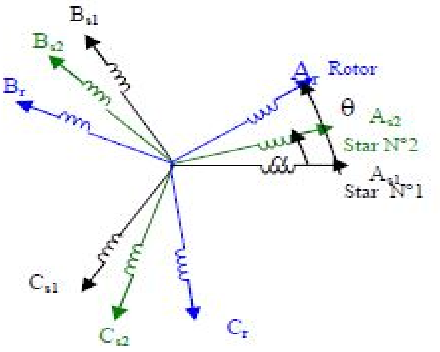

Fig.1.Phasor representation of Double star induction motor

The Voltage equations for stationary reference frame are expressed as

$$V_{ds1} = R_{S1} i_{ds1} + \frac{d}{dt}\psi_{qs1} \qquad (1)$$

$$V_{qs1} = R_{S1} i_{qs1} + \frac{d}{dt}\psi_{ds1} \qquad (2)$$

$$V_{ds2} = R_{S2} i_{ds2} + \frac{d}{dt}\psi_{qs2} \qquad (3)$$

$$V_{qs2} = R_{S2} i_{qs2} + \frac{d}{dt}\psi_{ds2} \qquad (4)$$

$$0 = R_r i_{qr} + \frac{d}{dt}\psi_{qr} - \omega_r \psi_{dr} \qquad (5)$$

$$0 = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \qquad (6)$$

The Torque equation is expressed as

$$T_e = \frac{3}{2} * \frac{P}{2}(i_{qs1} + i_{qs2}) i_{dr} - (i_{ds1} + i_{ds2}) i_{qr} \qquad (7)$$

The Speed equation is given as

$$\omega_m = \int (T_e - T_L) \frac{P}{2J} \frac{d}{dt} \qquad (8)$$

III.DIRECT TORQUE CONTROL

The basic principle of DTC [17] is to directly select stator voltage vectors according to the torque and flux errors which are the differences between the references of torque and stator flux linkage and their actual values. The governing equation for torque for this scheme is due to the interaction of stator and rotor fields. Torque and stator flux linkage are computed from measured motor terminal quantities i.e. stator voltages and current. An optimal voltage vector for the switching of VSI is selected among the six nonzero voltage vectors and two zero voltage vectors by the hysteresis control of stator flux and torque. A three-phase VSI has eight possible combinations of six switching devices. The six switches have a well defined state: ON or OFF in each configuration. So all the possible configurations can be identified with three bits (Sa, Sb, Sc), one for each inverter leg. The bit is set to 1 if the top switch is closed and to 0 when the bottom switch is closed. In order to prevent short circuit of the supply, the state of the upper switch is always opposite to that of the lower one. Block diagram of DTC-SVM of Double Star IM is shown in Fig.2.

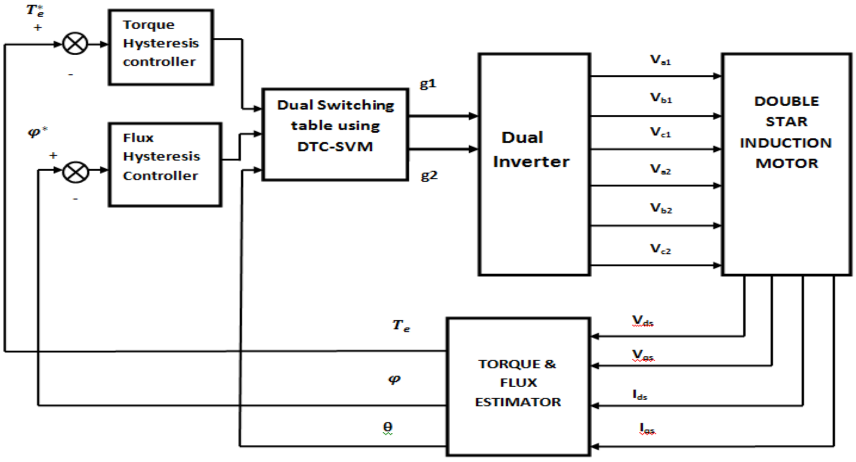

Fig.2.Block diagram of DTC-SVM of Double Star Induction Motor

The basic functional blocks used to implement the DTC-SVM of Double star Induction motor scheme is shown in the above figure. In the proposed system, torque & flux estimators are used to determine the actual values of the flux linkages & torque. The switching table & hysteresis controllers are used to determine the duration time of voltage vectors, & produces the Voltage command vector, approximate space vector can be generated with SVM and fixed switching frequency can be achieved. The output of the switching table is delivered to SVM block. The SVM block performs the space vector modulation of Vs to obtain the gate drive pulses for the inverter circuit.

A. Torque and Flux Estimator

The feedback flux and torque are calculated from the machine terminal voltages and currents. The components of stator flux is given as

$$\psi_{ds1} = \int (V_{ds1} - i_{ds1} R_{s1}) dt \qquad (9)$$

$$\psi_{ds2} = \int (V_{ds2} - i_{ds2} R_{s2}) dt \qquad (10)$$

$$\psi_{qs1} = \int (V_{qs1} - i_{qs1} R_{s1}) dt \qquad (11)$$

$$\psi_{qs2} = \int (V_{qs2} - i_{qs2} R_{s2}) dt \qquad (12)$$

$$\psi_s = \sqrt{\left((\psi_{ds1}^s + \psi_{ds2}^s)^2 + (\psi_{qs1}^s + \psi_{qs2}^s)^2 \right)} \qquad (13)$$

By using the flux components, current components and IM number of poles, the electromagnetic torque can be calculated as

$$T_e = p(\psi_{ds1} i_{qs1} + \psi_{ds2} i_{qs2} - \psi_{qs1} i_{ds1} + \psi_{qs1} i_{ds1}) \qquad (14)$$

B. Torque and Flux Controller

The instantaneous values of flux and torque are calculated from stator variables by using flux and torque estimator. The command stator flux and torque magnitude are compared with their respective estimated values and the errors are processed by the hysteresis band controllers. The flux loop controller has two levels of digital output according to the following equations

$$H_\psi = 1 \text{for } E_\psi + HB_\psi \qquad (15)$$

$$H_\psi = -1 \text{for } E_\psi > - HB_\psi \qquad (16)$$

Where $2HB_\psi$ is the total hysteresis bandwidth of the controller

The actual stator flux is constrained within the hysteresis band and tracks the command flux. The torque controller loop has three levels of digital output according to the following equations

$$H_T = 1 \text{for } E_T > + HB_T \qquad (17)$$

$$H_T = -1 \text{for } E_T > - HB_T \qquad (18)$$

$$H_T = 0 \text{for } - HB_T < E_T < + HB_T \qquad (19)$$

IV. SPACE VECTOR PULSE WIDTH MODULATION

SVPWM [10] is a form of PWM proposed in the mid-1980s that is more efficient compared to natural and regularly-sampled PWM. In the space-vector modulation, a three-phase two-level inverter can be driven to eight switching states where the inverter has six active states (1-6) and two zero states (0 and 7).Space Vector Modulation (SVM) [14] was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics.

A. *Mathematical Equivalent of SVPWM*

1. Read the sampled amplitudes of V_{AN}, V_{BN} and V_{CN} for the current sampling interval.
2. Determine the reference space-vector amplitude V_{SR} using relation

$$V_{SR} = V_{AN} + V_{BN} * e^{j120} + V_{CN} * e^{j240}$$

3. Determine the time equivalents of phase voltages, that is T_{as}, T_{bs} and T_{cs} as follows:

$$T_{as} = V_{AN} * \frac{T_s}{V_{dc}/(n-1)},$$

$$T_{bs} = V_{BN} * \frac{T_s}{V_{dc}/(n-1)} \text{ and}$$

$$T_{cs} = V_{CN} * \frac{T_s}{V_{dc}/(n-1)}$$

Where n is the number of levels.

4. Find out Toffset1 as $T_{offset1} = -(T_{max} + T_{min})/2$, where T_{max}, T_{min} are the maximum and minimum of T_{as}, T_{bs} and T_{cs}.
5. Determine T_{as}, T_{bs} and T_{cs} as $T_{as} = T_{as} + T_{offset1}$, $T_{bs} = T_{bs} + T_{offset1}$ and $T_{cs} = T_{cs} + T_{offset1}$.

Signals (T_{as}, T_{bs} and T_{cs}) are added with time offset $T_{offset.}$ To obtain modified time equivalents of the reference voltages namely, (T_{as}, T_{bs} and T_{cs}). The addition of $T_{offset1}$ to the reference phase voltage ensures that the modified reference voltages always remain within the carrier regions in the entire linear modulation range.

$T_{xs} = T_{xs} + T_{offset1}$, x = a, b, c where the magnitude of $T_{offset1}$ is given as $T_{offset1} = -(T_{max} + T_{min})/2$ [14].

V. SIMULATION RESULTS

A. *Block diagram of Controller design for DTC-SVM of Double star induction motor*

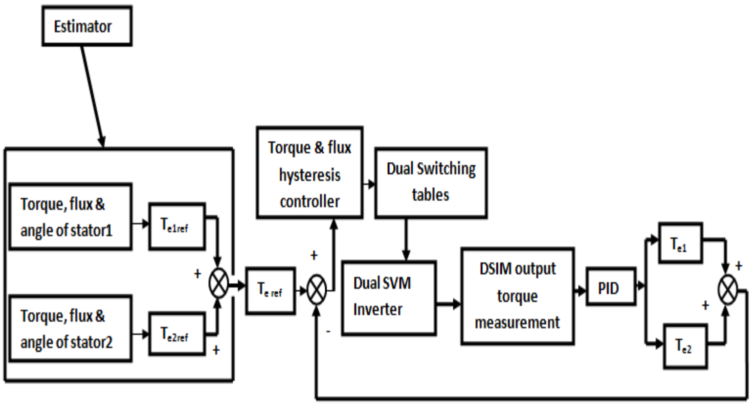

Fig.3. Controller design for DTC-SVM of Double star Induction motor

In the above controller design the torque & flux estimators are used to determine the actual values of the flux linkages & torque. The command stator flux and torque magnitude are compared with their respective estimated values and the errors are processed by the hysteresis band controllers. The dual Switching table produces the Voltage command vectors & the output is delivered to dual SVM block which performs the space vector modulation Vs to obtain gating signal of the inverter circuits. The PID controller is given as an input to the Double star induction motor (DSIM) output torque measurement to avoid unwanted oscillations when reference load is applied.

B. Inverter output waveforms with Filter

Inverter output voltage contains high frequency switching harmonics which are to be filtered before feeding the load. A typical second order low pass filter can be used to avoid harmonics of order of switching frequency or multiples of it. A second order filter gives better attenuation than first order at any given frequency. So, an LC filter is preferred over L filter.

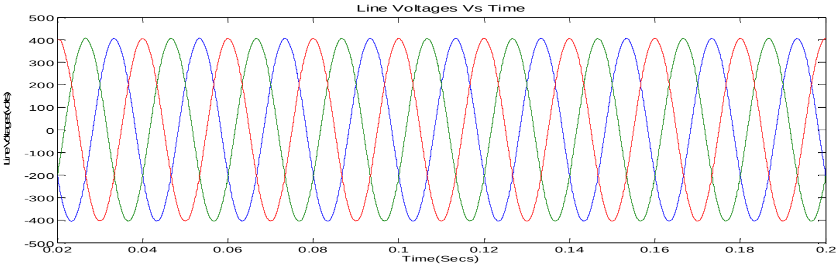

Fig.4 Line Voltage waveforms

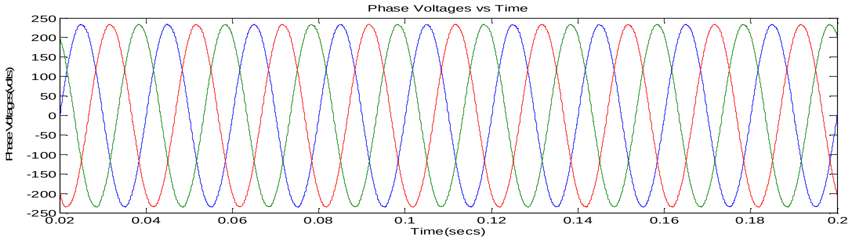

Fig.5. Phase Voltage waveforms

Filter parameters:

$$R_f = 0.29488\Omega$$
$$L_f = 1.47441mH$$
$$C_f = 0.4294963mF$$

C. Torque Response

Torque response is shown in Fig.6, and Fig.7.Initially the torque increases from zero to certain point and then decreases, when load of 30N-m is applied at 0.4secs the torque increases but still the oscillations can be seen from the Fig.6. To avoid such unwanted oscillations a PID controller is used, the waveforms for with PID controller can be seen from Fig.7.

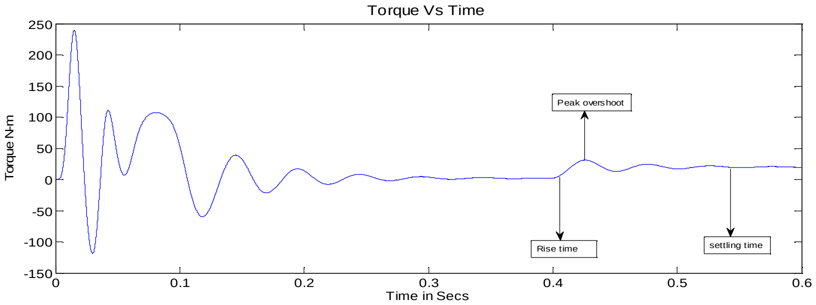

Fig.6. Torque response at t=0.4secs without PID controller

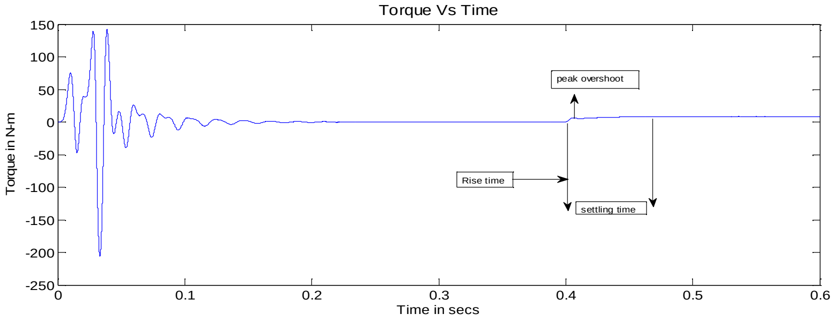

Fig.7. Torque response at t=0.4secs with PID controller

D. Speed response

A speed response is shown in Fig.8 & Fig.9.Initially the speed increases from zero to 3100rpm, when load is applied at 0.4secs speed slightly decreases but still oscillations can be seen from the Fig.8. To avoid such oscillations a PID controller is used, the waveforms for PID controller can be seen from the Fig.9.

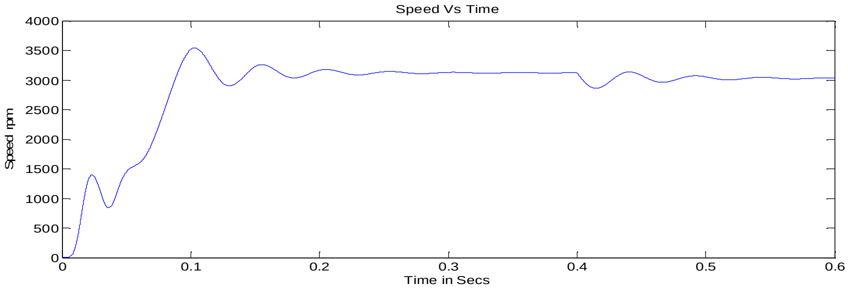

Fig.8. Speed response at t=0.4secs Without PID controller

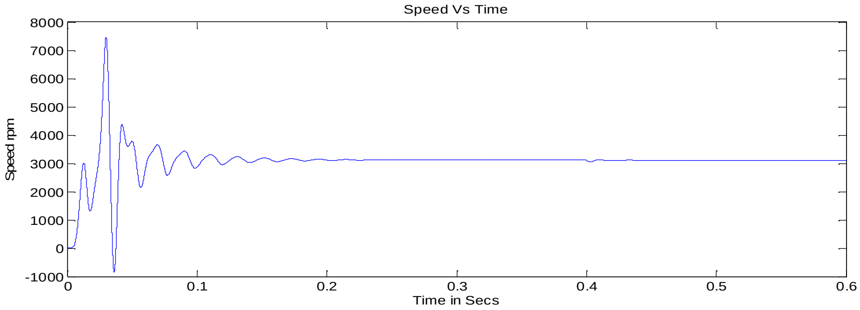

Fig.9.Speed response at t=0.4secs With PID controller

E. Current Response

Current waveforms are shown in Fig.10, Fig.11. Initially current increases for certain period and then decreases when load is applied at 0.4secs the currents of 5A rises, but still the oscillations can be seen from the Fig.10.To avoid such oscillations a PID controller is used.

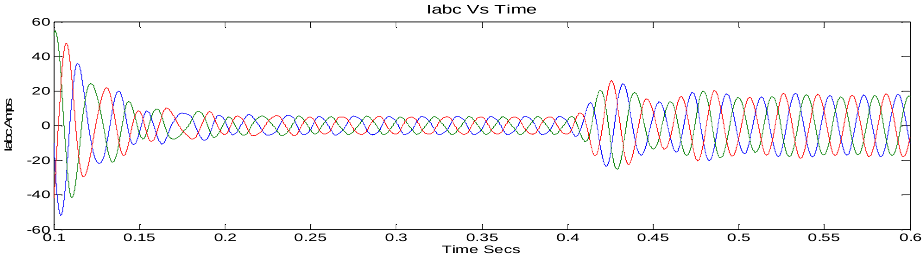

Fig.10.Current waveforms without PID controller

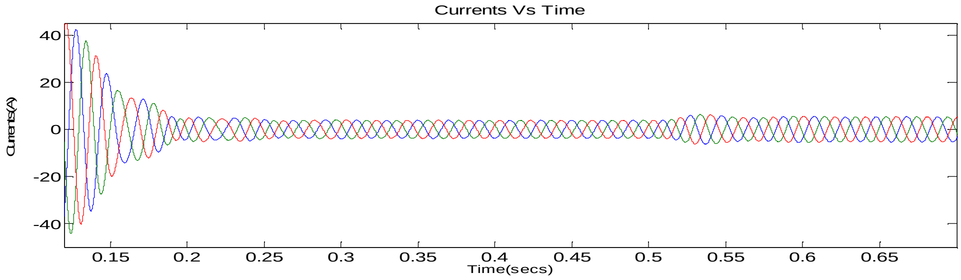

Fig.11.Current waveforms with PID controller

F. Flux response

Flux response for with & without PID controller is shown from Fig.12,Fig.13.Initially the Flux increases from zero to certain point and remains in a steady state condition, when reference load 30Nm is applied at 0.4secs Flux 0.8wb slightly decreases but still the oscillations can be seen from the Fig.12. To avoid such oscillations a PID controller is used. The waveforms for with PID controller are shown in Fig.13.

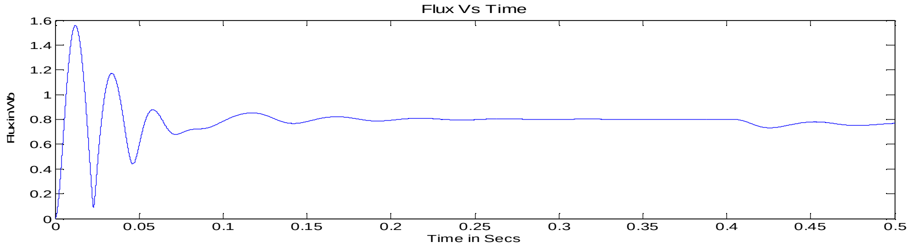

Fig.12.Flux response at 0.4secs without PID controller

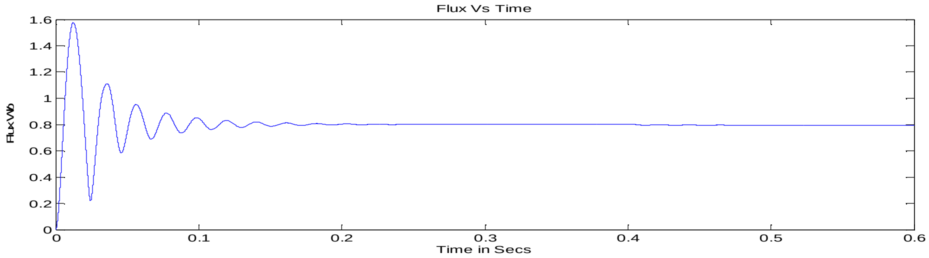

Fig.13. Flux response at 0.4secs with PID controller

VI. CONCLUSION

In this work the improved direct torque controller of dual two inverter fed Double star Induction motor is implemented and simulated in MATLAB environment. The comparison for with and without PID controller is shown in the Simulation results. The dual two level inverter is filtered before feeding to the motor. The DTC was introduced to give fast dynamic torque and flux. It is shown from the simulation results that the DTC with a PID controller avoids unwanted oscillations when reference torque is applied & response is very quick.

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APPENDIX

Parameters of three phase Induction Motor

Power (P_N)	3.5Kw
Rated Voltage	230V
Rated current	5A
Frequency	50Hz
Nominal Stator flux	0.8Wb
Rated Torque	10Nm
Reference Torque	30Nm
Rated Speed	3100rpm
Stator resistance1 (Rs1)	0.183Ω
Stator resistance2 (Rs2)	0.183 Ω
Rotor resistance (Rr)	0.277Ω
Mutual Inductance (Lm)	0.0538H
Stator self Inductance1 Ls1)	0.0553H
Stator self Inductance (Ls2)	0.0553H
Rotor self Inductance (Lr)	0.05606H
Moment of Inertia (J)	0.01667 kg-2
Number of poles (P)	4