Offline Parameter Estimation of an Induction Motor Based on a Complete Mathematical Model

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Abstract. This paper presents an offline parameter estimation method for a mathematical model of an induction motor. This technique would enable algorithm fine-tuning in real-world industrial applications. A DC injection and low-frequency AC injection technique are used to estimate the motor parameters. The former technique is used to estimate the stator resistance while the latter to estimate rotor resistance, leakage inductances and magnetizing inductance. The mathematical model of the test induction motor is validated in multiple reference frames including the stator, rotor and synchronous. Simulations are performed in MATLAB-Simulink to validate the estimation techniques and determine their accuracy. The obtained results are promising with an accuracy of 95%. This research provides a foundation for the development and performance evaluation of vector control algorithms for induction motors.

1 Introduction

The induction motor (IM) is one of the most preferred motors in industrial and automotive applications due to its low cost, robustness and high efficiency. The electrical and mechanical behaviour of the IM is governed by set of mathematical models. The mathematical transformations established by Park [1] and the primitive machine representation done by Kron [2] simplified the analysis of AC machines and ultimately led to development of the vector control. The different reference frame which can be used are the stationary, rotor and the synchronous frames. This will offer decoupling between the flux and the torque which is required for the advanced control methods [3]. The MATLAB-Simulink simulation platform already has the inbuilt induction motor model. But the internal states of the model will not be available, and the assumptions considered while implementing the inbuilt model is also not known. Hence the models built from the mathematical equations provide larger information on the operations occurring inside the model. The various parameters such as the voltage, frequency, different resistances and inductances, mechanical parameter such as the load torque, inertia and friction constants are required to run the new IM model.

The vector control of the induction motor or the field-oriented sensorless control requires accurate machine parameter identification. The parameters such as the stator resistance, stator inductance, rotor resistance and inductance and the magnetizing inductance plays a major role in accurate control of the motor [4]. The traditional methods of the parameter estimation is done using the no load test and the blocked rotor test. But this is difficult to implement at different load locations. Hence by using the three-phase inverter setup the parameter can be estimated. This can be divided into two types, online and offline parameter estimation. The online methods are based on model predictive adaptive systems [5], adaptive flux observers, signal injection-based methods [6] and Kalman filter based methods [7] where parameter is identified when the motor is running. But these online approaches require complex observers, high precision sampling or signal processing requirements.

Offline parameter estimation offers a simpler approach where parameter is identified before the start of the operation. The motor does not require to rotate during the estimation process. This involves two tests. A DC injection test, which is widely accepted method of stator resistance estimation due to its direct relationship between the DC voltage and currents [8]. For identifying other parameters, a single-phase low frequency AC injection-based test is preferred by utilizing the frequency dependent behaviour of the induction motor allowing clear separation between stator and rotor dynamics [9].

This work presents an offline parameter estimation approach for induction motor using DC and single-phase AC injection tests under standstill conditions. A sequential algorithm is built by calculating the stator resistance first and using this value other parameters are estimated. The simulation is conducted on a self-built MATLAB Simulink model of induction motor using the electrical and mechanical equations and it is implemented in different reference frames. This will eliminate the reliance on prebuilt blocks of MATLAB. The method reduces the complexity and duration along with maintaining the accuracy.

The subsequent sections present the mathematical modelling of the system along with the associated transformations. This is followed by a detailed explanation of the offline parameter estimation methodology. The simulation results and corresponding observations are then discussed, and the paper concludes by highlighting the current challenges and outlining potential future work.

2 Induction Motor Modelling

2.1 Introduction to Induction Motor

The induction motor consists of a stator and rotor. The stator is the stationary part of the motor and consists of 3 phase windings situated in the slots. The rotor is the rotating part of the motor. When the stator windings are fed by the 3 phase AC supply, a rotating magnetic field is generated in the stator of frequency, which is equal to the system frequency. These magnetic fields of the stator travel through the airgap and cut the rotor bars that are stationary at the start. This induces a current in the rotor based on the principle of electromagnetic induction. As the rotor bars are short circuited, current flows in the rotor. This produces a torque and the rotor rotates. However, the rotor rotates at a lower speed than that of the stator magnetic flux. This is due to the existence of the slip speed, which is the difference between the synchronous speed and rotor speed. The rotor frequency is equal to slip times of the system frequency. Under no load, the slip is very small, approximately 2-10% at full load.

The synchronous speed of induction motor is given by $N_S = \frac{120f}{P}$ (1)

where P is the total number of poles in the motor, and f is the supply frequency. The rotor speed will be lesser than the synchronous speed N_s, which is denoted as N.

The percentage slip of the motor is given by $\%s = \frac{N_S - N}{N_S} * 100$ (2)

2.2 Clarke and Park Transformations

The Clarke and Park transformations are widely used to simplify the analysis and control of three-phase machines. The Clarke transformation converts the time varying quantities in abc reference frame to an orthogonal αβ transformations for easier mathematical processing. The Park transformation further rotates the αβ variables into a synchronously rotating dq reference frame where the reference axis also rotates at the synchronous speed. The variables will appear like DC quantities for easier computations. The transformations done are power invariant meaning no power is lost during the transformation from one reference frame to another.
The Clarke transformation is implemented using

$$\begin{bmatrix} f_0 \\ f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\left(\frac{2}{3}\right)} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{(3)}}{2} & \frac{-\sqrt{(3)}}{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (3)$$

The park transformation is done using

$$\begin{bmatrix} f_0 \\ f_d \\ f_q \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & cos\omega t & sin\omega t \\ 1 & -sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} f_0 \\ f_\alpha \\ f_\beta \end{bmatrix} \quad (4)$$

Similarly, the inverse Clarke and park transformations are also possible where f can be either voltage or current.

2.3 Mathematical Modelling of Induction Motor

Let v_{ds} and v_{qs} be the coil voltages of stator d and q axis, v_{dr} and v_{qr} be the coil voltages of rotor d and q axis, let i_{ds}, i_{qs}, i_{dr} and i_{qr} be the currents flowing in respective coils and flux ψ_{ds}, ψ_{qs}, ψ_{dr} and ψ_{qr} are produced due to the currents in these coils. Assume the resistance and total inductance of the stator coils are equal and denoted by R_s and L_s. The same has been considered for the rotor resistance and its total inductance. It is denoted by R_r and L_r. Let M be the mutual inductance between the coils of the same axis. Assume machine is rotating with a speed of $\omega_r$elec.rad/s in anticlockwise direction. Let θ be the rotor angle in radians.

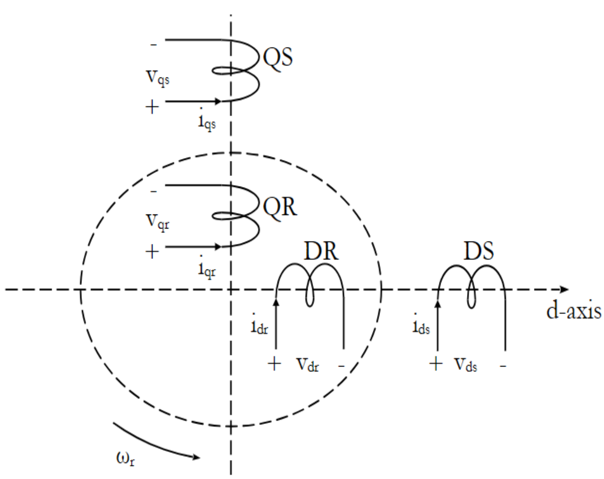

Fig. 1. – Primitive machine model

- The assumptions of the primitive model are
- The m.m.f distribution along the air gap periphery is sinusoidal. This effectively neglects space harmonics and their effect on torque and induced voltages.
- Saturation and hysteresis are neglected, i.e. linear coupled circuit is assumed valid.
- Slots do not cause appreciable variation of inductances with the relative movement between stator and rotor. This means that self and mutual inductances vary sinusoidally as the rotor moves.
- The initial model is in stator reference frame

The voltage equation of coil DS and QS is given by

$$v_{ds}^{st} = (R_s + L_s p)i_{ds}^{st} + \mathrm{M}pi_{dr}^{st} \text{ and } v_{qs}^{st} = (R_s + L_s p)i_{qs}^{st} + \mathrm{M}pi_{qr}^{st}$$

The voltage equation of rotor coils will have a back emf term included and it is given by

$$v_{dr}^{st} = (R_r + L_r p)i_{dr}^{st} + \mathrm{M}pi_{ds}^{st} + \omega_r\psi_{qr}^{st} \text{ and} v_{qr}^{st} = (R_r + L_r p)i_{qr}^{st} + \mathrm{M}pi_{qs}^{st} - \omega_r\psi_{dr}^{st}$$

The flux in each coil is developed due to the self-inductance of the coil and due to the mutual inductance with the coil present in the same axis.

Consider coil DS, $\psi_{ds}^{st} = L_s i_{ds}^{st} + \mathrm{M}i_{dr}^{st}$ (5)

Consider coil QS, $\psi_{qs}^{st} = L_s i_{qs}^{st} + Mi_{qr}^{st}$ (6)

Consider coil DR, $\psi_{dr}^{st} = L_r i_{dr}^{st} + \mathrm{M}i_{ds}^{st}$ (7)

Consider coil QR, $\psi_{qr}^{st} = L_r i_{qr}^{st} + Mi_{qs}^{st}$ (8)

The model in stationary frame is given by

$$\begin{bmatrix} v_{ds}^{st} \\ v_{qs}^{st} \\ v_{dr}^{st} \\ v_{qr}^{st} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & Mp & 0 \\ 0 & R_s + L_s p & 0 & Mp \\ Mp & \omega_r M & R_r + L_r p & \omega_r L_r \\ -\omega_r M & Mp & -\omega_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds}^{st} \\ i_{qs}^{st} \\ i_{dr}^{st} \\ i_{qr} \end{bmatrix} \quad (9)$$

And the torque equation can be obtained from

$$T_e = \frac{P_{mech}}{\omega_r} = T_e = \frac{P}{2} M\left(i_{qs}^{st} i_{dr}^{st} - i_{ds}^{st} i_{qr}^{st}\right) \quad (10)$$

The torque equation will remain the same in all the reference frames.

The induction motor can be modelled in an arbitrary frame of reference such that the transformation between the stator, rotor and synchronous reference frames becomes easier. By selecting the desired speed and angle the transformation to any reference frame is possible. The voltages and currents in this reference frame are denoted as v^a and i^a. Consider ω_a and θ_a are the speed of arbitrary reference frame and angle between d axis of rotating arbitrary reference and d axis of stationary stator reference frames. Using the inverse park relations, the model can be transformed to arbitrary frame such that

$$\begin{bmatrix} v_{ds}^{a} \\ v_{qs}^{a} \\ v_{dr}^{a} \\ v_{qr}^{a} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_a L_s & Mp & -\omega_a M \\ \omega_a L_s & R_s + L_s p & \omega_a M & Mp \\ Mp & -(\omega_a - \omega_r)M & R_r + L_r p & -(\omega_a - \omega_r)L_r \\ (\omega_a - \omega_r)M & Mp & (\omega_a - \omega_r)L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds}^{a} \\ i_{qs}^{a} \\ i_{dr}^{a} \\ i_{qr}^{a} \end{bmatrix} \quad (11)$$

The following values must be selected for ω_a and θ_a to get to different reference frames.

Selecting $\omega_a = \omega_r$ and $\theta_a = \frac{d\omega_r}{dt}$ transforms the motor model to rotor reference frame with rotor speed of ω_r

Selecting $\omega_a = \omega_s$ and $\theta_a = \frac{d\omega_s}{dt}$ transforms the motor model to synchronous reference frame with the stator frequency ω_s rad/sec

Selecting $\omega_a = 0$ and $\theta_a = 0$ transforms the motor model back to stator reference frame

After substituting for speed ω_a, we get the following model in synchronous frame

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \\ v_{dr}^s \\ v_{qr}^s \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_s L_s & Mp & -\omega_s M \\ \omega_s L_s & R_s + L_s p & \omega_s M & Mp \\ Mp & -(\omega_s - \omega_r)M & R_r + L_r p & -(\omega_s - \omega_r)L_r \\ (\omega_s - \omega_r)M & Mp & (\omega_s - \omega_r)L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \quad (12)$$

The mechanical equation of the motor is given by

$$T_e = J\frac{d\omega_{rm}}{dt} + B\omega_{rm} + T_L \text{ and } \omega_r = (P/2)\omega_{rm} \quad (13)$$

Where J is the inertia constant, B is the friction constant, ω_{rm} is the rotor speed in mech.rad/s and T_L is the load torque applied on the machine.

3 Parameter Estimation

During offline parameter estimation, the rotor of the IM is kept at standstill condition. The measurement method ensures that the rotor is magnetically locked at a certain position. The slip under the standstill condition is one. Hence slip is neglected during the calculation. No torque is also produced and hence the friction and inertia components are not needed to be considered. There are some assumptions made to ensure the reliable parameter identification. First, the magnetic circuit is assumed linear. Hence the saturation of magnetic circuit is neglected. Hence the magnetizing inductance is considered to be a constant. This allows the estimation without the nonlinear effects. The winding temperature is assumed as constant and its effect in parameter variation is ignored. The parameter drift over time is not considered in this study.

The per phase equivalent circuit of induction motor consists of stator and rotor resistance, the leakage inductance of stator, rotor and the magnetizing inductance as shown in figure 2. The DC injection test and low frequency single phase AC voltage tests are conducted to estimate the required parameters.

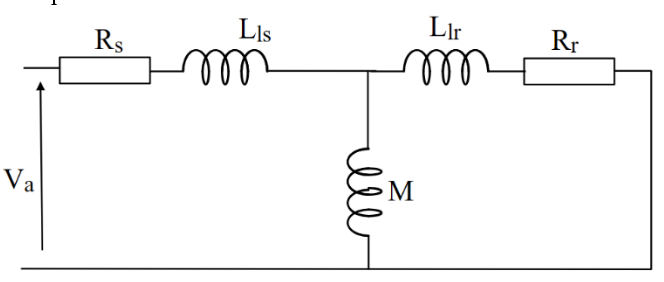

Fig. 2. –Equivalent circuit of the induction motor

3.1 DC Injection Test

The DC injection test is used to accurately measure the stator resistance of the induction motor. The test requires a three- phase inverter. The bottom switches of the leg 2 and leg 3 are always shorted as shown in figure 3. The complimentary PWM with a constant duty cycle is applied to the leg 1 of the inverter. The duty cycle selected is of very low value to avoid high currents in the windings. At steady state, all the inductance of the circuit can be neglected. Hence only the stator resistances of all the phases are considered as shown in figure 4.

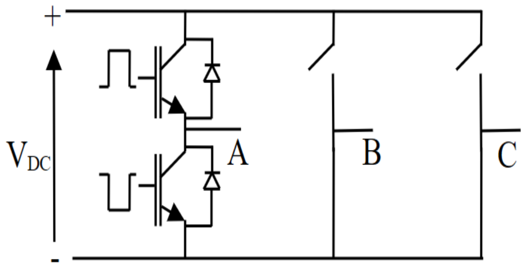

Fig. 3. – Inverter for DC Injection test

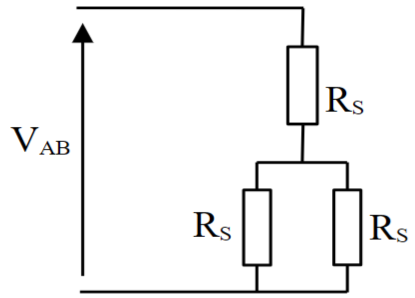

Fig. 4. – Equivalent circuit under DC injection test

The DC injection test is used to accurately measure the stator resistance of the induction motor. The test requires a three- phase inverter. The bottom switches of the leg 2 and leg 3 are always shorted as shown in figure 3. The complimentary PWM with a constant duty cycle is applied to the leg 1 of the inverter. The duty cycle selected is of very low value to avoid high currents in the windings. At steady state, all the inductance of the circuit can be neglected. Hence only the stator resistances of all the phases are considered as shown in figure 4.

The equivalent resistance of the circuit is given by $R_{s_{eq}} = 3R_s/2$. The DC voltage applied to the circuit can be calculated by $V = V_{dc} * D$, where V_{dc} is the DC bus voltage and D is the duty cycle selected. The current flowing in the phase A (i_a) must be measured using the current sensors. Then the stator resistance is calculated using the ohms law

$$R_s = (2 * V)/(3 * i_a) \quad (14)$$

To have more accurate estimation, this process can be repeated again with some other acceptable duty cycle. This will avoid the errors due to the non-linearity of inverter, cabling and other constant errors. This method has been discussed by A. Gastli [10]. The new equation to estimate the stator resistance is

$$R_s = (2 * \Delta V)/(3 * \Delta i_a) \quad (15)$$

where $\Delta V = V_1 - V_2$ and $\Delta i_a = i_{a_1} - i_{a_2}$, and $V_1 > V_2$, $i_{a_1} > i_{a_2}$.

3.2 Single Phase Low Frequency AC Injection Test

To estimate the other remaining parameter of the induction motor equivalent circuit, a single-phase AC voltage is injected to the motor. Only two legs of the three-phase inverter is considered and the both switches of the third leg is always kept open. The sinusoidal pulse width modulation is applied to the two legs to inject the AC voltage and the frequency of the injected sine wave is low.

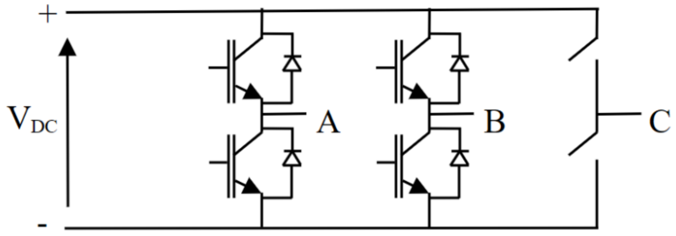

Fig. 5. – Inverter for AC Injection test

Thus, a sinusoidal current is injected through phase A and returns via phase B windings. The line voltage is reconstructed from the inverter switching states, while the current is measured using a current sensor. The instantaneous and RMS value of the current and voltage are noted. The real power (P_1) and the apparent power (S_1)is calculated using the measured voltage and current. The power factor of the circuit is obtained by the equation $\Phi = cos^{-1}\left(\frac{P_1}{S_1}\right)$ which is essential to calculate the equivalent impedance of the circuit.

The total impedance is given by $Z_{eq1} = \frac{V_{1,rms}}{2*I_{1,rms}}$ (16)

Since the stator resistance is a known parameter, it is subtracted from the equivalent resistance of the motor, which can be obtained by $R_{eq1} = Z_{eq1}\cos(\phi_1) - R_s$

The equivalent reactance of the motor is given by $X_{eq1} = Z_{eq1}\sin(\phi_1)$

Similar analysis is done for another selected frequency ω_2 rad/sec, also consider $\omega_2 < \omega_1$.

From the equivalent circuit of induction motor,

The actual equivalent resistance is $R_{eq}(\omega_1) = \frac{R_r(\omega_1 M)^2}{(R_r^2+(\omega_1 L_s)^2)}$ and $R_{eq}(\omega_2) = \frac{R_r(\omega_2 M)^2}{(R_r^2+(\omega_2 L_s)^2)}$

The actual equivalent reactance is $X_{eq}(\omega_1) = \omega_1 L_{ls} + \frac{R_r^2\omega_1 M+\omega_1^3 L_{ls} M L_s}{R_r^2+(\omega_1 L_s)^2}$ and $X_{eq}(\omega_2) = \omega_2 L_{ls} + \frac{R_r^2\omega_2 M+\omega_2^3 L_{ls} M L_s}{R_r^2+(\omega_2 L_s)^2}$

The equations to calculate the parameter from AC injection test is given by Zheng, J.; Wang, Y [11].

The magnetising inductance M is given by $M^2 = \frac{X_{eq}(\omega_1)K_1+X_{eq}(\omega_1)K_1K_2^2\omega_1^2+K_2\omega_1^3}{K_1^2K_2\omega_1+K_1^2K_2^3\omega_1^3}$ (17)

The rotor resistance R_r is given by $\mathrm{R_r} = K_1 M^2$ (18)

The stator leakage inductance L_{ls} is given by $L_{ls} = K_1K_2M^2 - M$ (19)

The rotor and stator leakage inductances are considered equal i,e $L_{ls} = L_{lr}$

Where $K_1 = \frac{\omega_1^2\omega_2^2(R_{eq}(\omega_1)-R_{eq}(\omega_2))}{R_{eq}(\omega_1)R_{eq}(\omega_2)(\omega_1^2-\omega_2^2)}$ and $K_2 = \frac{\sqrt{((R_{eq}(\omega_1)\omega_1^2)-(R_{eq}(\omega_1)\omega_2^2))/(R_{eq}(\omega_1)-R_{eq}(\omega_1))}}{\omega_1\omega_2}$

4 MATLAB Implementation and Results

The induction motor model is developed using the block diagram as shown in figure 6.

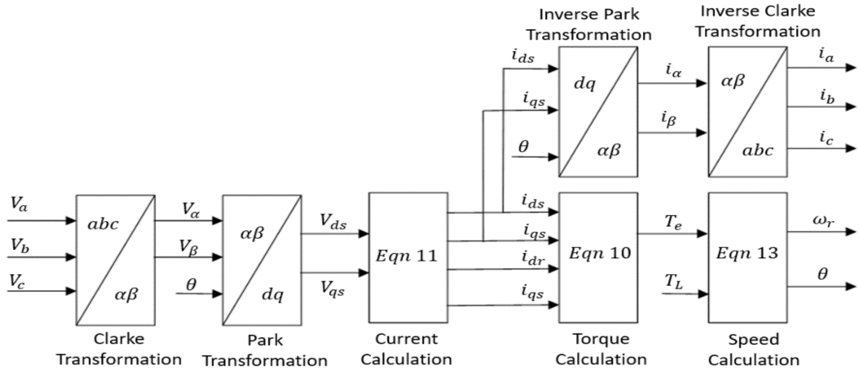

Fig. 6. – Block diagram of induction motor model

Using the built induction motor model, the DC estimation test is implemented as shown in figure 7. A constant duty is applied to one leg of the inverter. The current flowing in the phase A winding is measured.

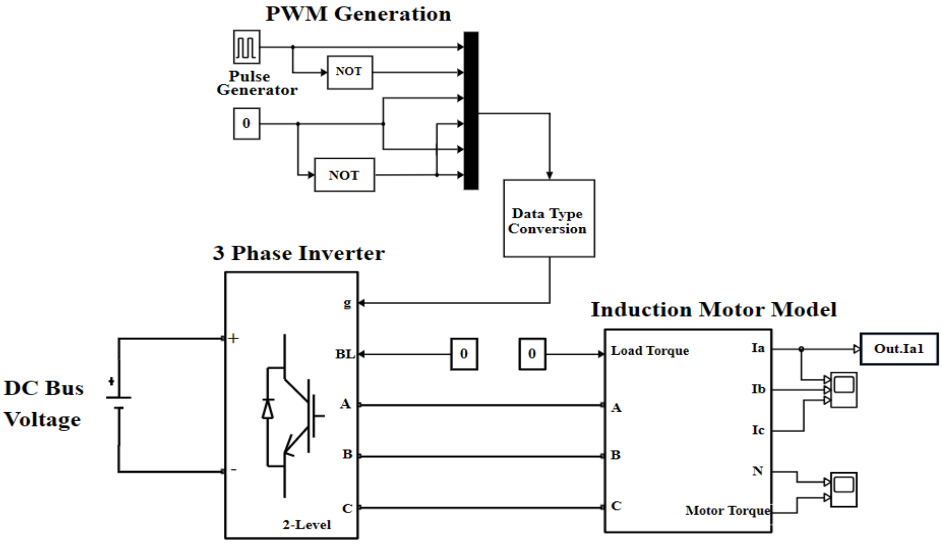

Fig. 7. – MATLAB implementation of DC injection test

The DC injection test is used to measure the stator resistance. The figure 8 shows the stator current waveform obtained when DC voltage is applied to the motor. The initial rise is due to the inductances present in the machine but the steady state value will have no effect on these inductances. Hence the steady state current is considered for stator resistance estimation.

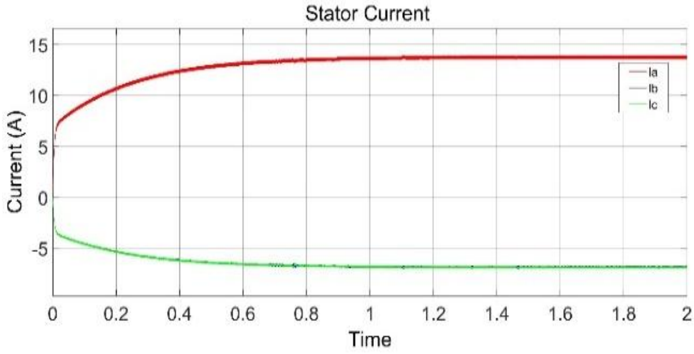

Fig. 8. – Stator current of DC injection test

The actual and estimated value of the stator resistance is provided in the table 1. It can be observed that the error in estimation is nearly 1%.

Table 1. - Stator resistance estimation

R_s Table	Actual	Estimated	%Error
Motor 1 (5HP)	1.405Ω	1.4195 Ω	1.03
Motor 2 (10HP)	0.7402 Ω	0.7476 Ω	1.24

Similarly, the AC injection test is implemented as shown in figure 9. The sinusoidal pulse width modulation technique is implemented to two legs of a three-phase inverter. The instantaneous and RMS voltages and currents are measured.

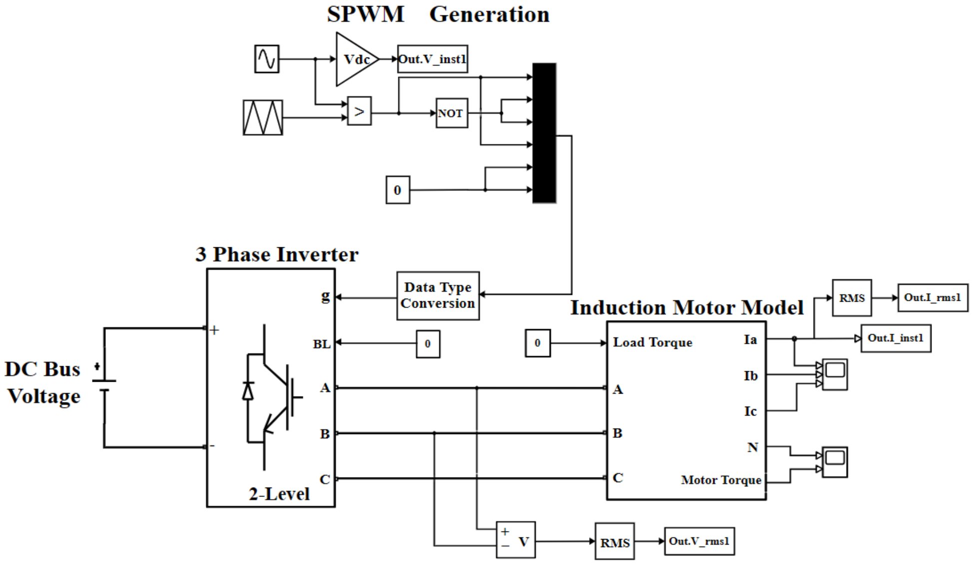

Fig. 9. – MATLAB Implementation of AC Injection test

This test was conducted to estimate the rotor resistance, magnetizing inductance and the leakage inductances. The leakage inductances of the stator and rotor are considered to be equal. The stator current and reconstructed voltage is shown in figure 10. It is observed to be following the sinusoidal wave. The instantaneous and RMS value of measured current and reconstructed voltage are measured.

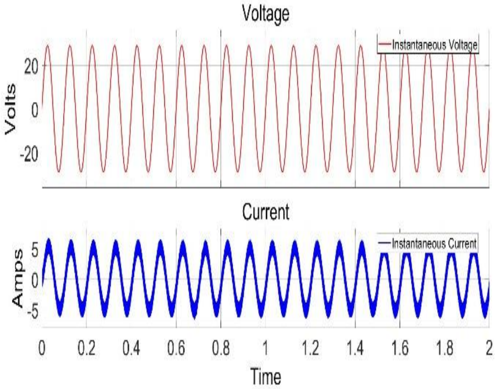

Fig. 10. – Instantaneous voltage and current

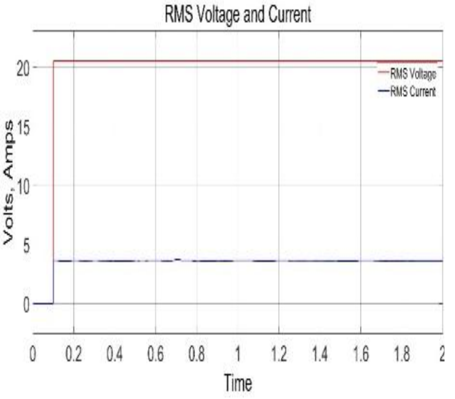

Fig. 11. – RMS value of voltage and current

Table 2 – Magnetizing inductance estimation

M Table	Actual	Estimated	%Error
Motor 1 (5HP)	0.1722H	0.1672H	-2.90
Motor 2 (10HP)	0.1241H	0.1205H	-2.88

Table 3 – Leakage inductance estimation

L_{ls} Table	Actual	Estimated	%Error
Motor 1(5HP)	0.005839H	0.005838H	-0.002
Motor 2 (10HP)	0.003045H	0.003040H	-0.14

Table 4 – Rotor resistance estimation

R_r Table	Actual	Estimated	%Error
Motor 1 (5HP)	1.395Ω	1.3814 Ω	-0.971
Motor 2 (10HP)	0.7402 Ω	0.7318 Ω	-1.13

From the results shown in tables, it can be observed that the estimated parameters closely match with actual parameters. The error percent is very minimal for all the quantities.

Compared to conventional offline methods—such as those requiring both high- and low-frequency injection tests or a blocked-rotor test—the proposed approach reduces the overall test duration while maintaining accuracy. DC injection is suitable primarily for resistance estimation, as it effectively eliminates the influence of inductances. In contrast, AC injection accounts for all inductive components present in the machine. Therefore, the proposed method offers a simple and efficient approach for estimating the parameters of an induction motor.

5 Conclusion

A MATLAB based model of the induction motor is developed using the mechanical and electrical equations. The DC test and single-phase AC tests are conducted to estimate the parameters. From these tests, electrical parameters of the induction motor such as the stator resistance, rotor resistance, magnetizing inductance and leakage inductance are estimated. The speed of the motor is observed to remain at zero, indicating that the motor is in standstill condition during the test. Since the magnetic saturation is neglected, the tests are conducted by injecting a low voltage resulting into a low current. If high current flows in the windings, then saturation cannot be ignored. This will also bring the variation in the stator resistance mainly due to the increase in winding temperature. This will act as a reason for drift in the parameter along with the ageing of the windings. Despite the limitations, the results show good consistency and accuracy in the estimation. The estimated values will act as a good starting point for the online estimation techniques or in the vector control of the induction motor.

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