Chapter 5

Development of a Model to Estimate the Parameters of Equivalent Circuit and Prediction of Performance

5.1 Introduction

The efficiency calculation of poly phase induction motor by summation of losses method includes the following losses.

[1] Constant losses:

This includes the [a] Losses in active iron and additional losses in other metal parts. [b] Losses due to friction (bearings and brushes, if not lifted during operation) not including any losses in a separate lubricating system. [c] The total windage losses in the machine, includes power absorbed in integral fans, and in auxiliary machines, if any, forming an integral part of the machine.

[2] Load losses:

This includes the [a] Resistance losses in primary winding. [b] Resistance losses in secondary winding. [c] Resistance losses in brushes if any.

[3] Additional load losses:

This includes [a] Losses introduced by the load in active iron and other metal parts other than the conductors. [b] Eddy current losses in primary or secondary winding conductors caused by current dependent flux pulsation.

The above [1] and [2] losses are normally calculated using the parameters of equivalent circuit and the third losses are vary as the square of the primary current assumed that their total value at full load is equal to 0.5 % of the rated input for motor. The calculation of parameters of equivalent circuit is requires the no load test readings at rated voltage and blocked rotor test readings at rated current. These third losses are known as stray load losses. In IEEE-112 method B it is suggested that these losses are assumed as follows.

Table 5.1 Stray Load losses	
Motor Horse Power	Stray Load Losses % of rated output
1 to 125	1.8
126 to 500	1.5
501 to 2499	1.2
2500 and greater	0.9

As per different standards energy efficient must operates with efficiency as given below.

Table 5.2: Motor efficiency				
Sr. no.	Motor rating	As per		
	KW	IS 12615*	US Mandatory**	Premium Efficiency**
1	0.75	73%	82.5%	86.5%
2	1.5	77	84	-
3	3.7	84	87.5	89.5
4	7.5	87.5	89.5	-
5	11	88.5	91	-
6	18.5	90	92.4	93
7	37	91	93	95

*Minimum Values- No Tolerance

** Nominal Values

In IS-12615:2004 two efficiencies are defined and performances for 2-Pole and 4-Pole induction motor are specified as below.

Table 5.3: Values of Performance Characteristic of 2 Pole Energy Efficient Induction Motors.								
Rated Output	Frame Desig-nation	Full Load Speed Min	Full Load Current Max	Break-away Torque In Terms Of full Load torque Min	Breakaway Current in Terms of full Load current Equal or below		Nominal Efficiency	
					Eff 2	Eff 1	Eff 2	Eff 1
KW		RPM	A	Percent	Percent	Percent	Percent	Percent
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0.37	71	2790	1.2	170	600	650	66.0	70.2
0.55	71	2760	1.6	170	600	650	70.0	74.0
0.75	80	2780	2.0	170	600	650	73.0	77.0

Table 5.4: Values of Performance Characteristic of 4 Pole Energy Efficient Induction Motors.								
Rated Output	Frame Designation	Full Load Speed Min	Full Load Current Max	Break-away Torque In Terms Of full Load torque Min	Breakaway Current in Terms of full Load current Equal or below		Nominal Efficiency	
					Eff 2	Eff 1	Eff 2	Eff 1
KW		RPM	A	Percent	Percent	Percent	Percent	Percent
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0.37	71	1330	1.4	170	550	600	66.0	73.0
0.55	80	1340	1.7	170	550	600	70.0	78.0
0.75	80	1360	2.2	170	550	600	73.0	82.5

However, above specifications are not available for smaller motors. In this work investigation is carried out for 470 W motor in frame 63.

5.2 ACCURACY OF ESTIMATION

The accuracy of estimation of efficiency using these parameters depends upon the value of parameters. If the parameters are exact one then accuracy of calculation of efficiency is more and vice-versa. Normally when we are taking observations for one test (say blocked rotor test) at different time then we may not have the observed value second time same as we have observed it at first time. So if we calculate the parameters using these two observations the answer will be different. Same thing will be repeated when instruments will change or recording person will change. To avoid this error in calculated parameters value, I am suggesting the following procedures for determining the parameters of equivalent circuit. The stator resistance is obtained from dc volt-amp method as given below, and rotor resistance, reactance, magnetizing branch resistance and reactance are calculated from no load test and blocked test and then presented to algorithm to modify it.

5.3.1 MEASUREMENT OF WINDING RESISTANCE

It can be measured by following methods

a) THE DROP OF POTENTIAL OR VOLTMETER-AMMETER METHOD :

For this method d.c. voltmeter & d.c. ammeter is used. The d.c. voltmeter is connected at the motor terminal and current is measured from d.c. ammeter when its value being steady. From this value the resistance can be calculated as follows:

$$R_{dc} = \frac{V}{I} \_\_(5.1)$$

b) THE BRIDGE METHOD :

- If the resistance value above 1 ohm then Wheatstone bridge can be employed.
- If the resistance value below 1 ohm then Kelvin Bridge is being used.

In case of bridge method the unknown resistance is compared with the known resistance by suitable bridge. With Wheatstone bridge, the resistance measured includes resistance of connecting leads which is to be subtracted from the total measured resistance.

In addition to these methods the advent of digital electronics has made possible a direct display of resistance of winding. Digital micro ohm meters are very fast and accurate for measurement of winding resistance.

In case of three phase motors, the winding resistance is measured between all three phases and calculates winding resistance per phase.

Stator winding resistance per phase for star connection

$$R_s = \left(\frac{R_{ry} + R_{yb} + R_{br}}{6}\right) \_\_(5.2)$$

Stator winding resistance per phase for delta connection

$$R_s = \left(\frac{R_{ry-yb} + R_{yb-br} + R_{br-ry}}{2}\right) \_\_(5.3)$$

If the winding resistance R_1 is known for any temperature t_1, it can be calculated at any temperature t_2 as below:

Winding resistance R_2 at temperature t_2

$$R_2 = \left(\frac{235 + t_2}{235 + t_1}\right) * R_1 \_\_(5.4)$$

5.3.2 NO LOAD TEST

This test is performed to finding out no load current, core loss and friction & windage losses. For this test an induction motor is run in no load condition at rated voltage & frequency. When the readings are being stable the readings of voltage, current, frequency, speed and power input are to be taken. Preferably this test should be conducted after temperature rise test. For finding out constant loss the I^2R Loss should be subtracted from no load input power.

$$Constant\ loss = P_0 - 3I_0^2 * R_s\ for\ star\ connection\_\_\_(5.5)$$

$$Constant\ loss = P_0 - I_0^2 * R_s\ for\ delta\ connection\_\_\_(5.6)$$

Where P_0 and I_0 is no load input and current.

The constant loss comprises core loss, friction and windage losses. For separating core loss and friction & windage loss, take the readings of current, no load input power at different voltage varying from 15 to 125% of rated voltage. Then plot the graph between V_s and input power in watts and extend the curve to zero voltage axis which gives value of friction and windage losses. These losses are subtracted from constant losses which gives core losses.

Magnetizing branch parameter of equivalent circuit can be determined by following equations:

$$P_o = \sqrt{3}V_0 I_0 \cos\emptyset\_\_(5.7)$$

$$R_{FE} = \frac{V_s}{I_0 * \cos\emptyset}\_\_(5.8)$$

$$X_m = \frac{V_s}{I_0 * \sin\emptyset}\_\_(5.9)$$

5.3.3 BLOCKED ROTOR TEST

In this case rotor is blocked (slip is unity) and a reduced voltage is applied to stator terminals to avoid exceeding of the rated current. This test performed for determining starting current, starting torque and the parameters of the equivalent circuit. It also gives information regarding power factor, impedance and circle diagram.

The test under locked rotor condition involves very high mechanical stresses and high rates of heating. Hence following precautions should be taken while doing the test:

- The direction of rotation should be checked prior to locking the rotor

- The mechanical means of locking the rotor is of adequate strength to prevent possible injury to personnel or damage equipment.
- As the winding get heated rapidly during this test, the test should be carried as rapidly as possible.

This test allows the resistance Rr and Xr to be found. Since the rotor current is much larger than the magnetizing current, the excitation branch can be neglected.

$$R_r = (V_2/I_2) * \cos \emptyset - R_s \_\_(5.10)$$

$$X_r = X_s = \frac{(V_2/I_2) * \sin \emptyset}{2} \_\_(5.11)$$

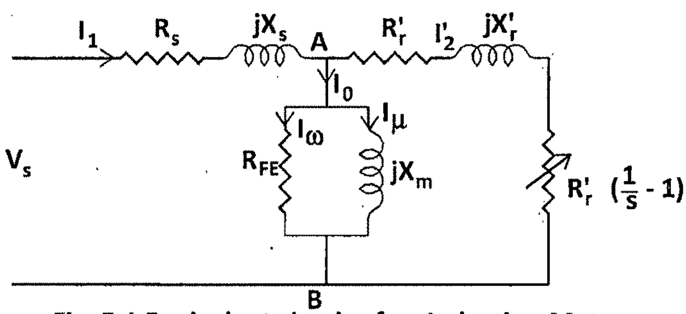


Fig. 5.1 Equivalent circuit of an Induction Motor

5.4 MATHEMATICAL MODELING OF INDUCTION MOTOR BASED ON EQUIVALENT CIRCUIT METHOD

For any closed circuit we can write that

$$Z - \frac{V_s}{I_s}(\cos \emptyset + j \sin \emptyset) = 0 \_\_(5.12)$$

The equivalent impedance of circuit diagram shown figure 5.1 is

$$Z_{eq} = (R_s + jX_s) + \left(\frac{jR_{FE} * X_m}{R_{FE} + jX_m}\right) \parallel \left(\frac{R_r}{s} + jX_r\right) \text{\_\_(5.13)}$$

$$or \quad Z_{eq} = (R_s + jX_s) + \frac{\left(\frac{jR_{FE} * X_m}{R_{FE} + jX_m}\right) * \left(\frac{R_r}{s} + jX_r\right)}{\left(\frac{jR_{FE} * X_m}{R_{FE} + jX_m}\right) + \left(\frac{R_r}{s} + jX_r\right)} \text{\_\_(5.14)}$$

$$or \quad Z_{eq} = (R_s + jX_s) + \frac{jR_{FE} * X_m * \frac{R_r}{s} - R_{FE} * X_m * X_r}{jR_{FE} * X_m + (R_{FE} + jX_m)\left(\frac{R_r}{s}\right) + (R_{FE} + jX_m)(jX_r)} \text{\_\_(5.15)}$$

$$or \quad Z_{eq} = (R_s + jX_s) + \frac{-R_{FE} * X_m * X_r + j\frac{R_r}{s} * R_{FE} * X_m}{R_{FE} * \frac{R_r}{s} - X_m * X_r + j\left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right)} \text{\_\_(5.16)}$$

Multiplying and dividing second term by

$$R_{FE} * \frac{R_r}{s} - X_m * X_r - j\left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right) \text{\_\_(5.17)}$$

$$or \quad Z_{eq} = (R_s + jX_s) + \frac{\left(-R_{FE} * X_m * X_r + j\frac{R_r}{s} * R_{FE} * X_m\right)}{\left[R_{FE} * \frac{R_r}{s} - X_m * X_r + j\left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right)\right]} * \frac{\left(R_{FE} * \frac{R_r}{s} - X_m * X_r - j\left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right)\right)}{\left(R_{FE} * \frac{R_r}{s} - X_m * X_r - j\left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right)\right)} \text{\_\_(5.18)}$$

$$or \quad Z_{eq} = (R_s + jX_s) + \frac{\left(-R_{FE} * X_m * X_r + j\frac{R_r}{s} * R_{FE} * X_m\right)\left(R_{FE} * \frac{R_r}{s} - X_m * X_r - j\left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right)\right)}{\left[\left(R_{FE} * \frac{R_r}{s} - X_m * X_r\right)^2 + \left(R_{FE} * X_m + R_{FE} * X_r + X_m\frac{R_r}{s}\right)^2\right]}$$

$$\text{\_\_(5.19)}$$

Now for simplification not considering stator impedance we have

$$\frac{\left(-R_{FE}*X_m*X_r+j\frac{R_r}{s}*R_{FE}*X_m\right)\left(R_{FE}*\frac{R_r}{s}-X_m*X_r-j\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)\right)}{\left[\left(R_{FE}*\frac{R_r}{s}-X_m*X_r\right)^2+\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)^2\right]}$$

_(2.20)

Taking product of numerator's first term of first bracket and second bracket

$$(-R_{FE}*X_m*X_r)\left(R_{FE}*\frac{R_r}{s}-X_m*X_r-j\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)\right)$$

$$=(-R_{FE}*X_m*X_r)\left(R_{FE}*\frac{R_r}{s}-X_m*X_r\right)$$
$$-(-R_{FE}*X_m*X_r)\,j\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)$$

$$=(-R_{FE}*X_m*X_r)\left(R_{FE}*\frac{R_r}{s}-X_m*X_r\right)$$
$$+(R_{FE}*X_m*X_r)\,j\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)$$

Writing real part with green letter and imaginary part with blue letter we have

$$-R_{FE}*X_m*X_r*R_{FE}*\frac{R_r}{s}+R_{FE}*X_m*X_r*X_m*X_r+jR_{FE}*X_m*X_r*R_{FE}*X_m$$
$$+jR_{FE}*X_m*X_r*R_{FE}*X_r+jR_{FE}*X_m*X_r*X_m\frac{R_r}{s}\text{\_\_(5.21)}$$

Similarly taking product of numerator's second term of first bracket and second bracket

$$\left(j\frac{R_r}{s}*R_{FE}*X_m\right)\left(R_{FE}*\frac{R_r}{s}-X_m*X_r-j\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)\right)$$

$$j\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*\frac{R_r}{s}-j\frac{R_r}{s}*R_{FE}*X_m*X_m*X_r+\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*X_m$$
$$+\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*X_r+\frac{R_r}{s}*R_{FE}*X_m*X_m\frac{R_r}{s}\text{\_\_(5.22)}$$

Combining real part of equation (5.21) and (5.22) we have

$$=\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*X_m+\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*X_r+\frac{R_r}{s}*R_{FE}*X_m*X_m$$
$$*\frac{R_r}{s}-R_{FE}*X_m*X_r*R_{FE}*\frac{R_r}{s}+R_{FE}*X_m*X_r*X_m*X_r$$

$$=\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*X_m+\frac{R_r}{s}*R_{FE}*X_m*X_m*\frac{R_r}{s}+R_{FE}*X_m*X_r*X_m*X_r$$

Or real part is

$$=\left(R_{FE}*{X_m}^2\right)\left(\frac{R_r}{s}*R_{FE}+\left(\frac{R_r}{s}\right)^2+{X_r}^2\right)\_\_(5.23)$$

Combining imaginary part of equation (5.21) and (5.22) we have

$$j\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*\frac{R_r}{s}-j\frac{R_r}{s}*R_{FE}*X_m*X_m*X_r+jR_{FE}*X_m*X_r*R_{FE}*X_m+jR_{FE}*X_m*X_r*R_{FE}*X_r+jR_{FE}*X_m*X_r*X_m*\frac{R_r}{s}$$

$$=j\left(\frac{R_r}{s}*R_{FE}*X_m*R_{FE}*\frac{R_r}{s}R_{FE}*X_m*X_r*R_{FE}*X_m+R_{FE}*X_m*X_r*R_{FE}*X_r\right)$$

Or imaginary part is

$$=j\left({R_{FE}}^2*X_m\left(X_m*X_r+\left(\frac{R_r}{s}\right)^2+{X_r}^2\right)\right)\_\_(5.24)$$

Hence real part of equation (2.20)

$$Re\{\boldsymbol{Z}\}=R_s+\frac{R_{FE}X_m^2\left(\frac{R_r}{s}R_{FE}+\left(\frac{R_r}{s}\right)^2+{X_r}^2\right)}{\left[\left(R_{FE}*\frac{R_r}{s}-X_m*X_r\right)^2+\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)^2\right]}\_\_(5.25)$$

And imaginary part of equation (5.20)

$$Im\{\boldsymbol{Z}\}=X_s+\frac{\left({R_{FE}}^2*X_m\left(X_m*X_r+\left(\frac{R_r}{s}\right)^2+{X_r}^2\right)\right)}{\left[\left(R_{FE}*\frac{R_r}{s}-X_m*X_r\right)^2+\left(R_{FE}*X_m+R_{FE}*X_r+X_m\frac{R_r}{s}\right)^2\right]}\_\_(5.26)$$

The equations for current, Power factor, output power, torque, input power, Efficiency from the equivalent circuit,

$$I_{eq} = \frac{V_s}{Z_{eq}}, \qquad PF = \cos\left[\tan^{-1}\frac{Im\{Z\}}{Re\{Z\}}\right] \_\_\_(5.27)$$

$$P_{out} = 3I_r^2 R_L \; where \; R_L = R_r\left(\frac{1}{s} - 1\right) \_\_\_(5.28)$$

$$T_g = \frac{P_g}{\omega_m}, \qquad P_{in} = 3 * V * I_{eq} * \cos\emptyset, \qquad Efficiency = \frac{P_{out}}{P_{in}} * 100 \_\_\_(5.29)$$

Once R_s is obtained from direct measurement and the stator and rotor reactance are assumed proportional as in IEEE Std 112,

$$x_s = k_{12} * x_r \_\_\_(5.30)$$

the no load and block rotor tests yield a system of four non linear equations (subscript B stands for 'Block-rotor' and subscript V for 'No load')

$$F_1 = Re\{Z_B\} - \frac{V_{sB}}{I_{sB}}\cos\emptyset_B, \qquad F_2 = Im\{Z_B\} - \frac{V_{sB}}{I_{sB}}\sin\emptyset_B \_\_\_(5.31)$$

$$F_3 = Re\{Z_V\} - \frac{V_{sV}}{I_{sV}}\cos\emptyset_V, \qquad F_4 = Im\{Z_V\} - \frac{V_{sV}}{I_{sV}}\sin\emptyset_V \_\_\_(5.32)$$

5.4.1 MACHINE MODEL FOR INVERTER FED INDUCTION MOTOR

r_{1k} and L_{1k}: Stator resistance and leakage reactance inductance for K^{th} harmonic

r_{2k} and L_{2k}: rotor resistance and leakage reactance inductance for K^{th} harmonic

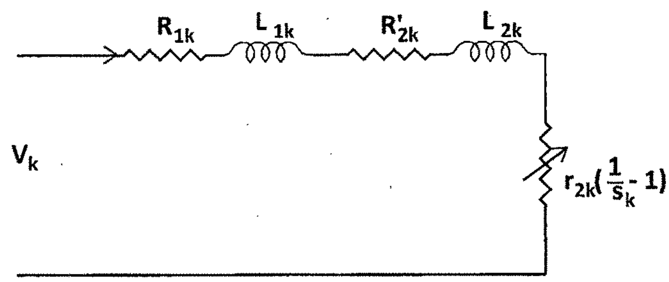


Fig. 5.2 Harmonic equivalent circuit of an Induction Motor

It is important to note that the rotor parameters r_{2k} and l_{2k} are frequency dependent due to skin effect in the rotor bars. Since an inverter fed induction motor is usually started at low frequency. The values of r_{2k} and l_{2k} should be those corresponding to the harmonic frequency K_f, where f is the starting frequency and k is the order of harmonic. The iron loss resistance R_{FE} is also frequency dependent, and should be the value corresponding to the starting frequency. As for the exciting inductance L_m, it does not depend on frequency, but is influenced by magnetic saturation. Since the magnetic saturation tends to occur when the starting frequency is low, it should be considered in the value of L_m.The stator parameters r_{1k} and l_{1k} are- assumed, for simplicity, to be independent of frequency.

5.5 NUMERICAL ALGORITHM FOR PARAMETER ESTIMATION

The parameters obtained from no load test and blocked tests are liable to give incorrect performance values. This is because of the possible errors in parameter value due to instrument error, measurement error, human error, deviation of voltage magnitude, deviation of voltage frequency. When evaluated parameters are not exact then they will not satisfy the equation of closed circuit given by equation (5.12). The simplification of closed loop equation for blocked rotor condition and no load condition is given by equations (5.31) and (5.32) respectively. These two equation are non linear and hence are to be evaluated by numerical method. Here below *Newton-Raphson* method is suggested for solution of above equations.

The perfọrmance calculated [1] using the parameters obtained from blocked rotor test and no load test [2]] using the parameters obtained from blocked rotor test and no load test and then modifying it using *Newton-Raphson* are compared with the actual load test performance. The resulted are presented at the end.

The *Newton-Raphson* method is a fast local convergence procedure used to solve nonlinear equations given by equation

$$f(x) = 0 \_\_\_ (5.33)$$

Using the recurrence formula of equation (5.33) and starting the iterative process with a value $x^{(0)}$ as first guess, the solution of equation (5.32) is obtained. The parameters values which are which are obtained in this way are very much closer to the exact value of parameter.

$$x^{(j+1)} = x^{(j)} - \frac{f(x)^j}{f'(x)^j} \_\_\_ (5.34)$$

As in our case there are more number of simultaneous nonlinear equations, the equation (2.36) can be written in the form of matrix as below

$$X^{(j+1)} = X^{(j)} - \frac{F(x)^j}{F'(x)^j}$$

$$X^{(j+1)} = X^{(j)} - J'(x)^{j^{-1}} F(x)^j \_\_\_ (5.35)$$

Where

$X^{(j+1)}$, $X^{(j)}$, $F(x)^j$ *are n − dimensional coulomn vector and* $J'(x)^{j^{-1}}$ is n*n dimensional Jacobian matrix.

$$J^{(j)} = \begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1}\right)^{(j)} & \left(\frac{\partial f_1}{\partial x_2}\right)^{(j)} & \left(\frac{\partial f_1}{\partial x_3}\right)^{(j)} & \_\left(\frac{\partial f_1}{\partial x_n}\right)^{(j)} \\ \left(\frac{\partial f_2}{\partial x_1}\right)^{(j)} & \left(\frac{\partial f_2}{\partial x_2}\right)^{(j)} & \left(\frac{\partial f_2}{\partial x_3}\right)^{(j)} & \_\left(\frac{\partial f_2}{\partial x_n}\right)^{(j)} \\ \left(\frac{\partial f_3}{\partial x_1}\right)^{(j)} & \left(\frac{\partial f_3}{\partial x_2}\right)^{(j)} & \left(\frac{\partial f_3}{\partial x_3}\right)^{(j)} & \_\left(\frac{\partial f_3}{\partial x_n}\right)^{(j)} \\ \_ & \_ & \_ & \_ \\ \left(\frac{\partial f_n}{\partial x_1}\right)^{(j)} & \left(\frac{\partial f_n}{\partial x_2}\right)^{(j)} & \left(\frac{\partial f_n}{\partial x_3}\right)^{(j)} & \_\left(\frac{\partial f_n}{\partial x_n}\right)^{(j)} \end{bmatrix} \_\_\_ (5.36)$$

$$X^{(0)} = \begin{bmatrix} X_1{}^{(0)} \\ X_2{}^{(0)} \\ X_3{}^{(0)} \\ \vdots \\ X_n^{(0)} \end{bmatrix}, \quad X^{(j)} = \begin{bmatrix} X_1{}^{(j)} \\ X_2{}^{(j)} \\ X_3{}^{(j)} \\ \vdots \\ X_n^{(j)} \end{bmatrix} \quad (5.37)$$

Its application to the circuit non linear equations yields the following numerical algorithm:

$$\begin{bmatrix} R_r{}^{(j+1)} \\ X_r{}^{(j+1)} \\ R_{FE}{}^{(j+1)} \\ X_m^{(j+1)} \end{bmatrix} = \begin{bmatrix} R_r{}^{(j)} \\ X_r{}^{(j)} \\ R_{FE}{}^{(j)} \\ X_m^{(j)} \end{bmatrix} - \begin{bmatrix} \left(\frac{\partial F_1}{\partial R_r}\right)^{(j)} & \left(\frac{\partial F_1}{\partial X_r}\right)^{(j)} & \left(\frac{\partial F_1}{\partial R_{FE}}\right)^{(j)} & \left(\frac{\partial F_1}{\partial X_m}\right)^{(j)} \\ \left(\frac{\partial F_2}{\partial R_r}\right)^{(j)} & \left(\frac{\partial F_2}{\partial X_r}\right)^{(j)} & \left(\frac{\partial F_2}{\partial R_{FE}}\right)^{(j)} & \left(\frac{\partial F_2}{\partial X_m}\right)^{(j)} \\ \left(\frac{\partial F_3}{\partial R_r}\right)^{(j)} & \left(\frac{\partial F_3}{\partial X_r}\right)^{(j)} & \left(\frac{\partial F_3}{\partial R_{FE}}\right)^{(j)} & \left(\frac{\partial F_3}{\partial X_m}\right)^{(j)} \\ \left(\frac{\partial F_4}{\partial R_r}\right)^{(j)} & \left(\frac{\partial F_4}{\partial X_r}\right)^{(j)} & \left(\frac{\partial F_4}{\partial R_{FE}}\right)^{(j)} & \left(\frac{\partial F_4}{\partial X_m}\right)^{(j)} \end{bmatrix}^{-1} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \quad (5.38)$$

Where F_1 *to* F_4 are given by equations (5.31) and (5.32)

5.5.1 INITIAL VALUES OF PARAMETER AND STOPPING CRITERIA

5.5.1.1 INITIAL PARAMETER VALUE

The values for the first guess vector will be obtained from no-load and blocked-rotor tests voltage, current and power measurements, and no-load test slip measurement, assuming simplified equivalent circuits generally admitted. Approximate values for rotor parameters may be reached from blocked rotor test measurements taking into account the approximate equivalent circuit of Fig.5.3

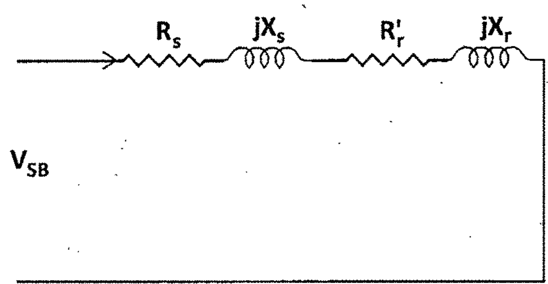


Fig. 5.3 Blocked rotor simplified equivalent circuit of an Induction Motor

The rotor parameter's approximate values will be found from

$$R_{01} = R_s + R_r = \frac{P_B}{{I_{sB}}^2}$$

$$R_r = \frac{P_B}{{I_{sB}}^2} - R_s \_\_(5.39)$$

$$Z_T = \frac{V_{sB}}{I_{sB}} = \sqrt{(R_{01})^2 - (X_{01})^2}$$

$$X_r = \frac{f}{f_B}\frac{X_{01}}{(k_{12}+1)} \_\_(5.40)$$

Where f is rated frequency and f_B is frequency at which blocked rotor test is carried out.

A first guess for the magnetizing branch parameters may be reached from no-load test measurements and taking into account the approximate equivalent circuit of Fig. 5.4

The approximate Values for the magnetizing branch parameters (series equivalent) will be found from equations (5.41) and (5.42)

$$R_{FEs} = \frac{P_V}{{I_{sV}}^2} - R_s \_\_(5.41)$$

$$X_{ms} = \frac{\sqrt{(V_{sV} * I_{sV})^2 - P_V^2}}{I_{sV}^2} - X_s \_\_(542)$$

Where X_s is given by equation (5.29)

At last, we find a first guess for the magnetizing branch (parallel equivalent) parameters from following equations (5.43) and (5.44).

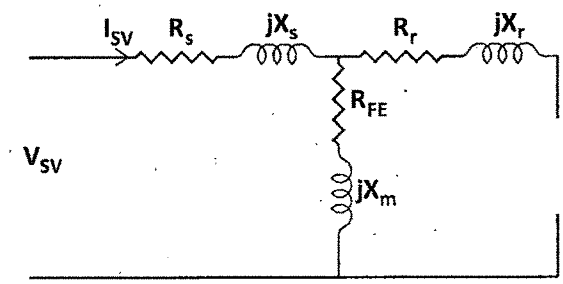


Fig. 5.4 No load simplified equivalent circuit of an Induction Motor

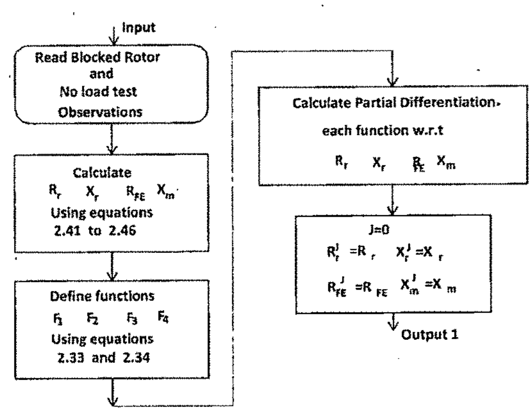
$$R_{FE} = \frac{R_{FEs}^2 + X_{ms}^2}{R_{FEs}} \quad (5.43)$$

$$X_m = \frac{R_{FEs}^2 + X_{ms}^2}{X_{ms}} \quad (5.44)$$

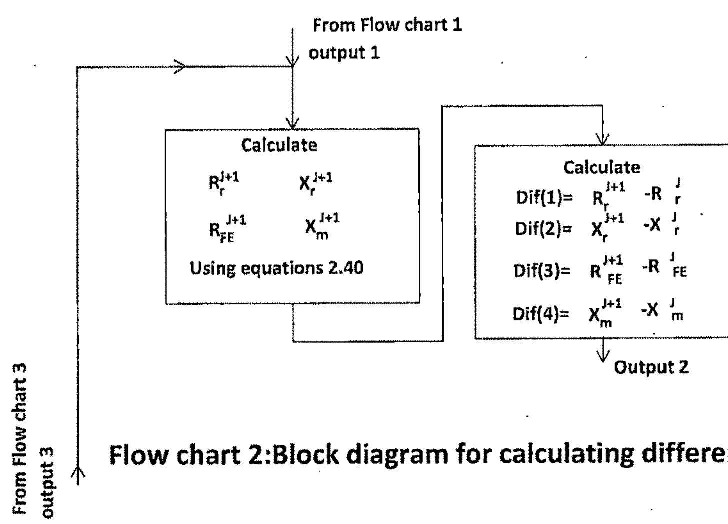
5.5.1.2 STOPPING CRITERIA

Due to the round character of an iterative process, it becomes still necessary to define a stopping criterion to impose when reached results are found to be adequate or when convergence is not achieved. Assuming that initial guesses for parameters are a good approximation to final values, the stopping criterion adopted was that all the absolute differences between the values of each parameter, in consecutive iterations, to be smaller than a fraction of the corresponding starting value. To prevent situations where convergence may not be achieved, the iterative process is also stopped after a given number of iterations, namely 10.

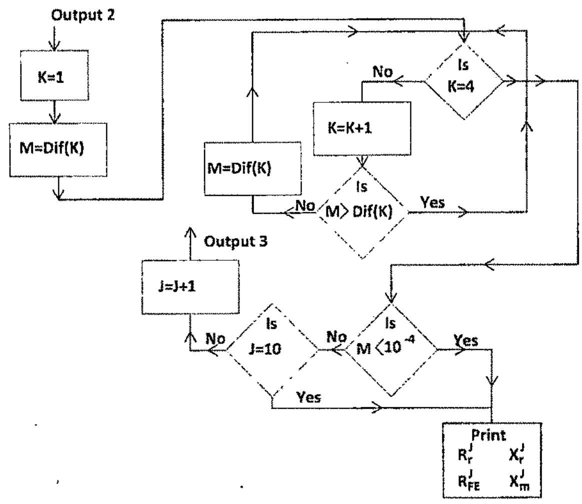
5.6 FLOW CHART FOR CALCULATION OF PARAMETERS.



Flow chart 1: Block diagram for calculating first iteration



Flow chart 2:Block diagram for calculating difference



Flow chart 3: Block diagram for printout of result

5.7 SENSITIVITY ANALYSIS

Taking into account the dependence on measurements whose accuracy, among others, is related with the quality of instrumentation, the developed algorithm was also applied to study the influence of measurement errors on the calculation of parameters.

To check the effectiveness of algorithm for variation in measurements on final value of parameters, the measurements with deviation are presented to algorithm.

- Sensitivity analysis in terms are :

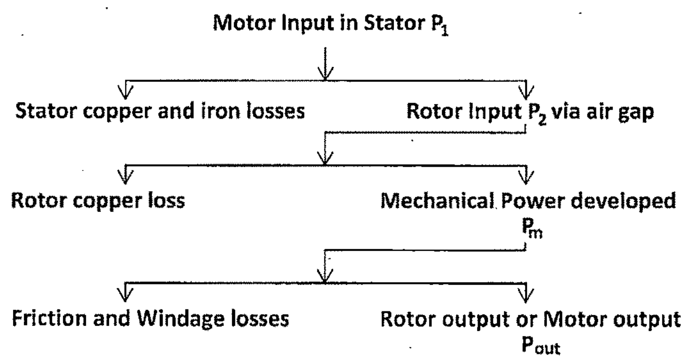
1. Sensitivity of Parameter to errors in current measurement in a Block-Rotor Test:
   a) Magnetizing branch parameters; b) Rotor Parameters

2. Sensitivity of Parameter to errors in Voltage measurement in a No-Load Test:
   a) Magnetizing branch parameters; b) Rotor Parameters

5.8 STEADY STATE PERFORMANCE OF INDUCTION MOTOR

Steady state performances of induction motor are found out algebraically as well as graphically.

Power stages in an induction motor are as below:



Power Stages in an Induction Motor

Performances are determined from following equations from equivalent circuit (Fig 2.1):

Stator input = Stator output + Stator losses

The stator output is transferred entirely inductively to the rotor circuit.

Obviously, Rotor input = Stator output

Rotor gross output = Rotor input – Rotor Cu losses

This Rotor output is converted into mechanical energy and gives rise to gross torque T_g.

Let N r.p.s. be the actual speed of the rotor and if T_g is an N-m, Then

$2\pi N * T_g$= Rotor gross output in watts

$$R_L = R_r\left(\frac{1}{s} - 1\right)\_\_\_\_(5.45)$$

$$Z_r = \frac{R_r}{s} + jX_r\_\_\_\_(5.46)$$

$$\frac{1}{Z_0} = \frac{1}{R_{FE}} + \frac{1}{jX_r} \_\_\_\_(5.47)$$

$$\frac{1}{Z_{co}} = \frac{1}{Z_2} + \frac{1}{Z_0} \_\_\_\_(5.48)$$

$$Z_{eq} = Z_{co} + Z_s \_\_\_\_(5.49)$$

$$I_1 = {}^{V}/_{Z_{eq}} = I_0 + I_2 \_\_\_\_(5.50)$$

$$I_2 = I_2 * \frac{Z_0}{Z_0 + Z_r} \_\_\_\_(5.51)$$

$$P_{out} = 3I_2^2 R_L \_\_\_\_(5.52)$$

$$T_g = P_{out}/\omega_m \_\_\_\_(5.53)$$

$$Rotor\ input = T_g * 2\pi N_s \_\_\_\_(5.54)$$

$$Rotor\ cu\ loss = T_g * 2\pi(N_s - N) \_\_\_\_(5.55)$$

$$\emptyset = \left[\tan^{-1}\left\{\frac{Im(Z_{eq})}{Re(Z_{eq})}\right\}\right] \_\_\_\_(5.56)$$

$$Power\ factor = \cos\emptyset \_\_\_\_(5.57)$$

$$Power\ Input\ P_{in} = 3VI_{eq}\cos\emptyset \_\_\_\_(5.58)$$

$$Efficiency = \frac{P_{out}}{P_{in}} * 100 \_\_\_\_(5.59)$$

5.9 MATLAB PROGRAMS FOR PREDICATING PERFORMANCE OF INDUCTION MOTOR AND TRANSIENT OVER VOLTAGE.

Matlab Programs for Predicating Performance of induction motor and Transient over Voltage are developed. The programs are as mentioned below in table 5.5,

Table 5.5 MATLAB Programs

Program No.	Name of the Program
B1	This Program calculates Parameters of equivalent circuit of Induction motor.
B2	This Program calculates performance of Induction motor from equivalent circuit of the motor at any slip 's'.
B3	Program for Speed torque characteristic rated voltage and frequency.
B4	Program for Speed torque characteristic for variable voltage and rated frequency.
B5	Program for Speed torque characteristic for variable voltage and variable frequency i.e. constant V/f.
B6	Program for drawing Efficiency vs Output characteristic.
B7	Program is B6 but will draw Power factor vs Output and Stator current Vs Output. .
B8	Program is B6 but will draw Speed vs Output. For adjusting scale on Y-axis, dummy points C and D are inserted.
B9	Program is B6 but will draw Torque vs Output.
B10	Program for calculating voltage Transient.
A1	Simulation for No Load test and Load Test
A2	Simulation for Blocked rotor test
A3	Simulation for Voltage Transient

The details of programs are given in Annexure.