International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 1, January- 2013

An Off-Line Technique for Prediction of Performance Characteristics of Three Phase Induction Motor

Dr C V Ghule,
Principal
Agnel Polytechnic,
Navi Mumbai, India

MrsSuhasini S D
Lecturer-Selection Grade
Agnel Polytechnic
Navi Mumbai, India

Mrs Jewel Samanta
Lecturer-Selection Grade
Agnel Polytechnic
Navi Mumbai, India

Abstract

A new off-line technique is proposed to estimate performance characteristics from motor parameters and manufacturer's data. This technique uses estimating the performance characteristics like current, speed, power factor, efficiency and torque from the mathematical formulae relating with the equivalent circuit parameters. Performance of motor has been presented into a set of output graphs. The output graphs permit analysis of various motor parameters. This paper describes ETAP and MATLAB/Simulink implementation of three phase induction motor tests, namely dc, no-load, and blocked-rotor tests performed to identify equivalent circuit parameters. The computed values of the performance parameters have been compared with measured values for verification and validation of the technique. The reasons for deviation from the measured values have been diagnosed. The aim of the paper is to investigate the performance characteristic of available squirrel cage induction motor.

Keywords: equivalent circuit parameters, performance characteristics, ETAP, MATLAB SIMULINK

1. Introduction.

The equivalent circuit parameters for an induction motor can be determined using specific tests on the motor. Three phase induction motors are the motors most frequently encountered in industry. These motors are also called workhorses of the industry. In designing any motor, the accuracy of its performance prediction and economy are the chief objectives. The performance of the three phase induction motor from the parameters of its equivalent circuit is evaluated in the usual way. The necessity of knowing the equivalent circuit parameters of IM is constantly growing. Electric drives using induction motors are one of the main fields of interest to the control systems and electrical engineering specialists. The quality and effective control of induction motors (IM) is based on their equivalent circuits [1]. The inputs required for ETAP simulation are stator resistance and reactance, rotor resistance and reactance power rating of the motor and full load-current of the motor. The formulae are derived for these parameters and calculated values are compared with the ETAP simulation results and errors i.e. the difference between the calculated values and the simulation results is calculated. Performance of motor has been presented into a set of output graphs. The output graphs permit analysis of various motor parameters.

2. Equivalent circuit of 3 Phase Induction Motor.

The equivalent circuit can be used to predict the performance characteristics of the induction motor. The important performance characteristics in the steady state are the efficiency, power factor; current, starting torque etc. The performance characteristics of a 3-phase induction motor can be visualized by equivalent circuit parameters. Figure 1 shows the equivalent circuit offers a convenient and versatile method of analysis. There are common test procedures in order to determine the motor resistances and inductances. The "*DC test*" is used to determine the stator per-phase resistance R_s. From the *"no-load test"* at rated stator frequency and current can be determined the stator inductance (approximate value) and also the power loss due to friction and windage including also core losses. The *"blocked-rotor test"* is useful to determine the rotor per-phase resistance (corresponding to an equivalent three-phase winding referred to the stator turn numbers) and the sum of the leakage inductances of the stator- and rotor windings (referred also to the stator)[2]

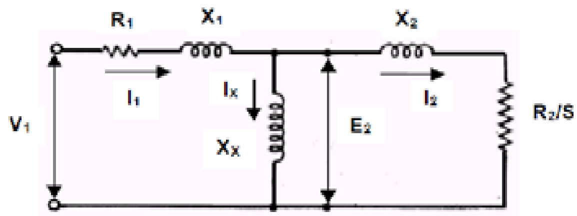

Figure1. Equivalent Circuit

In this circuit R_1 and X_1 represent stator resistance and leakage reactance, respectively; R_2 and X_2 denote the rotor resistance and leakage reactance referred to the stator, respectively; X_m represents magnetizing reactance; and S denotes the slip. The equivalent circuit is used to facilitate the computation of various operating quantities, such as stator current, input power, losses, induced torque, and efficiency. When power aspects of the operation need to be emphasized, the shunt resistance is usually neglected; the core losses can be included in efficiency calculations along with the friction, windage, and stray losses[3] The impressed voltage V_1 causes a current, I_1, to flow in the primary winding. Usually a star connected winding is assumed, making V_1 equal to the line voltage divided by $\sqrt{3}$. A voltage drop occurs in the primary winding, due to its resistance, R_1, and its leakage reactance X_1. The leakage flux in part links the end turns, and in turn crosses the stator slots, without linking the secondary winding. The remaining voltage E_2 is consumed in the magnetizing reactance. The equivalent circuit parameters are found from two tests. They are no-load test and blocked rotor test.

3. Parameter Estimation.

The equivalent circuit parameters can also be found from manufacturer's name plate details. All circuit parameters are listed as follows:

R_s: stator resistance
X_s: stator leakage reactance
X_m: magnetizing reactance
R_c: resistance representing core losses
X_r: rotor reactance= $(1+K'_x S)X_r$,fl
$X_{r,fl}$: rotor reactance at full-load
$X_{r,lr}$: rotor reactance at locked rotor(s=1)
K_x=rotor reactance cage factor to account for deep bars and double cage effects.
R_r: rotor resistance= $(1+K_r S)R_{r,fl}$
$R_{r,fl}$=rotor resistance at full-load
$R_{r,lr}$=rotor resistance at locked rotor
K_r: rotor resistance cage factor
S: slip speed
S_{fl}: slip at full load

The parameters of a simplified equivalent circuit that omits the magnetizing branch are obtained. The performance characteristics required for this method grouped according to various load conditions(locked rotor, maximum torque and full load) usually specified for induction motors are as follows:

Full-load power factor, PF_{fl}
Efficiency, EFF_{fl}
Locked rotor power factor, PF_l
Stator current, $I_{s,lr}$
Torque, T_{lr}
Maximum torque torque , T_m
Slip, S_{Tm}

To illustrate the application of the method, a three-phase 260kW, 6.6kV, 50Hz induction motor was selected.

Name plate data of motor given as input to ETAP- Electro –magnetic Transient Analysis Program (50Hz): 260kW, 6.6kV

Table 1 shows the name plate data of motor given as input to ETAP.

Table 2 shows the estimated rotor parameters using ETAP. When the input from Table 1 is given to ETAP, the rotor parameters were estimated as percentages which were converted into their ohmic values for future analysis.

Table 3 shows the comparison between calculated values using mathematical formulae and the measured values using ETAP. The calculated values were simulated using MATLAB SIMULINK.

Locked rotor			Max.torque	Rated full-load					
Current (Amp)	Torque N-m	p.f	N-m	Current (Amp)	Torque N-m	slip	RPM	p.f	%E FF
161.4	833.2	0.2	1999.6	26.9	833.2	0.0067	2980	0.89	95

"Table 1 Name plate data of motor "

R_s	X_s	X_m	R_c	R_r		X_r	
				@LR	@FL	@LR	@FL
0.96	11.88	355.4	3055.3	2.43	0.69	4.52	10.62

"Table 2 Estimated motor parameters (%)"

slip 'S'%	**Calculated speed 'Nr'**	**Measured Speed 'Nr**	**torque Nm**	**Measured Value Torque Nm**	**Calculated current 'A'**	**Measured current 'A'**	**Calculated % p.f**	**Measured % p.f**	**Calculated Eff=Po /Pi**	**Measured Eff=Po/Pi**
1	**0**	**0**	**849**	**834**	**161**	**161.2**	**20**	**20**	**0**	**0**
.9	300	300	937	799	160	155.6	23.6	19.6	7	7.2
.8	600	600	1044	771	159	150.4	28.2	19.4	13	14.5
.7	900	900	1178	752	158	145.5	34.9	19.4	18	22
.6	1200	1200	1349	744	157	140.8	45	19.5	21	29.7
.5	1500	1500	264	750	119	136.4	11.9	20	29	37.8
.4	1800	1800	329	771	119	132	19.2	29.9	39	46.5
.16	2520	2520	791	1107	116	120.1	24	29.6	69	71.9
.15	2550	2550	839	1144	116	119.4	25.3	30.6	70	73.2
.14	2580	2580	892	1186	116	118.5	26.8	31.7	72	74.6
.11	2670	2670	1100	1345	114	115.3	33	36.2	77	78.9
.10	2700	2700	1189	1414	113	113.9	35.8	38.2	79	80.4
.09	2730	2730	1293	1492	112	112.2	39.2	40.5	81	82
.05	2850	2850	1866	1896	100	98.6	62.9	56.3	89	89.1
.0335	**2900**	**2899**	**2077**	**2004**	**86**	**84.7**	**72.9**	**68**	**92**	**92.4**
.03	2910	2910	2084	1993	82	80.3	84.4	71.1	93	93.1
.0067	**2980**	**2980**	**891**	**835**	**25**	**26.2**	**100**	**88.6**	**98**	**98.3**

"Table3 Calculated values"

4. Calculations Based On the Motor Name Plate Data.

V_1=6.6*10^3/√3=3687V
Z_{base}= (6.6*10^3)/(√3*26.9)
=141.65Ω

R_s= 0.0096*141.65=1.3598Ω

X_s=0.1188*141.65=16.82Ω

X_m=3.554*141.65=503.42Ω

R_c=30.553*141.65=4327.83Ω

$R_{r,lr}$=0.0243*141.65=3.442Ω

$R_{r,fl}$=0.0069*141.65=0.9773Ω

$X_{r,lr}$=0.0452*141.65=6.402Ω

$X_{r,fl}$=0.1062*141.65=15.043Ω

The formulae used are:

Torque=$(3/2\pi N_s)(V_1^2/(R_1+R_2^{'}/S)^2+(X_1+X_2^{'})^2)(R_2^{'}/S)$

$P_G=3I_1^2*R_2^{'}/S$

$P_{grossmech}=(1-S)*P_G$

Output=260kW

Efficiency=output/input=260kW/0.95=273.68kW

Input=$\sqrt{3}*V_L*I_L*\cos\Phi$

Impedance= $Z=\sqrt{((R_1+R_2'/S)**2 + (X_1+X_2')**2)}$

Power factor=R/Z

Current=V_1/Z

These formulas, while presenting idealized conditions in a relatively simplified manner, provide the engineer a basic understanding of the variables to be considered in the design of motors. Factors such as motor starting methods (i.e. high inrush currents), varying speeds and other items all would need to be considered in the total design.The effective secondary resistance and inductance vary in some degree at different secondary frequencies, because of magnetic saturation and also the varying “skin effect”, or current shifting into the lowest impedance paths, at the particular frequency existing at any speed.

5. Performance Characteristics of Induction Motor at Rated Voltage and Frequency using MATLAB Simulink

The parameters determined by test have to be correlated in order to realize the rated data of the motor. The performance of the motors calculated from estimated parameters and calculated parameters from no-load and locked rotor tests results are compared also with measured motor performance at rated torque condition.[4] The calculated performances in the tables are done at the slip value. These graphs represent the complete spectrum of performance of a three phase induction motor. They also help in analysing the motor characteristics.

Figure 2 shows characteristics between slip and efficiency. The losses occurring in a 3-phase induction motor are Cu losses in stator and rotor windings, iron losses in stator and rotor core and friction and windage losses. The iron losses and friction and windage losses are almost independent of load. Had I^2R been constant, the efficiency of the motor would have increased with load. But I^2R loss depends upon load. Therefore, the efficiency of the motor increases with load but the curve is dropping at high loads.

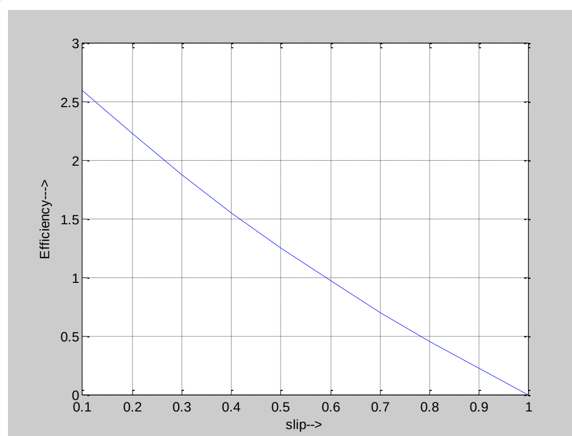

Figure 2

Figure 3 shows characteristics between slip and power factor. As load is added, the active or power component of current increases resulting in a higher power factor. However, because of the large value of magnetizing current, which is present regardless of load, the power factor of an induction motor even at full-load seldom exceeds 90%..

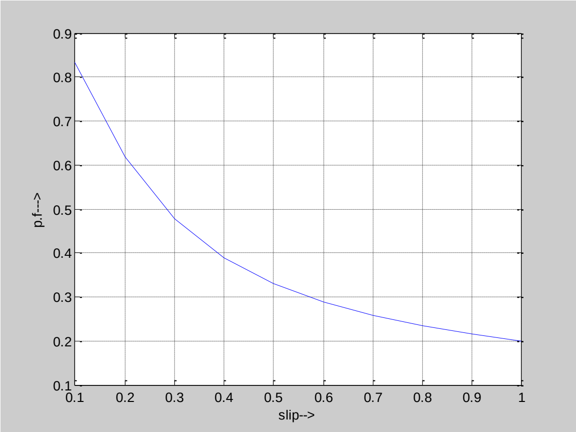

Figure 3

Figure 4 shows the characteristics between slip and current. At no-load, the current drawn by an induction motor is largely a magnetizing current; the no-load current lagging the applied voltage by a large angle. Thus the power factor of a lightly loaded induction motor is very low. Because of the air gap, the reluctance of the magnetic circuit is high, resulting in a large value of no-load current as compared with a transformer.

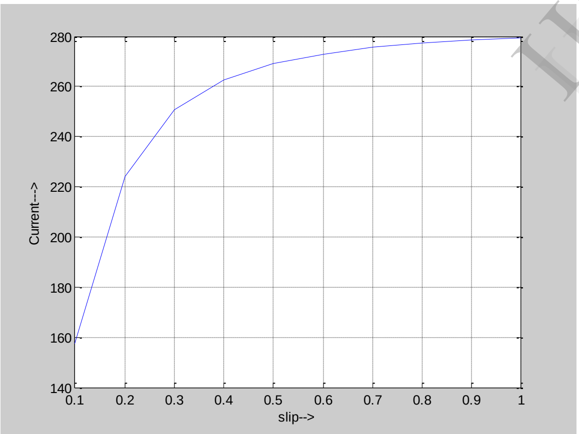

Figure 4

Figure 5 shows the characteristics between slip and torque. As load and slip are increased beyond full-load, the increase in rotor reactance becomes appreciable. The increasing value of rotor impedance not only decreases the rotor power factor but also lowers the rate of increase of rotor current. As a result, the torque and stator current do not increase directly with slip. With the decreasing power factor and the lowered rate of increase in rotor current, the stator current and torque increase at a lower rate. Finally, torque reaches the maximum value at about 25% slip in the standard squirrel cage motor. This maximum value of torque is called the pullout torque or breakdown torque. If the load is increased beyond the breakdown point, the decrease in rotor power factor is greater than the increase in rotor current, resulting in a decreasing torque. The result is that motor slows down quickly and comes to a stop.

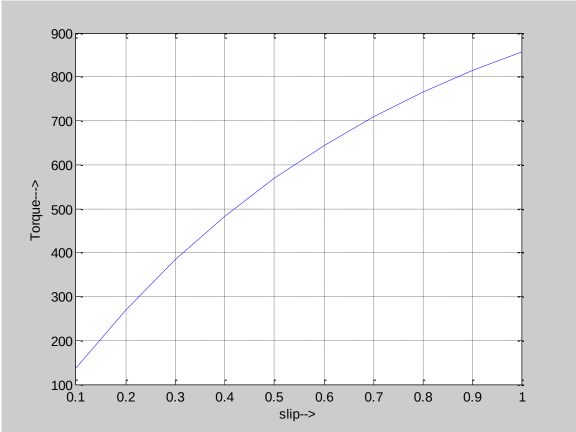

Figure 5

6. Analysis of Performance Characteristics.

The performance curves of a 3-phase induction motor indicate the variations of speed, power factor, efficiency, stator current and torque for different values of load. However, before giving the performance curves in one graph, it is desirable to discuss the variation of torque, and stator current with slip. The no- load test is used to determine the core loss resistance. The blocked rotor test enables to determine the rotor resistance, the magnetizing reactance and the sum of the stator and rotor leakage reactances. By this approach, however, it is not possible to know how the leakage reactances are shared between the rotor and stator. This deteriorates the accuracy when predicting the dynamic performance of the motor. The data from this investigation will be useful to those involved in the design of induction motor drive systems as well as motor manufacturers where the data can aid in the design of more efficient machines. The parameter variations identified here will be used to model the performance of a three-phase induction motor undergoing various methods of synthetic loading.[5]

7. Conclusion

The approach to this off-line method is very simple and convenient to implement.There is a deviation between the calculated values and the measured values with reference to Table 3.The reasons for the deviation can be accounted as follows. The machine parameters in the equivalent circuit hardly remain constant during operating condition. Both stator and rotor resistances increase linearly with temperature, depending on the temperature coefficient of the resistance of the material. There is skin effect due to harmonics. This effect causes current crowding on the conductor surface, which causes an increase of resistance, but decrease of leakage inductance. The skin effect is negligible on the stator winding, but its effect is dominant on the rotor bars. The magnetizing inductance is subjected to saturation with higher magnetizing current The skin effect in the rotor winding and the iron core saturation effect lead to complications in the modeling process of a squirrel cage motor. Therefore indirect measurement methods and calculations must be used for the parameter determination from the data given by reference or by experimentally measured speed-torque characteristics [6]. Since the most important aim of this method is based on the motor nameplate and catalogue they can be applied to various equivalent circuit modifications.

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