# Virtual Laboratory Platform for Enhancing Undergraduate Level Induction Motor Course Using MATLAB/Simulink

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**Abstract—With the advent of various simulation software packages and low cost personal computing devices in the market, computer-aided teaching tools have become an important part of present pedagogy. These tools support the classroom teaching by enabling the instructor to illustrate the working of various systems by means of computer generated graphics. This paper presents a very easy and interactive model based on computer simulation in MATLAB/Simulink to simulate the no load test, load test and blocked rotor test on 3-phase slip ring and squirrel cage induction motors. The well known equivalent circuit model along with the torque equation is used to model the motor without considering the effects of magnetic saturation. The simulation environment plots all relevant graphs including circle diagram of the given motor, thus acting as a complete graphical teaching aid for the induction machine course at undergraduate level. This model facilitates learning especially for the students pursuing a distance-learning/correspondence course which does not provide them with the laboratory facilities.**

***Keywords- Induction motor, squirrel cage, slip ring, experimental tests, simulation, MATLAB/Simulink***

## I. INTRODUCTION

In the domain of electrical engineering, courses related to induction motor (IM) at undergraduate level are the budding stages of the pedagogy of electrical machine analysis and design. Therefore, a proper understanding of the concepts taught in these courses is of utmost importance for a student who wants to pursue a career in power and electric machinery engineering. At undergraduate level, for having a basic understanding of the steady state behaviour of an IM, the following tests are usually conducted: 1) no load test; 2) blocked rotor test; and 3) load test, followed by the plotting of circle diagram. The results of these tests form a near-complete picture of the steady state behaviour of the IM under study. So, out of all concepts such as magnetic coupling, rotating magnetic field, induction phenomena etc. related to the IM, the understanding of the above mentioned tests and the plot of circle diagram becomes imperative because they give the practical values of the electrical parameters.

This paper introduces specialized computational tools as a part of laboratory experiments to enhance the classroom teaching of the courses related to IM by providing the students with an opportunity to compare the results of their laboratory experiments by those obtained through computer simulation. Such a comparison will help the students to realize the superiority of simulation tools over hardware experiments. Moreover, an undergraduate electric machinery course that integrates up-to-date computer hardware and software tools in both lecture and laboratory sessions, also meets with the expectations of today's students who want to use computers and simulation tools in every aspect of the courses, thus possibly attracting more students. To make the simulation even more efficient and user friendly, the following special features are incorporated in the model: 1) the model consists of self designed 'data collector' blocks, which help in real time collection of simulation data; 2) a MATLAB script file is used along with the model, which compiles the simulation data collected by the data collector blocks and plots the results in the form of graphs. It also provides the user a freedom to make further use of that data; 3) an option is provided to choose between automatic and manual modes of loading the IM; and 4) proper arrangements for the measurement of power, voltage, current, phase angle, power factor, speed, torque and efficiency have been provided for a complete understanding of the state of the machine.

The remainder of the paper is organized as follows. Section II covers the basic theory of IM. Section III describes the dc test, no load test, blocked rotor test and determining the mechanical parameters of the IM under study. Section IV explains the MATLAB/Simulink model of 3-phase slip ring and squirrel cage induction motors and its working in full detail. Section V describes the simulation results of the models. Section VI concludes the paper.

## II. BASIC THEORY OF INDUCTION MOTOR

Like any conventional electrical machine, the IM has two active elements, the stator and the rotor, which are nothing but two balanced 3-phase windings. They interact via an air gap where the energy exchange takes place. In normal operation, the stator is excited by alternating voltage (ac voltage), which creates a rotating magnetic field. Due to this field, which is evidently time varying alternating currents (ac current) are induced in the rotor windings. Now these rotor currents in turn interact with the rotating magnetic field to produce a torque.

Because of the symmetry of the balanced 3-phase rotor and stator windings, it is sufficient to take only one phase into account. Each phase has a power loss and a leakage flux associated with it, which is modelled by a resistance $R_1$ and a reactance $X_1$, respectively, in series with it. The windings are magnetically coupled and suffer a constant real power loss that is the core loss. This is taken into account by the magnetizing branch, which is nothing but a parallel combination of a mutual inductive reactance $X_m$ and a core loss resistance $R_c$, respectively. The frequency of the currents in rotor windings depends on the rotation speed ($N$) of the shaft and hence the slip ($s$), which is given by;

$$s = \frac{N_s - N}{N_s} \tag{1}$$

where $N_s$ is the synchronous speed of the IM.

The leakage reactance of the rotor windings is expressed as $X'_2/s$. But since the concept of a varying reactance is not very comprehensible, it is found in the textbooks related to electric machinery that the resistance of the rotor winding is shown as $R'_2/s$ [1]. Fig. 1 shows the per phase equivalent circuit of the 3-phase IM.

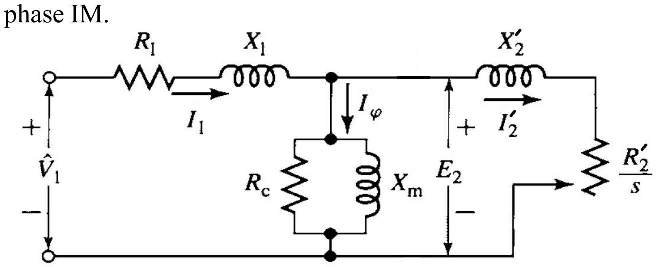



Figure 1. Per phase equivalent circuit of IM

Although it is possible to compute the operating characteristics of an induction motor by using the equivalent circuit, it is simpler and more convenient to use a circle diagram for this purpose.The circle diagram is basically a polar plot, which is the result of plotting either voltage (V) or power (VA) versus polar coordinates of current. For plotting the circle diagram for an IM, the imaginary component of input line current on its x-axis, i.e. I*sin $\phi$ and input power consumed per phase equivalent circuit of the 3-phase IM on y-axis. Using the circle diagram, all the performance characteristics of an induction motor like power factor, efficiency, stator losses, rotor losses, maximum output power, maximum torque etc. can be predicted.

## III. Determination of Equivalent Circuit Parameters From The Experimental Tests

The equivalent circuit parameters needed for studying the performance of the IM can be obtained from the results of no load test, blocked rotor test and dc test.

### A. DC Stator Resistance Test

This test is done to find the stator resistance. It can be done by simple voltmeter-ammeter test or even a multimeter is sufficient. By this method, the value of stator resistance was found to be, $R_1$=1.8667 Ω/phase.

### B. No Load Test

The no load test [1] is performed on an IM to determine the core loss resistance $R_c$ and reactance due to mutual inductance of the stator and rotor windings, $X_m$. This test is generally performed at the rated frequency (50 Hz) and with balanced 3-phase voltages applied to the stator terminals. The readings are taken at rated line-to-line voltage i.e. $V_{nl}$ = 440 V, after the machine has been running long enough for it to be in steady state condition. The following measurements are available from the no load test:

$I_{nl}$ = line current = 3.0 A;

$P_{nl}$ = total 3-phase power input = 160 W

At no load, the rotor current has a very small value, which is just sufficient enough to produce a torque to overcome the friction and windage losses associated with rotation. The no load $I^2R$ loss is therefore very small, but in comparison with that of the no load test on a transformer, it is appreciable because of the larger excitation current required due to the presence of air gap. The reflected rotor resistance ($R_2/s$) is very large, since the slip at no load is very small ($s \approx 0$). So the rotor branch of the equivalent circuit can be considered to be open as shown in Fig. 2.

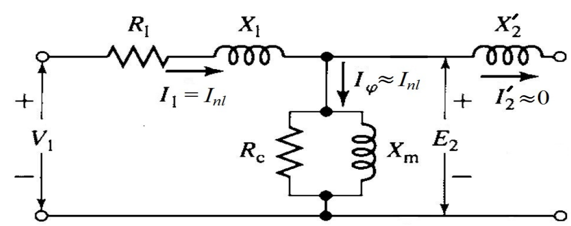



Figure 2. Equivalent circuit for the no load test

If $S_{nl}$ is the apparent power and $\phi_{nl}$ is the no load power angle, the power equation (in complex form) for the circuit is given by:

$$S_{nl} = I_{nl}^2 R_1 + (I_{nl}\cos\phi_{nl})^2 R_c + j(I_{nl}^2 X_1 + (I_{nl}\sin\phi_{nl})^2 X_m) \tag{2}$$

Let us assume that the equivalent no load resistance and reactance, $R_{nl}$ and $X_{nl}$ respectively, are in parallel, so that:

$$S_{nl} = (I_{nl}\cos\phi_{nl})^2 R_{nl} + j(I_{nl}\sin\phi_{nl})^2 X_{nl} \tag{3}$$

Consequently, the expressions for the calculation of core loss resistance $R_c$ and magnetizing inductance $X_m$ can be deduced from the above equations as follows:

$$R_c = R_{nl} - \frac{R_1}{\cos^2\phi_{nl}} \quad \text{and} \quad X_m = X_{nl} - \frac{X_1}{\sin^2\phi_{nl}} \tag{4}$$

Since the calculations are based on the per phase equivalent circuit of the 3-phase IM, the equivalent no load resistance and reactance of the stator can be determined as:

$$R_{nl} = \frac{P_{nl}}{3(I_{nl}\cos\phi_{nl})^2} \quad \text{and} \quad X_{nl} = \frac{Q_{nl}}{3(I_{nl}\sin\phi_{nl})^2} \tag{5}$$

where $Q_{nl} = \sqrt{S_{nl}^2 - P_{nl}^2}$

Using (2) to (5), the values of the parameters are:

$S_{nl} = \sqrt{3} * V_{nl} I_{nl} = 2286.3071$ VA

$P_{nl}$ = 160 W (measured from experiment)

$Q_{nl}$ = 2280.7016 VAr

$\sin\phi_{nl} = Q_{nl}/S_{nl} = 0.9975$ and $\cos\phi_{nl} = P_{nl}/S_{nl} = 0.07$

$R_{nl}$ = 1210.0 Ω/ phase and $X_{nl}$ = 84.8862 Ω/ phase

### C. Blocked Rotor Test

The blocked rotor test gives the information about the leakage impedances. The blocking of rotor is usually done by mechanical locking. Since the rotor is blocked, so slip $s$ = 1. The balanced 3-phase voltages are applied to the stator terminals and the magnitude of the phase voltages are such that the rated current is circulated in the circuit. It is similar to the short circuit test done in transformers where the secondary side is shorted as shown in Fig. 3.

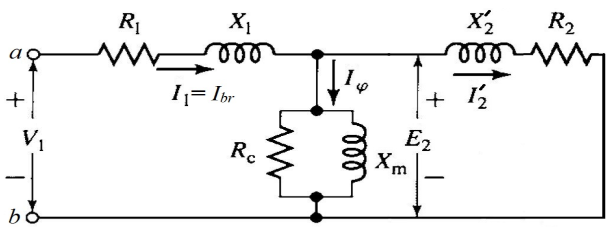



Figure 3. Equivalent circuit for the blocked rotor test

Measurements available from blocked rotor test are:

$V_{br}$ = line-to-line voltage = 114 V

$I_{br}$ = line current (rated current) = 7.0 A

$P_{br}$ = total 3-phase power input = 540 W

Considering the equivalent blocked rotor resistance, $R_{br}$ and reactance, $X_{br}$ are in series, the parameters can be calculated using the following equations:

$$R_{br} = \frac{P_{br}}{3I_{br}^2} \quad \text{and} \quad X_{br} = \frac{Q_{br}}{3I_{br}^2} \tag{6}$$

where $Q_{br} = \sqrt{S_{br}^2 - P_{br}^2}$

Using (6), the values of the parameters are:

$S_{br} = \sqrt{3} V_{br} I_{br} = 1382.1765$ VA

$P_{br}$ = 540 W (measured from experiment)

$Q_{br}$ = 1272.3254 VAr

$R_{br}$ = 3.6735 Ω/phase and $X_{br}$ = 8.6553 Ω/ phase

Now there is a need to find the values of the rotor and stator parameters explicitly. Looking at the circuit shown in Fig. 3, the equivalent impedance $Z_{br}$ across the terminals 'ab' can be deduced as:

$$Z_{br} = (R_1 + jX_1) + \{(R_2 + jX_2) \parallel jX_m \parallel R_c\} \tag{7}$$

Assuming that $R_2 << X_m$, the expression is reduced to the following form:

$$Z_{br} = \left[\left(R_1 + R_2\left(\frac{X_m}{X_2 + X_m}\right) \parallel R_c^2\right) + j\left(X_1 + X_2\left(\frac{X_m}{X_2 + X_m}\right) \parallel R_c\right)\right] \tag{8}$$

Assuming that $R_1 + R_2 << R_C$, the values of $R_2$ and $X_2$ can be calculated as:

$$X_2 = (X_{br} - X_1)\left(\frac{X_m}{X_m + X_1 - X_{br}}\right) \tag{9}$$

$$R_2 = (R_{br} - R_1)\left(\frac{X_2 + X_m}{X_m}\right)^2 \tag{10}$$

Also, $\sin\phi_{nl} = 0.9975$, $\sin^2\phi_{nl} = 0.9951$

Hence $X_m$ in (4) can be modified as:

$X_m \approx X_{nl} - X_1$

$$X_2 = (X_{br} - X_1)\left(\frac{X_{nl} - X_1}{X_{nl} - X_{br}}\right) \tag{11}$$

To find the value of $X_1$ and $X_2$, the standard empirical ratio of stator to rotor reactance has been used [4]. This ratio depends upon the class of the motor. The IM on which the experiments were performed belongs to class C, which implies $X_1$: $X_2$ = 7:3. Substituting $X_2 = 7X_1/3$ in (11) and solving for $X_1$ while knowing the fact that $X_m = X_{nl} - X_1 > 0$, the value of $X_1$ is:

$$X_1 = \frac{5X_{nl} - 2X_{br}}{3} - \sqrt{\left(\frac{5X_{nl} - 2X_{br}}{3}\right)^2 - X_{nl}X_{br}} \tag{12}$$

Using above relations, the values of the equivalent circuit parameters of the IM under consideration at $f$ = 50 Hz are:

| | |
|---|---|
| $R_1$ = 1.8667 Ω/ phase | $X_2$ = 6.3806 Ω/ phase |
| $X_1$ = 2.7345 Ω/ phase | $L_1$ = 0.0087 H/ phase |
| $R_c$ = 828.850 Ω/ phase | $L_2$ = 0.0203 H/ phase |
| $X_m$ = 82.1382 Ω/ phase | $L_m$ = 0.2689 H/ phase |
| $R_2$ = 2.0984 Ω/ phase | |

### D. Determining Mechanical Parameters

The dynamics of the IM is assumed to be a 2nd order LTI system which is governed by the following differential equation [1]:

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - T_m - F\omega_m) \tag{13}$$

where $\omega_m = d\theta_m / dt$ and $\theta_m$ = rotor position (angle) in space; $T_e$ = torque developed; $T_m$ = mechanical load on IM; $H$ = kinetic energy (Per unit) of rotor; $F$ = damping constant due to friction.

#### 1) Moment of Inertia, J (kg.m²)

The moment of inertia of a solid cylindrical body can be found using the formula, $J = 0.5MR^2$, where

$M$ = mass of rotor shaft + mass of brake drum = 10 kg

$R$ = radius of brake drum = 0.155 m

The value was found to be, $J = 0.1201$ kg.m$^2$

*2) Damping Constant, F (N.m.s)*

To find an approximation to $F$, the IM was started at no load, i.e. $T_m = 0$ and after some time when it attained steady state condition, the electrical supply was cut off ($T_e = 0$). Therefore,

$$\frac{d}{dt}\omega_m = \frac{-F\omega_m}{2H} \Rightarrow \frac{d\omega_m}{\omega_m} = \frac{-Fdt}{2H} \tag{14}$$

Now, the speed of the IM is allowed to drop to half of its no load speed by constant monitoring with a digital tachometer and simultaneously noting the time taken. Now integrating over the practical limits, i.e. from no load speed to half the speed attained after cutting off the electrical supply the resultant is:

$$\int_{\omega_{nl}}^{\omega_{nl}/2}\left(\frac{d\omega_m}{\omega_m}\right) = \int_0^t\left(\frac{-Fdt}{2H}\right) \Rightarrow F = \frac{2H\ln(2)}{t} \tag{15}$$

Now, $H = \frac{Rotational\ Kinetic\ Energy}{Apparent\ Electrical\ Power} = \frac{0.5J\omega_{nl}^2}{\sqrt{3}*V_{nl}I_{nl}}$

$\omega_{nl} = 1498*2\pi/60 = 156.8702$ rad/s;

Knowing that, $V_{nl} = 440$V and $I_{nl} = 3$A;

$H = 0.6465$ J/VA ; $t = 199$ seconds (from experiment);

From the above data and using (15), $F$ can be calculated. The value was found to be: $F = 0.004504$ N.m.s

Along with the equivalent circuit parameters determined earlier in this section, and $J$ and $F$ can now be used to complete the parameters of the asynchronous machine block used in the simulation model.

## IV. Development of Virtual Laboratory

### A. Simulation model description

The computer software package MATLAB/Simulink is used to implement the no load test, load test and blocked rotor test on both squirrel cage and slip ring IMs in two separate model files as shown in Fig. 4 (a) and (b).

Each model consists of the conventional asynchronous machine block available in the SimPowerSystems blockset [7]. This asynchronous machine block is modified to fit the description of the test motor, which is available with the institute's electric machinery laboratory. The motive behind designing this simulation environment is to develop a simple and yet comprehensive model, which gives the user the exact experience of performing the experiment in a laboratory. In the model, a three phase IM is excited by a 3-phase voltage source with current and voltage measurement blocks connected in between. The power is measured by the help of the two wattmeter method. The load on the motor is simulated by a ramp function from the Math Operations blockset [7], which keeps increasing linearly with time with a slope of 10 units. This slope can be changed by the user as desired. This means, with each one second of the simulation time, the load on the IM increases by 10 Nm. This ramp function block is named as 'automatic load' in the model diagrams shown in Fig. 4 (a) and (b). In order to provide the user an opportunity to check the response of the machine at a load of his/her choice, a manual loading is also simulated using the slider function from the same blockset. Finally the output of machine is taken using a bus selector block and so the results such as rpm, output torque, output mechanical power, slip and efficiency are displayed. These model are designed to 'pause the simulation' when the rpm of the motor goes below 0 by using the assertion block in tandem with mathematical comparator blocks [7].

### B. Model functioning

The user can select between automatic and manual loading with the help of the switch provided. When the simulation is started and if the automatic load has been selected, then during the period of 0 to 4 seconds the motor is running on no load. When the time equals 4 seconds the load starts increasing on the machine with a slope of 10 units. If the user has selected manual loading, then the load can be changed anytime as desired. For simulating the blocked rotor test, the user needs to change the inertia of the motor to 'inf' in the asynchronous machine block. The user may 'pause' the simulation anytime to check the performance of the motor. The display boxes show the changes in rpm, torque etc. continuously. At the end of simulation, various graphs along with the circle diagram are plotted using the simulation data by the help of MATLAB-script files. The circle diagram is also generated by writing a code for plotting through coordinate geometry. This provides a comparison between the simulation data plot and the geometrical plot and hence becomes an effective means of validation for the simulation model.

### C. Description of the data collector blocks

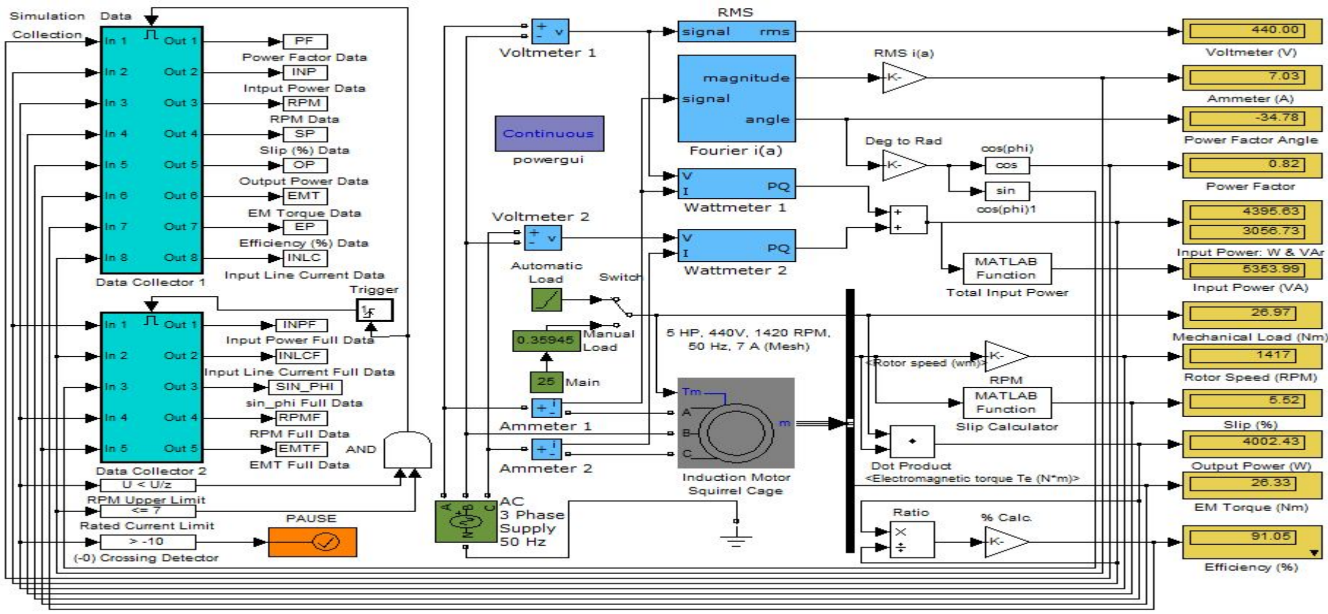
In the model two data collector blocks have been used, which are activated on simple Boolean logic. The term 'data collection' refers to storing the simulation data in the MATLAB workspace, so that it can be used after simulation ends. These blocks are activated when time equals 4 seconds, so that the data during the time period of 0 to 4 seconds is ignored owing to the fact that no load is being applied on the machine during that period. The data collector block-I collects the data from the model up to the rated current of the machine (7A in this case). The collected data namely power factor, input power, rpm, slip, output power, electromagnetic torque and input line current are stored in the workspace. A script file was written in MATLAB to make appropriate use of them. The data collector block-II is used to collect the full range of data, i.e. when the time equals 4 seconds till the motor stops. This data is required for plotting of the circle diagram and the torque v/s speed (rpm) characteristics.

## V. Results and Validation

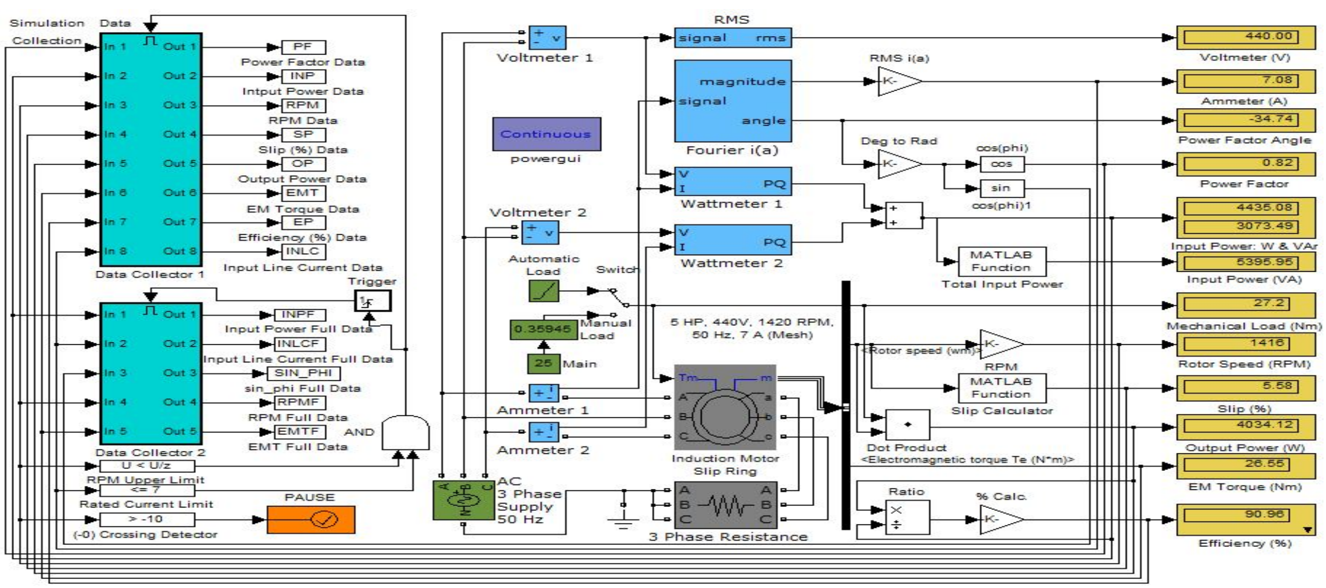
The tests mentioned in section III were physically conducted on 3-phase, 440 V, 5 HP, 7A (mesh), squirrel cage and slip ring IMs available with the institute's electric machinery laboratory. Keeping in view the various observational errors and the errors in measuring instruments, a satisfactory level of validation was obtained between the values obtained by performing the related experiments physically in the laboratory and those obtained from the simulation model, thus demonstrating the fair accuracy of the presented model. The same can be referred from Table 1 and the various characteristics of the induction motors from the simulation models including circle diagram are described in Fig. 5 to 8.

TABLE I. PRACTICAL AND SIMULATION RESULTS

| S. No. | Parameter | Practical | | Simulation | |
|---|---|---|---|---|---|
| | | ***No Load*** | ***Blocked Rotor*** | ***No Load*** | ***Blocked Rotor*** |
| 1 | Voltage (V) | 440 | 114 | 440 | 114 |
| 2 | Current (A) | 3 | 7 | 3 | 6.97 |
| 3 | Power (W) | 160 | 540 | 161 | 535.40 |




(a)




(b)

Figure 4. Induction motor simulation environment for no load test, blocked rotor test: (a) squirrel cage IM (b) slip ring IM

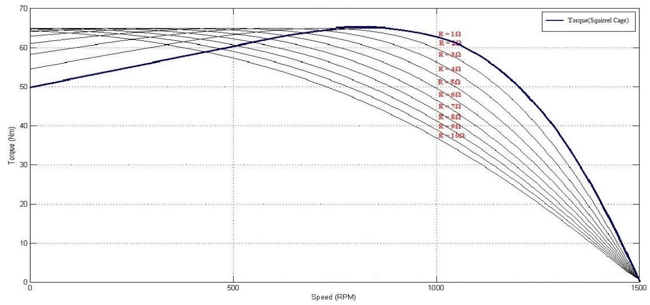



Figure 5. Torque v/s speed (rpm) - slip ring IM (resistace varries from 1Ω to 10Ω)

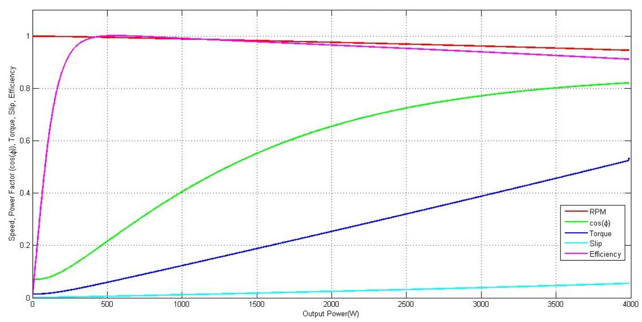



Figure 6. The normalized parameters of speed, power factor (cosϕ), torque, slip, efficiency v/s output power

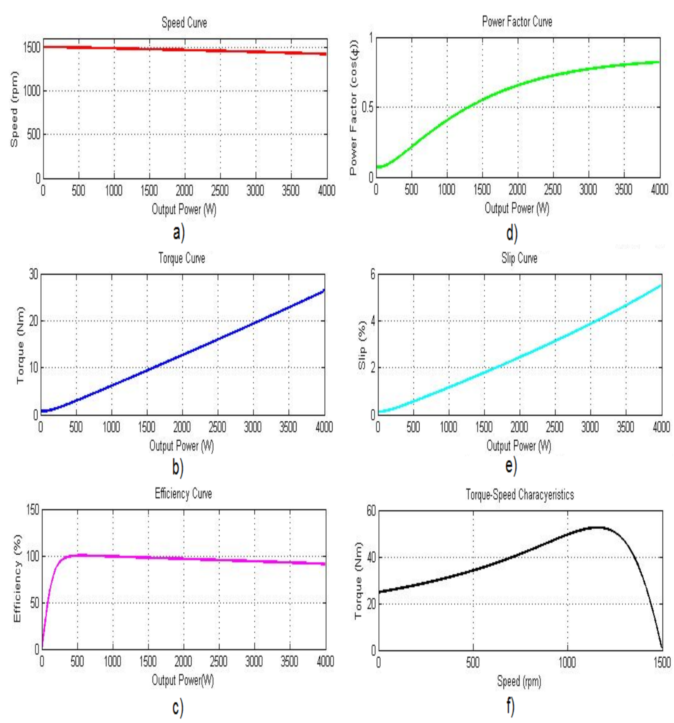



Figure 7. (a) speed (rpm) v/s output power; (b) torque v/s output power; (c) efficiency v/s output power; (d) power factor v/s output power; (e) slip(%) v/s output power; and (f) torque v/s speed (rpm)

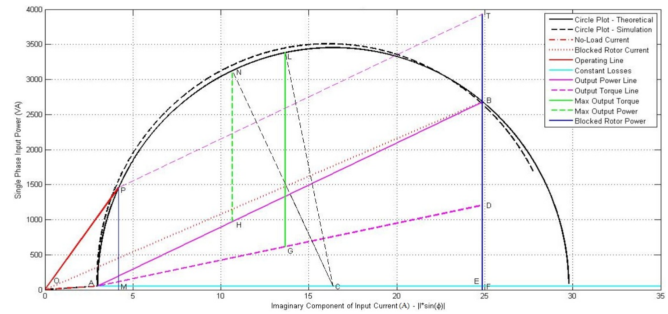



Figure 8. Circle diagrams: plotted from simulation data and coded geometry

## VI. Conclusions And Future Prospects

Due to the cumbersome nature of these experimental tests, a proper and extensive laboratory setup and a keen set of observational skills are required. But as observed, these laboratories are subjected to an extensive maintenance processes and even after that the experiments are not guaranteed to be hassle-free and accurate. By the help of these simulation models, the experimentation can be done on a virtual platform even by a user with superficial understanding of MATLAB/Simulink with much more flexibility and increased accuracy along with a greater understanding of both observations and results.

Comparing the time taken for generating the simulation results with that required for physical experimentation, shows the superiority of the simulation approach over its less technical and erroneous counterpart. A logical extension of this work would be expanding this virtual laboratory to include simulink models of experiments related to transformers, dc machines and synchronous machines, so that a complete simulation package is available to support courses related to electric machinery.

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