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Load Characterization Tool for Induction Motors on the Basis of Laboratory Tests

Fredy H. Martínez S., Holman Montiel A. and Fernando Martínez S.

Universidad Distrital Francisco José de Caldas, Bogotá D.C., Colombia.

Abstract

This paper presents a novel tool for the characterization of induction motors from laboratory tests. The relevance of this identification lies in the industrial importance of these engines, due to their great massification, high efficiency and low cost. The tool supports the calculation of the induction motor parameters from four physical tests on the machine: winding resistance test, locked rotor test, mechanical loss test and no-load motor test. In addition to the estimation of the machine parameters, the software can develop the torque, power and efficiency curves of the machine. We have carried out tests on a 1 kW induction motor, applying the different tests required to determine the performance, and comparing the final results with those supplied by the manufacturer.

Keywords: Blocked rotor, induction motor, mechanical losses, model, parameter identification, winding resistance.

INTRODUCTION

The induction motor, or asynchronous motor, is an AC electric motor in which the current in the rotor is produced by electromagnetic induction from the magnetic field of the stator. This construction feature avoids the use of mechanical switches, which is why its cost and maintenance are lower than other electrical machines (DC motors, universal motors and large synchronous motors) [1].

The rotor of the induction motor can be of two types: squirrel cage or winding. In either case, the coils are three-phase and 120-degree offset. When three-phase alternating current is applied to the stator coils, a rotating magnetic field is produced that induces currents in the rotor, and a torque on the rotor, which causes the rotor to rotate. This only occurs if there is a difference between the stator and rotor field velocities (sliding). Sliding varies according to the mechanical load applied to the motor shaft. In spite of this, and the torque variations, the engine varies little its speed, so they are considered constant speed motors.

At start-up the sliding is very high (the rotor is at rest), so the induced current in the rotor is very high. The stator impedance is very low and the current consumed is very high (up to seven times the rated current). Although this feature is transitory, and the motor is designed to support it, it does cause problems to the power grid. Now, very frequent start-ups can raise the stator temperature and reduce the life of the machine. This is the reason for the use of starters that control the starting of the engine. In fact, this equipment has evolved from simple starter to speed controls, which are now widely used due to their high efficiency and power factor correction (and therefore cost reduction) [12].

It is precisely the high present development of these drives, together with the need to use the electric machines in their maximum performance point and stability that has led to the obligation to determine the parameters of the induction motors, as well as their operation characteristics [11].

The machine's estimated parameters are used to construct a behavioral model that can be emulated in real time within a digital processor [5, 7]. Speed control schemes include V/Hz scalar control, direct torque control (DTC) and field-oriented control [9]. These are closed loop schemes in which transducers are not used on the motor shaft, but use a flow observer from the machine's currents and voltages [3, 6].

In the model of the induction machine it is of particular interest to achieve the most accurate description possible of the non-linear phenomena of the machine, especially the saturation, the skin effect and the losses. Only at these points a multitude of schemes have been proposed, ranging from numerical methods to bio-inspired algorithms of uninformed searches and finite elements [4, 8].

In recent years new control strategies have emerged for induction motors, in particular for the description of the model at the non-linear operating points. Among these methods are: nonlinear model predictive control, sliding mode and nonlinear control [10]. The predictive control model is currently the most widely used in both research and practical applications. This scheme focuses on optimizing the dynamic model of the engine for each sampling interval of its variables. Again it is important to evaluate a momentary model of the machine from its parameters, in this case in real time.

This paper presents a tool to calculate the model of an induction machine from its four basic parameter identification tests: winding resistance, blocked rotor, mechanical losses and vacuum test [2]. Later the identified model is used to plot the characteristic curves of the machine.

The paper is organized as follows. Section 2 presents preliminary concepts and problem formulation. Section 3 illustrates the development methodology of the tool, and its use for model construction. In Section 4 we present some results from actual engine tests. And finally, in Section 5, we present our conclusions.

PROBLEM FORMULATION

The different levels and categories of efficiency of induction motors are not standardized, and there are different categories in different countries. This causes problems in the selection and use of different machines. A good practice is to classify the machine according to its efficiency with respect to the IEC 60034-30 standard.

These classifications are based on the identification and modeling of the machine, which are performed through laboratory tests.

As support in the development of linearized and non-linear models of three-phase induction motors, the development of a software tool for the processing and visualization of machine parameterization information from laboratory tests is proposed. This tool must be intuitive, easy to use and capable of showing the most relevant operating characteristics of the machines in summarized form. The test machine selected was a motor widely documented by the research group: 208 V three-phase motor, three poles, 60 Hz and 1 kW nominal power. The nominal values of the machine manufacturer are also known.

For integration with other software tools of the research group, it is required that the software development be done in MatLab (Matrix Laboratory by MathWorks) with graphical user interface (GUI).

METHODOLOGY

As a step prior to the use of the tool we must perform the four laboratory tests on the machine. In the case of the test machine, the results were as follows:

- Winding resistance:
  - V_{dc} = 1 V
  - C_{dc} = 0.41 A
- Locked rotor:
  - Nominal current (line) = 2.77 A
  - $V_{br(line)}$ = 27 V
  - $Power_{3\phi br}$ = 59.4 W
- Without charge:
  - Nominal current (line) = 1.56 A
  - $V_{br(line)}$ = 208 V
  - $Power_{3\phi 0}$ = 450 W
- Mechanical losses:
- Friction and wind $losses_{3\phi}$ = 450 W

The tool was designed to guide the user in determining the machine model. In addition, it validates the coherence of each of the values entered, presenting error messages when detecting inconsistencies. The first window of the tool introduces its function and the required previous data (Figure 1). This window does not request data from the user, but it details the required tests on the machine, tests that will generate the data required for analysis.

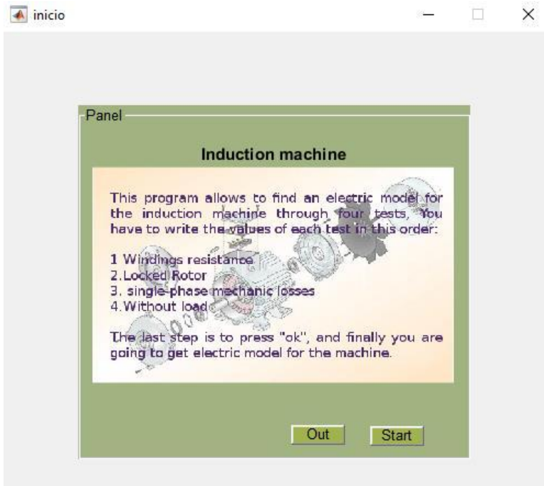

Figure 1: Software presentation panel

There is no specific order to apply the tests on the machine, but it is necessary to apply them all. These tests are not detailed here, but must follow the procedures specified in the relevant standard.

The test data will begin to be entered in the next window. The software starts with the winding resistance, and proceeds with the following step-by-step information. As mentioned, the software checks the consistency of the entered values, in case of inconsistencies, it presents an error window, as the case shown in Figure 2.

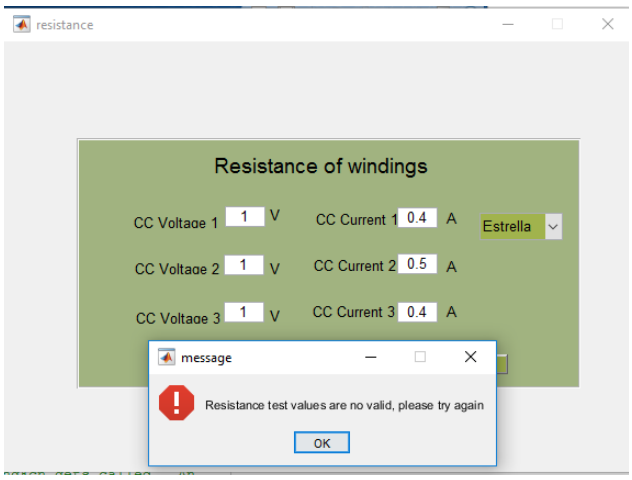

Figure 2: Error message due to inconsistency with test values

In this particular case the data is filtered according to the expected values for the winding resistors (Figure 3). The check is carried out by calculating the mean value and the standard deviation. If the values are consistent, the tool proceeds by asking for the motor connection.

```
M3=sum(vec3)/3;
S3=std(vec3);

M4=sum(vec4)/3;
S4=std(vec4);

for i=1:3

if  (vec3(i)>= M3-S3) &&  (vec3(i)<= M3+S3) && (vec4(i)>= M4-S4) &&  (vec4(i)<= M4+S4)
    if (i==3)
          % Y motor

        if(connection==1)


         R1 = (M3/M4)*0.5
        % Delta motor

        elseif(connection==2)

        R1 = (2*M3/3*M4)

        end

```

Figure 3: Consistency verification code in the winding resistance test

The next window starts with the results of the locked rotor test (Figure 4). Again, this section checks the consistency of the data.

Figure 4: Locked rotor test results capture window

In this window it is possible to select the motor class. From this selection the series reactance is defined. In the case shown in the figure, the motor is class A. The definition of the reactance is done as shown in Figure 5.

```
        end
    if(class==1)

        X1 = (Xe/2)
        X2 = (Xe/2)

    elseif (class==2)

        X1 = 0.4*Xe
        X2 = 0.6*Xe

    elseif (class==3)

        X1 = 0.3*Xe
        X2 = 0.7*Xe

    elseif (class==4)

        X1 = 0.5*Xe
        X2 = 0.5*Xe
    end
```

Figure 5: Definition of series reactance for locked rotor test

The next window involves the mechanical loss test results (Figure 6). In the fields of the window it is necessary to enter the corresponding values per phase.

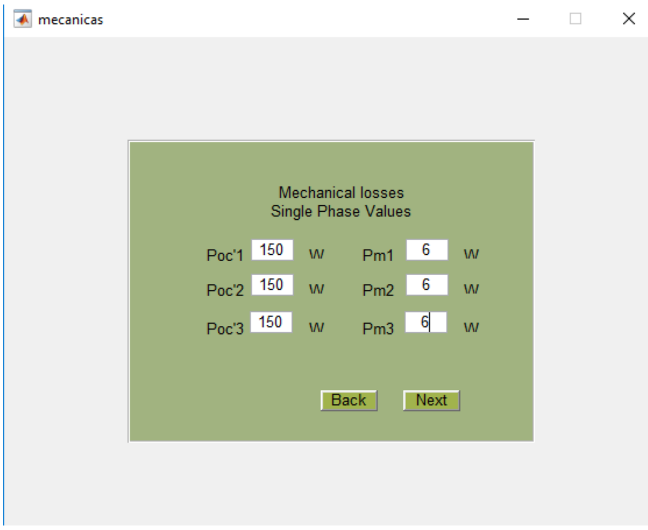

Figure 6: Mechanical losses test results capture window

Finally, the next window is for the data capture of the last test, the no-load motor test (Figure 7).

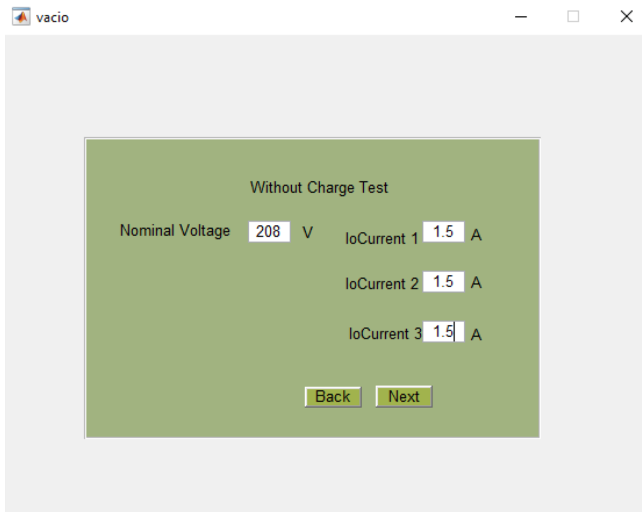

Figure 7: No-load motor test results capture window

With all this information it is possible to calculate the electric model of the induction motor considering the connection of the machine.

When the loading of values into the tool is complete, and after pressing the *Next* button on the window, the software verifies the final data and shows the electrical model of the machine (Figure 8). The window shows an equivalent electrical circuit diagram with the numerical values of each of the linear elements of the model, with their respective units.

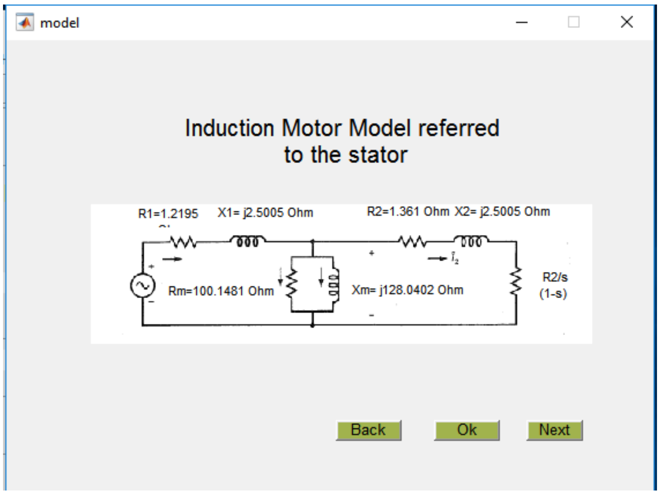

Figure 8: Induction motor model referred to the stator

From this electrical model it is possible to calculate the relationship between developed torque against sliding and developed power against sliding. Both calculations are performed by the tool, and presented graphically in the following window (Figure 9). These values are also stored internally for external analysis.

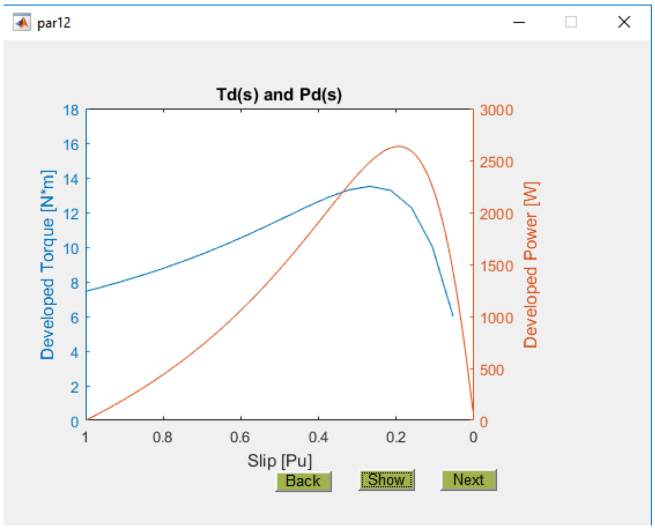

Figure 9: Machine performance curves. Blue curve: torque developed against sliding. Red curve: Power developed against sliding

For the calculation of the efficiency we assume many load values, and for each of these cases the software calculates the corresponding input power values, and therefore the efficiency in each case. However, the input power also depends on the sliding, therefore, according to equation 1:

$$Pd = \frac{3V_1^2 R_2 \left[\frac{1-s}{s}\right]}{R_E^2 + X_E^2 + \left[\frac{R_2(1-s)}{s}\right]^2 + 2R_E R_2 \left[\frac{1-s}{s}\right]}$$

$$Pd\left[R_E^2 + X_E^2 + \left[\frac{R_2(1-s)}{s}\right]^2 + 2R_E R_2 \left[\frac{1-s}{s}\right]\right] - 3V_1^2 R_2 \left(\frac{1-s}{s}\right) = 0$$

$$\mathrm{Pd}\left[\frac{R_2(1-s)}{s}\right]^2 + (2R_E - 3V_1^2)\left[R_2\left(\frac{1-s}{s}\right)\right] + Pd(R_E^2 + X_E^2) = 0 \quad (1)$$

Equation 1 is the $ax^2+bx+c=0$ form, but in this case:

$$x = R_2\left(\frac{1-s}{s}\right) \quad (2)$$

From which we calculate the quadratic equation solution. The sliding for the output power is calculated with Equation 3.

$$s = \frac{R_2}{x + R_2} \quad (3)$$

From these equations the sliding can be calculated for a given output power. With the sliding it is possible to determine the start-up current of the machine and therefore the input power value.

With these input and output power values it is possible to set the efficiency of the machine. This efficiency curve is shown in a graphical window of the tool (Figure 10).

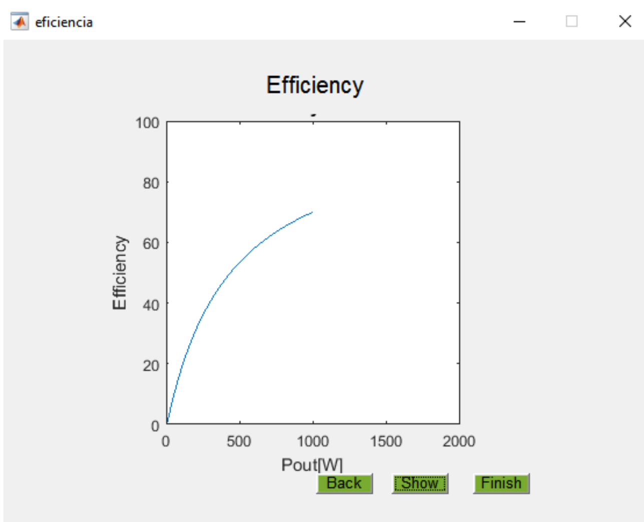

Figure 10: Machine efficiency curve estimated from laboratory tests

RESULTS AND DISCUSSIONS

The tool was used to model and characterize a 1 kW three-phase motor widely studied by the research group, and whose manufacturer's data are known. With respect to the torque and power curves, the performance calculated by the tests is within 7% of the error with respect to the machine operating data, and below 5% with respect to the manufacturer's data. With respect to efficiency, the curve generated by the tool is above the results in engine operation, but with a margin of error that does not exceed 4% in the worst case scenario. In addition, the tool was integrated with other software of the group allowing to import data from other machines for comparison, and to export information for external documentation and analysis.

CONCLUSIONS

We present a software tool developed to characterize induction motors from laboratory tests, and determine their true performance curves in terms of torque, power and efficiency. The tool is developed in MatLab for design requirements, and allows for the analysis of data derived from machine tests: winding resistance test, locked rotor test, mechanical loss test and no-load motor test. The test data is analyzed to evaluate its consistency, and then used to calculate the electrical model of the machine and its torque, power and efficiency characteristics. The tool was evaluated with data from a 1 kW three-phase motor widely known by the research group. The results of the machine analysis match the machine's operating logs and the manufacturer's data. This tool is integrated with others of the research group aimed at the analysis of the electrical power system.

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