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SMIT

Simulador do Motor de Indução Trifásico
Three-Phase Induction Motor Simulator

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CHAPTER 1

Introduction

1.1 Introduction

The SMIT, an acronym for *Simulador do Motor de Indução Trifásico* (Three-Phase Induction Motor Simulator), is a program developed by Lucas Henrique Gonçalves Ribeiro, a master's student in the Graduate Program in Electrical Engineering (PPGEL) at the Federal University of São João del-Rei, and Dr. Lane Maria Rabelo, advisor and professor at PPGEL.

The objective of this work was to implement both symmetrical and asymmetrical models of the three-phase induction motor (TIM), as studied in Baccarini (2005), and integrate them into a graphical interface. This approach aims to democratize access to these models, facilitating their use in new methodologies for MIT fault detection and Machine Learning applications.

To provide additional benefits to SMIT users, a parameter estimation tool for TIM, developed by Amaral et al. (2021), was also implemented. Additionally, a functionality was introduced that allows the generation of a database with a single configuration, repeating the simulation process while automatically randomizing some input parameters.

The software was developed using the Python programming language and is considered an open-source project. Therefore, it is expected that updates and modifications will also come from the community.

This document presents a brief user manual detailing the functionality of SMIT, including its features and input parameters. Questions and feedback regarding its operation can be submitted through the product's GitHub and SourceForge channels or via email: lucash.gribeiro@gmail.com.

CHAPTER 2

Simulator

2.1 Taskbar

The taskbar on the SMIT home page contains three buttons. In this chapter, the first three will be discussed:

- File;
- Parameter Estimator;
- Database.

2.1.1 Archive

When the **Archive** button is clicked, a menu opens where three more buttons are made available: Open, Save, and Exit.

The **Open** and **Save** functions are related, as the latter allows saving the motor data present on the simulator page. When selecting this function, the program requests the path where the .txt file will be saved.

To access the saved data, the **Open** function is used, where the program prompts for the file and, in the end, inserts the entries into their respective locations.

Finally, the **Exit** button is a redundant function to the Windows close button ("X"), allowing the application to be closed.

Figure 2.1: Initial screen of the SMIT program, where the main simulator is configured.

2.1.2 Parameter Estimator

The **Parameter Estimator** button triggers the parameter estimator function, which allows finding the parameters of the three-phase induction motor circuit based on the machine's catalog data. The correct configuration and operation are further explained in Chapter 3.

2.1.3 Database

Finally, the **Database** button activates the Database mode of SMIT, where the user can obtain data for as many simulations as desired, with random variations of some configurations. The operation of this mode is further explained in Chapter 4.

2.2 Start Simulation

The button represented by a green triangle is used to start the simulation of the three-phase induction motor. After configuring the simulator and pressing the button, SMIT performs a check of the entered data, providing feedback to the user through a pop-up window if there is anything that will prevent the simulation from running.

If there are no issues, the program asks the user which output variables they wish to save and display at the end of the simulation, as shown in Figure 2.2. While the variables "Supply Voltage" and "Stator Current" are always saved, the other variables can be selected by checking the box to the left of each name to be saved as well.

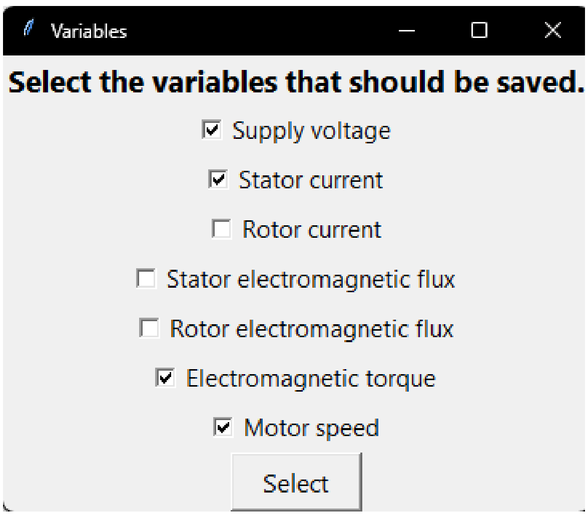

Figure 2.2: Location where the user selects which variables will be saved and displayed at the end of the simulation.

Finally, the program asks for the path where the .txt file with the selected output vectors will be saved, so that the user can access it in the future.

After this last interaction, the program will start the simulation, replacing the button consisting of a green triangle with a red square. This new button has the function of interrupting the simulation, causing SMIT to return to its configuration stage.

However, if not interrupted, the progress of the simulation can be monitored via a progress bar that appears at the bottom of the main screen. At the end of the process, graphs of the selected variables in relation to time are shown, along with the Fast Fourier Transform (FFT) of the stator phase a current, in order to assist in verifying the inserted faults.

2.3 Simulation Variables

In this part of the simulator, the configuration of the step and time settings is inserted, which not only impacts its functioning but also the processing speed of the results. Only numeric values are accepted as inputs.

2.3.1 Sampling Frequency

This input determines the simulation step, with its value directly affecting the simulation time. Very small values can cause the program to fail, while very large values require significant processing power. It is recommended to keep the sampling frequency between 10 and 100 kHz, for a balance between good resolution and time.

2.3.2 Simulation Time

This indicates the total simulation time, i.e., how many seconds of the motor's operation will be simulated in total. It is also an input that affects the program's functioning, as a small value may not be sufficient for the motor to reach steady-state operation — for example, ending the simulation before the start-up is completed — while a large value also increases the simulation time, as it will have a higher number of points.

2.4 Machine Data

The inputs that make up this part of the program are obtained from the motor catalogs and nameplates, as well as tests or estimators. The **Save** function stores this data, along with the Simulation Variables, to be used later. Only numeric values are accepted as inputs.

2.4.1 Line Effective Voltage

This is the effective line voltage in V that powers the motor, found both in the catalog and on the nameplate of the machine. It is possible to alter it, in relation to the nominal value, to verify the impact on the simulation outputs.

2.4.2 Supply Frequency

Given in Hz, this is the frequency at which the motor's supply signal operates. Its value directly impacts the final speed of the machine, making it possible to explore it, along with the voltage, to study the behavior of the simulation at different speeds.

2.4.3 Number of Poles

Indicates the number of magnetic poles present in the motor. Being a construction characteristic of the machine, the number of poles should be entered correctly so that the output is properly related to the simulated motor.

2.4.4 Nominal Speed

Inserted in RPM, the nominal speed is primarily used for the simulation of Mechanical Failures. It can be found in the catalog and on the motor's nameplate.

2.4.5 Line Effective Current

The line effective current, given in A, is also found in the catalog and on the nameplate of the machine. In the program, it is only used when there is a Short Circuit in the Stator Windings, having no impact when this failure is not present.

2.4.6 Moment of Inertia

The moment of inertia, given in kgm², indicates the resistance that the motor's shaft has against motion, impacting the startup time and, when not entered correctly, the simulator's operation. Normally, this data is found in the machine's catalogs.

2.4.7 Nominal Load

Given in Nm, it indicates what will be moved by the motor, i.e., the coupled load. In this input, it is recommended to always keep the nominal value, as later there is an input where it is possible to control how much of this load will be applied to the machine.

2.4.8 Circuit Parameters

Finally, there are the motor's circuit parameters, i.e., the values of the stator and rotor resistances, as well as the stator, rotor, and mutual reactances, all given in Ω.

These inputs are also of great importance for the correct operation of the simulation, needing to always be close to real values and for the star connection equivalent circuit, as the models were developed for this configuration.

Their values can be obtained through tests with the motors you want to simulate or by using parameter estimators, which use available data and mathematical tools to estimate these values. In SMIT, a parameter estimator is provided, presented in Chapter 3, already integrated with the main simulator.

2.5 Load Settings

In this step, the user must configure the startup and the load to be applied throughout the simulation.

2.5.1 Startup Type

This variable indicates the type of startup to be used in the simulation. This input is controlled using a selectable list, which has two options:

- No load: In this mode, it is not possible to apply any type of load, but the user needs to enter a startup time. Therefore, as long as the set time is not exceeded, neither the load nor the faults will be applied to the simulation;
- With load: In this mode, the motor starts with the load already applied, making it possible to determine the type of load.

2.5.2 Load Type

When the motor starts with a load, it is possible to select from three types of load, which vary with speed:

- Constant;
- Linear;
- Quadratic.

Note: It is important to highlight that the Constant load type can cause divergence in the model used, especially when the parameters are obtained through the Parameter Estimator implemented. This problem is caused by the fact that the parameters are calculated for the operating regime close to the nominal, not covering the startup. If the application of load during startup is essential, it is recommended to test the other two load variation types.

2.5.3 Startup Time

Given in seconds and used when simulating a motor starting without load, the startup time, by default, assumes the value of one-third of the simulation time, but it can be modified. During this interval, loads and faults are not applied to the simulation; however, if this variable is equal to or greater than the total time, the simulation will occur, but the loads and faults will not be applied.

2.5.4 Applied Load

Indicates the percentage of load that will be applied during the simulation, ranging from 0 to 110% of the nominal load, entered in the Machine Data.

2.5.5 Moment of Inertia

Also given in kgm^2, it indicates the moment of inertia added to the system by the addition of the load. This value should be calculated or estimated by the user, as it depends not only on the load but also on the type of coupling and other parameters.

2.6 Voltage Imbalance

The first of the available faults in SMIT, voltage imbalance occurs when there is a difference in the amplitude and/or angle of the voltage signal. In the simulator, the imbalance occurs in phase a, but it also impacts phase c, as it is calculated using the sum of the other two. To apply this fault in the simulation, simply select the checkbox next to the name, enabling the fault settings.

2.6.1 Imbalance Percentage

The imbalance percentage is a multiplier applied to the amplitude of phase a voltage, allowing it to vary from 90 to 110% of the nominal value.

2.6.2 Angular Imbalance

The angular imbalance applies the angle chosen by the user — but within the limit of ± 30º — to phase a, which normally has its phase equal to 0º.

2.7 Short-Circuit in Stator Windings

Analogous to Voltage Imbalance, to apply the fault in the stator, simply check the checkbox next to the name, enabling its configuration. The short-circuit — or low insulation — occurs when the insulating material that protects the windings forming the induction motor stator is lost. This fault depends not only on the percentage of shorted windings but also on the resistance of this new path, impacting the final simulation.

2.7.1 Shorted Winding Ratio

Also referred to as the percentage of shorted windings, this variable represents the ratio of windings that are faulty compared to the total number, varying from 0 to 100%. For testing purposes, it is recommended to use small values for this ratio, from 1 to 5%.

2.7.2 Multiplier

To associate the short-circuit resistance with the simulated motor, a methodology is used that calculates this parameter based on the expected short-circuit current. Therefore, the **Multiplier** input consists of the value to be multiplied by the motor's nominal current to determine the short-circuit current and, consequently, the fault resistance.

Thus, if the user wishes to work with a short-circuit current equal to half of the nominal current, they can enter the value 0.5, whereas, if they want to work with a higher current, they could enter a multiplier of 6, for example. This allows for simulating scenarios ranging from low insulation to a full short-circuit.

However, due to the construction characteristics of the machine and the model used, a high value for the **Multiplier** variable may result in a negative or non-existent resistance, indicating that the current exceeds the maximum developed by the motor. Therefore, the SMIT is designed to replace the resistance value with 0, resulting in the most critical short-circuit situation for that motor at that shorted winding percentage.

2.8 Broken Rotor Bars

Faults in the rotor bars occur when one or more bars are damaged, which can be due to a crack or complete breakage. The fault is activated and configured using the checkbox.

2.8.1 Total Number of Bars

The first input of the broken bars fault is a construction characteristic of the machine, consisting of the total number of bars that make up the rotor. This value affects the model used and needs to be as accurate as possible.

2.8.2 Number of Broken Bars

This variable is a major indicator of the severity of the defect, indicating how many of the bars are broken. Its value cannot exceed the total number of bars, and for convenience, the faults always occur in sequential bars, as this simplifies the model application.

2.8.3 Fault Level

Finally, by modifying the input **Fault Level**, it is possible to control the stages of the fault, which can be:

- Crack;
- Fracture;
- Break.

Each type defines how much the current in the damaged bars is reduced, being 10, 50, and 100%, respectively. This way, it is possible to simulate motors with incipient or severe faults.

2.9 Mechanical Failures

Mechanical failures occur when there are mechanical problems in the motor, such as looseness, imbalance, bearing defects, among other eccentricities. To simulate it, a variable torque is applied to the load torque, depending on the motor's nominal torque.

2.9.1 Fault Torque

The input **Fault Torque** indicates to the program the percentage of the load torque inserted in the simulator that will be used to develop the fault signal. In other words, the input is a percentage that will be multiplied by the nominal torque and the load percentage, two inputs discussed earlier, resulting in the amplitude of the variable signal added to the load torque.

CHAPTER 3

Parameter Estimator

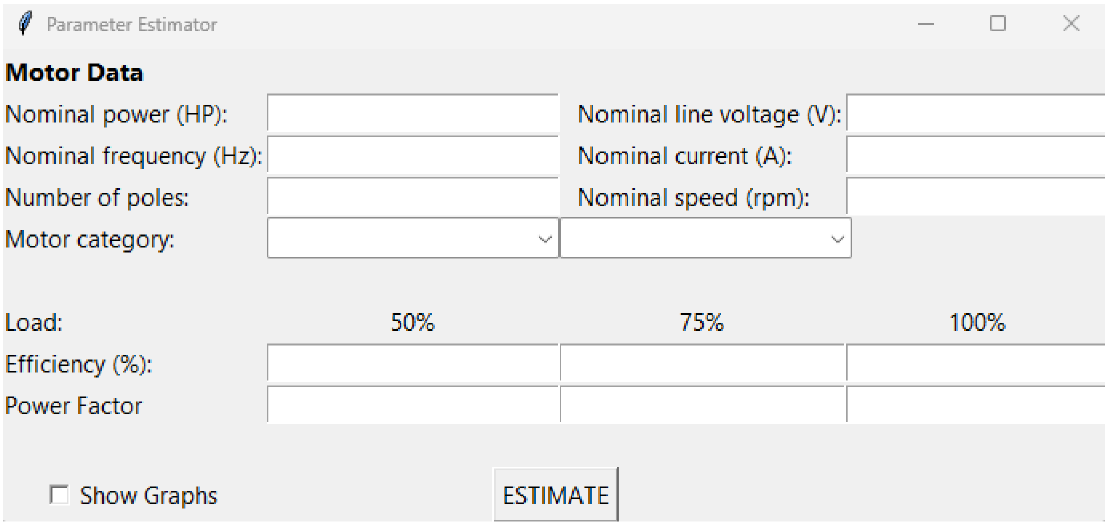

Figure 3.1: Screen of the parameter estimator integrated into SMIT.

The Parameter Estimator consists of an algorithm capable of using the catalog data of three-phase induction motors to determine the parameters of the equivalent circuit of the machine.

For this, as shown in Figure 3.1, the SMIT requires the following data:

- Nominal power, in HP;
- Nominal line voltage, in V;
- Nominal frequency, in Hz;
- Nominal current, in A;
- Number of poles;
- Nominal speed, in RPM;

- Motor category, which can be A, B, C, or D (NEMA), or D, N, or H (NBR);
- Efficiency for 50, 75, and 100% load;
- Power Factor for 50, 75, and 100% load.

Once this data is entered, the software uses mathematical relations to estimate the parameters when the **ESTIMATE** button is pressed. However, before proceeding, the program checks each variable to ensure it is in the correct format and prompts for the file path where the parameter values will be saved in a .txt format for future access by the user.

Automatically, after estimation, the SMIT transfers the catalog data entered in this window and the estimated parameters to the main simulator, reducing the number of configurations required to simulate the desired motor.

For verification purposes, an option called **Show Graphs** has been developed, which is activated through the checkbox in the lower left corner. When the estimation is performed with this option checked, the SMIT also constructs and saves efficiency and power factor graphs, in relation to the ratio of output power to nominal power. This allows the user to verify the estimation error by comparing it with the catalog variables.

Note: The implemented Parameter Estimator was developed to calculate the parameters of the three-phase induction motor in a regime close to the nominal. Thus, the simulator's responses during startup and at other speeds may contain a higher degree of error.

CHAPTER 4

Database Mode

The SMIT Database Mode was developed to facilitate its use in testing new fault detection methods and Machine Learning techniques, as it allows multiple simulations of a motor in different situations with a single configuration. Below, the operation of each quadrant of the screen, presented in Figure 4.1, is explained, along with how to configure it.

To develop the database with different situations, a randomization algorithm was applied to the possible inputs, which include:

- Applied load;
- Inertia moment of the load;
- Unbalance percentage;
- Angular unbalance;
- Shorted coil ratio;
- Multiplier;
- Number of broken bars;
- Fault torque.

Thus, the user enters the maximum and minimum intervals, and with each simulation, the program selects a number between these values. If no randomization is desired for a particular input, simply input the same value in both intervals, and that variable will always assume this same value.

It is important to highlight that the Database Mode has the same method for activating faults as the main simulator. Simply check the respective defect checkbox to enable its settings.

4.1 Back

The **Back** button is used when the user wants to return to the single simulation mode.

4.2 Start Simulation

The **Start Simulation** button behaves identically to the one in the main simulation mode. Once pressed, the program performs an input check, and if there are no issues, it requests the user to specify the variables that need to be saved and the path for storing the results.

The outputs, saved in .txt format, are grouped in a single folder to facilitate the user's access. Also stored are the inputs that went through the randomization process, so it is possible to compare the inputs with the corresponding outputs.

To allow for tracking of simulations, the Database Mode of the SMIT also presents a progress bar to indicate the current simulation's progress, and below the bar, there is an indicator showing how many simulations have already been completed.

4.3 Motor Selection

In this section, the program receives the basic operational data: the motor to be simulated and the number of simulations to be performed.

4.3.1 Motor

To input the motor data to be simulated, as well as the simulation settings, the **Save** tool from the main simulator is used. Therefore, it is necessary to open the .txt file using the **Select File** button, which opens a system window where the user can choose the file containing the motor data.

4.3.2 Number of Simulations

In this input, the user informs the program how many simulations should be performed to construct the desired database. Now, in addition to the sampling frequency and total time provided in the saved file, the number of simulations also impacts the task's duration, as a larger number of simulations means repeating the motor simulation for a longer time.

4.4 Load Configurations

While the inputs **Starting Type**, **Starting Time**, and **Load Type** function the same as in the single simulation mode, the variables **Applied Load** and **Moment of Inertia** can be modified in each repetition, with the user simply entering the maximum and minimum intervals.

4.5 Voltage Imbalance

The two settings for voltage imbalance in the model are subject to randomization: **Imbalance Percentage** and **Angular Imbalance**, with the user required to input the interval values.

4.6 Short Circuit in Stator Windings

Similarly to voltage imbalance, the settings for the short-circuit fault in the stator windings also require interval values: **Short-circuit Windings Ratio** and **Multiplier**.

4.7 Broken Rotor Bars

While the **Total Number of Bars** and **Fault Level** remain unchanged when compared to the simple simulation, the broken rotor bar defect allows the randomization of the **Number of Broken Bars**.

4.8 Mechanical Failures

Finally, the **Fault Torque**, for applying mechanical failures, allows the user to enter the maximum and minimum intervals so that it can be altered in the database simulations.

Figure 4.1: Screen of the database mode.

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