Virtual Laboratory for Study of Synchronous Machine Parameters

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Abstract: - In the areas of engineering education due to various shortcomings of the traditional laboratories, virtual laboratories have appeared as a potential alternative to traditional laboratories. Every system – mechanical, electrical, biological– can be accurately described by a mathematical model. The models can be applied in practice because the computers allow us to solve it in a numerically way. In this paper, we focus on the theory of the modeling, applied on the areas of electrical machines. Three key problems are discussed in this application: the purpose, the content and the impact of such a laboratory in studying and learning the scientific and engineering principles of electrical machines areas.

Key-Words: - virtual laboratory**,** mathematical model, synchronous machine, Park – Blondel's equations, d, q reference system, per unit normalization, GUIDE of Matlab.

1 Introduction

Laboratory work classes are an integral part of any educational program and their purpose is bringing the students closer to real situations of the area of studies

The typical traditional laboratory consists in sharing and grouping the students, discussing the theoretical problems together, working directly on a set of equipment and apparatus following a set of written guidelines, evaluating the results and elaborating personal conclusions.

From this short description we can see the next shortcomings of the traditional laboratories:

(a) the sets of equipment can be significantly high and the institution can't modernize them;

(b) the students access to laboratories is restricted only to the laboratory periods;

(c) since the students can see only the inputs and outputs of the system, those laboratories cannot fully backup the understanding / intuitiveness of the physical phenomena illustrating the functionality of electrical machines;

(d) operating under unfamiliar conditions, accidents may happen..

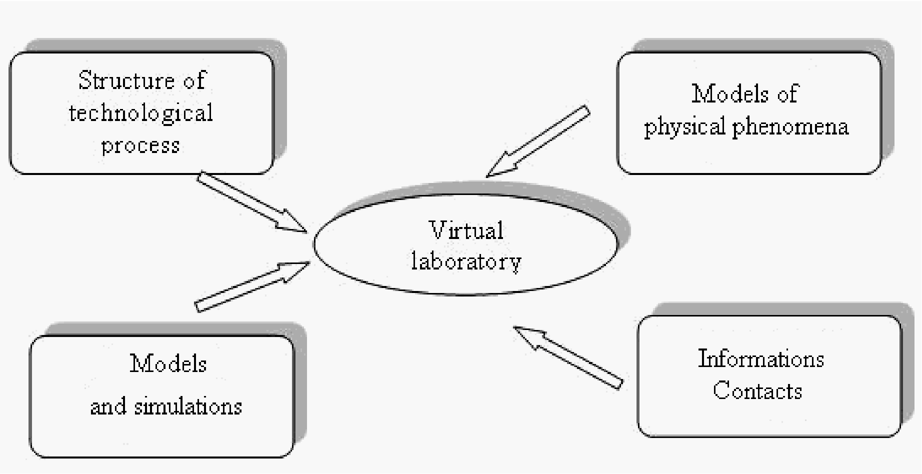


Fig. 1. Basic information's for a virtual laboratory

Considering the new developments and trends in the information systems field, those educational shortcomings can be replaced with virtual laboratories.

A virtual laboratory is the space where the elements are expressed virtually using interactive graphics, and a conceptual and interactive design. The modular content of a virtual laboratory, organized as a database, permits a quick access to the structured information.

2 Problem Formulation

The statement '*Nature has laws, and we can find them*' (I. Newton) implies that every system – mechanical, electrical, biological – can be accurately described by a mathematical model.

The models can today also be applied in practice as the computers allow us to numerically solve process models of such complexity that could hardly be imagined a couple of decades ago. Models would be constructed in a simple manner yet in every way reproduce the true process behavior.

The word 'model' has a wide spectrum of interpretations: mental model, linguistic model, visual model, physical model and mathematical model. In this work we will restrict ourselves to mathematical models, that is, models within a mathematical framework where equations of various types are defined to relate inputs, outputs and characteristics of a system.

Primarily, mathematical models are an excellent method of conceptualizing knowledge about a process and to convey it to other people. Models are also useful for formulating hypotheses and for incorporating new ideas that can later be verified (or discarded) in reality. An accurate model of a process allows us to predict the process behavior for different conditions and thereby we can optimize and control a process for a specific purpose of our choice. Finally, the models serve as an excellent tool for many educational purposes.

2.1 General Modeling Strategy

We need a general strategy for model building. The modeling of any system consists in five distinct steps, as illustrated in figure 2.

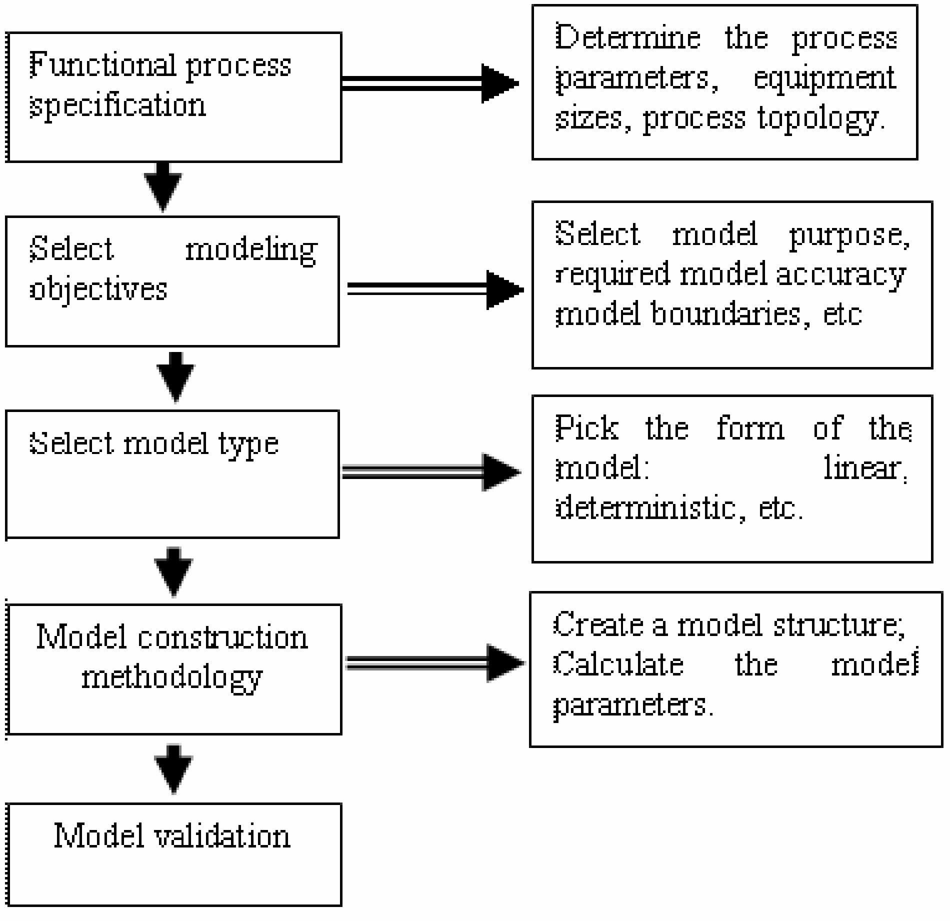


Fig. 2. Modeling process

First step is to define the system being modeled as a functional specification. Is required a quantitative understanding of the structure and parameters which are describing the process. The modeling objectives are decided and then the desired model type selected.

We can define a number of general purposes for mathematical models (also applicable to many other fields): the design, the research, the process control, forecasting, etc..

The Design – models allow the exploration of the impact of varying system parameters and development of an object designed to meet the desired process objectives at minimal cost.

Research – models serve as a tool to develop and test hypotheses and in this manner gaining new knowledge about the processes.

Process control – models allow for the development of new control strategies by investigating the system response to a wide range of inputs without endangering the actual solution.

Forecasting – models are used to predict future solution performance when exposed to foreseen input changes and provide a framework for testing appropriate counteractions.

Performance analysis – models allow for analysis of total performance of the solution over time when compared with laws and regulations and what is the impact of new effluent requirements on solution design and operational costs will be.

Education – models offer students with a tool to actively explore new ideas and improve the learning process as well as allowing technical solution operators training facilities and thereby increasing their ability to handle unexpected situations.

2.1.1 Modeling the synchronous machine

To illustrate the modeling strategy used to create a virtual laboratory, we choose the synchronous machine and we choose to calculate its parameters, in an interactive way.

The problem of the parameters of the synchronous machine is an interesting subject, debated very much.

To simulate the behavior of a synchronous machine, we must adopt a physical model bringing into discussion the principal electro-mechanical characteristics. In general, the elaboration of a mathematical model and the experimental methods of determination of the machine's parameters, although are correlative problems, they are treated separate.

The aim of this laboratory is to correlate these subjects and to response of two practical problems: the identification of the parameters and the study of the different regimes of the synchronous machine. Also, this virtual laboratory can allow to the user, to see all the consequences of any variation of the parameters on the behavior of the machine.

The identification of the parameters of the synchronous machine by experiment is made by analyzing of the measurements made on the output of the stator's windings a, b, c, and field winding E. The difficulty is that the damped windings D, Q are closed and inaccessible to the measurements.

In these conditions, we can't find all the electrical parameters of the windings (resistances and inductances), but we can find only the parameters of some mathematical models which can allow to us, to calculate the state variables on the output of the windings a, b, c, and E.

First, it is established, for the three-phased machine, the equations in different reference systems. We considered the following assumption:

- the stator has 3 identical, symmetrically placed, lumped windings a, b, c;
- the rotor windings E, D, Q are placed in the direction of the two orthogonal axis: d (direct) and q (quadrate);
- the winding E represents the field winding;
- the windings D and Q are fictitious windings to account for: damper windings and the effects of currents in the iron parts of the rotor;
- characteristic magnetic linear;
- absence of losses iron;
- couple losses by friction and ventilation proportional.

We assume that the synchronous machine can be represented by three armature phase windings, one of field winding and two fictive, named damper windings, which representing the effect of distributed currents on the rotor.

Associating the positive sense for the receptor, we group the equations in [1], [2]:

$$\begin{Vmatrix} u_S \\ u_r \end{Vmatrix} = \begin{Vmatrix} |R_S| & \\ & |R_r| \end{Vmatrix} \cdot \begin{Vmatrix} i_S \\ i_r \end{Vmatrix} + \frac{d}{dt} \begin{Vmatrix} \Psi_S \\ \Psi_r \end{Vmatrix} \tag{1}$$

where:

- $|u_S|$, $|u_r|$ are phase and rotor voltage sub-matrices;
- $|R_S|$, $|R_r|$ are phase and rotor resistances sub-matrices;
- $|i_S|$, $|i_r|$ are currents sub-matrices; and
- $|\Psi_S|$, $|\Psi_r|$ are stator's and rotor's fluxes sub-matrices.

Fluxes are, in terms of currents:

$$|\Psi| = \left\| \begin{array}{c} \Psi_S \\ \hline \Psi_r \end{array} \right\| = \left\| \begin{array}{c|c} |L_S| & |L_{rS}| \\ \hline |L_{rS}| & |L_r| \end{array} \right\| \cdot \left\| \begin{array}{c} i_S \\ \hline i_r \end{array} \right\| = |L| \cdot |i| \qquad (2)$$

where:

- $|L_S|$, $|L_r|$ and $|L_{Sr}| = |L_{rS}|$ are inductance sub-matrices (as in literature [1]): the first describe armature inductances, the second rotor inductances and the third the stator-to- rotor inductances.

2.1.2 Park – Blondel's equations – (d, q) system model

Park's transformation (1929) made the equations invariant in time [3]. Express stator flux linkages in the rotating d, q reference system instead of the stator fixed reference system. Replace the stator windings by two fictitious windings that are fixed to the rotor. One winding is chosen to coincide with the d-axis and the other with the q-axis.

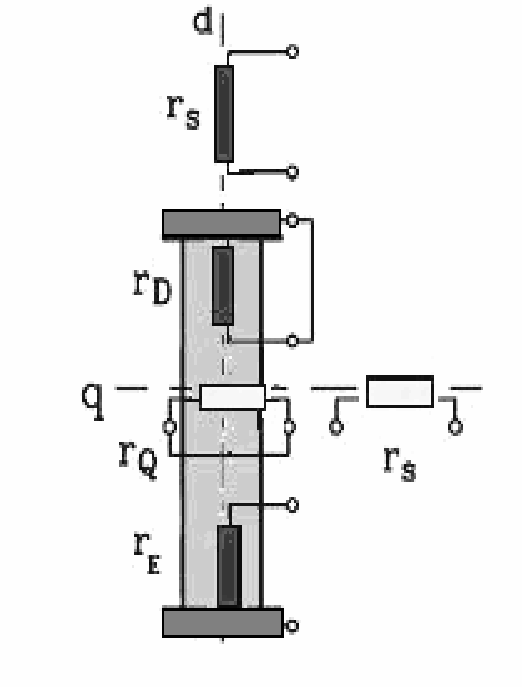


Fig.3. Synchronous machine:
d, q axis; s: stator winding; *D, Q*: damper windings; E: field windings

As we know, the d current i_{sd} excites air gap Φ_{dh}. It links stator winding with rotor excitation winding and damper cage like in a three winding transformer.

The q current i_{sq} excites air gap Φ_{qh}. It links stator winding and rotor damper cage like in a two winding transformer. The q air gap flux Φ_{qh} is not linked with excitation winding (figure 4).

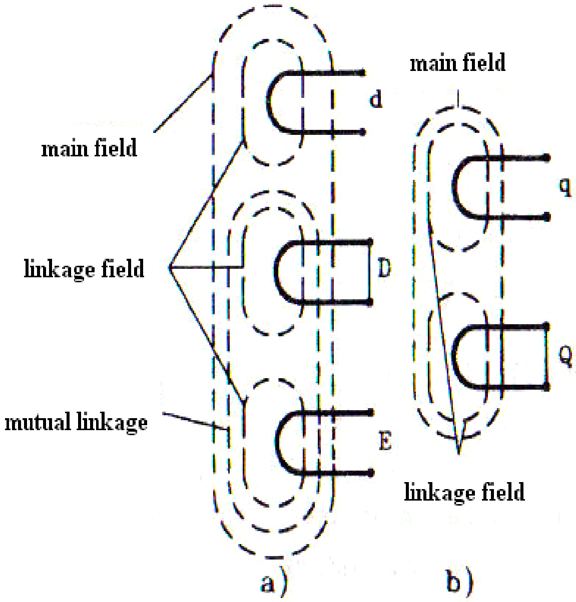


Fig. 4. Magnetic fields of the machine in: a). d - axis and b). q - axis.

There are few steps in the development of an adapted model [4]. After a substantial amount of algebra, we express the voltages equations matrix of machine, in (d, q) frame [5]:

$$\left| \begin{array}{c} u_{ds} \\ u_{qs} \\ u_{0s} \\ \hline u_{dr} \\ uqr \\ u_{0r} \end{array} \right| = \left| \begin{array}{ccc|ccc} R_s & & & & & \\ & R_s & & & & \\ & & R_s & & & \\ \hline & & & R_r & & \\ & & & & R_r & \\ & & & & & R_r \end{array} \right| \bullet \left| \begin{array}{c} i_{ds} \\ i_{qs} \\ i_{0s} \\ \hline i_{dr} \\ i_{qr} \\ i_{0r} \end{array} \right| +$$

$$\left| \begin{array}{ccc|ccc} \frac{d}{dt} & \frac{d\beta_B}{dt} & & & & \\ \frac{d\beta_B}{dt} & \frac{d}{dt} & & & & \\ & & \frac{d}{dt} & & & \\ \hline & & & \frac{d}{dt} & & \\ & & & & \frac{d}{dt} & \\ & & & & & \frac{d}{dt} \end{array} \right| \bullet \left| \begin{array}{c} \Psi_{ds} \\ \Psi_{qs} \\ \Psi_{0s} \\ \hline \Psi_{dr} \\ \Psi_{qr} \\ \Psi_{0r} \end{array} \right|$$

We may deduce that the torque is given by:

$$M = \frac{3}{2} p(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \,, \tag{3}$$

We defined, in the limits of two axes theory, the parameters of the synchronous machine with salient poles. We note $\omega = \frac{d\beta_B}{dt}$ the instantaneous electrical angular rotor's speed and we have:

$$\begin{vmatrix} \psi_d \\ \psi_q \\ \psi_E \\ \psi_D \\ \psi_Q \end{vmatrix} = \begin{vmatrix} L_d & & L_{dh} & L_{dh} & \\ & L_q & & & L_{qh} \\ L_{dh} & & L_E & L_{dh} + L_{ED\sigma} & \\ L_{dh} & & L_{dh} + L_{ED\sigma} & L_D & \\ & L_{qh} & & & L_Q \end{vmatrix} \cdot \begin{vmatrix} i_d \\ i_q \\ i_E \\ i_D \\ i_Q \end{vmatrix}$$

The voltage matrix equations became [1]:

$$\begin{vmatrix} u_d \\ u_q \\ u_E \\ 0 \\ 0 \end{vmatrix} = \begin{vmatrix} R_s & & & & \\ & R_s & & & \\ & & R_E & & \\ & & & R_D & \\ & & & & R_Q \end{vmatrix} \bullet \begin{vmatrix} i_d \\ i_q \\ i_E \\ i_D \\ i_Q \end{vmatrix} +$$

$$+ \begin{vmatrix} \frac{d}{dt} & \omega & & & \\ \omega & \frac{d}{dt} & & & \\ & & \frac{d}{dt} & & \\ & & & \frac{d}{dt} & \\ & & & & \frac{d}{dt} \end{vmatrix} \bullet \begin{vmatrix} \psi_d \\ \psi_q \\ \psi_E \\ \psi_D \\ \psi_Q \end{vmatrix}$$

2.1.3 Per unit normalization

The per unit method of power system analysis eliminates the need for conversion of voltages, currents and impedances across every transformer in the circuit [6].

Advantages of a per-unit system are:

- imposes proper scaling, which is good for the numerical solution;
- yields valuable relative magnitude information;
- simplifies searching for erroneous data since parameters tend to fall in relatively narrow numerical ranges;
- eliminates transformation of quantities due to transformers and number of generator poles.

The reason for per-unit normalization of the machine system is that, when the machine parameters (current, voltage, power and impedance) are referred to normal operating parameters, the behavior characteristics of all types of machines become quite similar, giving us a better way of relating how a particular machine works reasonable standard.

The first step in normalization is to establish a set of base quantities [7],[8]. Per-unit quantities are derived dividing the ordinary variable (with unit) by the corresponding base.

Using per unit quantities, all inductances, are equal with their apposite reactance. After a substantial amount of algebra, arise from the repetitive scheme, we express [9]:

$$L_d = L_{s\sigma} + L_{dh} \,/:\omega_0 \Rightarrow x_d = x_{s\sigma} + x_{dh} \,, \tag{4}$$

$$\begin{aligned} &L'_d = L_{s\sigma} + L_{dh} \,||\, L_{E\sigma} \,/:\omega_0 \Rightarrow \\ &x'_d = x_{s\sigma} + x_{dh} \,||\, x_{E\sigma} \end{aligned} \tag{5}$$

$$\begin{aligned} &L''_d = L_{s\sigma} + L_{dh} \,||\, L_{E\sigma} \,||\, L_{Dd\sigma} \,/:\omega_0 \\ &\Rightarrow x''_d = x_{s\sigma} + x_{dh} \,||\, x_{E\sigma} \,||\, x_{Dd\sigma} \end{aligned} \tag{6}$$

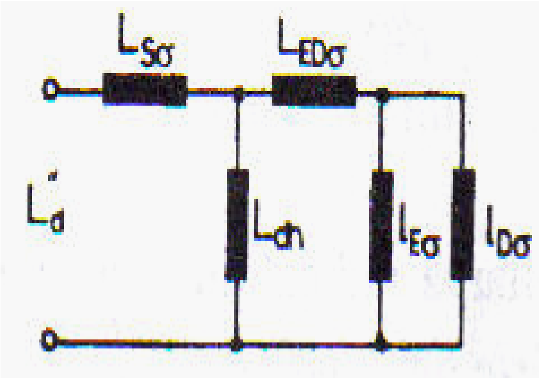


Fig. 5. Sub transient reactance of d axis

$$\begin{aligned} &L_q = L_{s\sigma} + L_{qh} \,/:\omega_0 \Rightarrow \\ &x_q = x_{s\sigma} + x_{qh} \end{aligned} \tag{7}$$

$$\begin{aligned} &L''_q = L_{s\sigma} + L_{qh} \,||\, L_{Qq\sigma} \,/:\omega_0 \Rightarrow \\ &x''_q = x_{s\sigma} + x_{qh} \,||\, x_{Dd\sigma} \end{aligned} \tag{8}$$

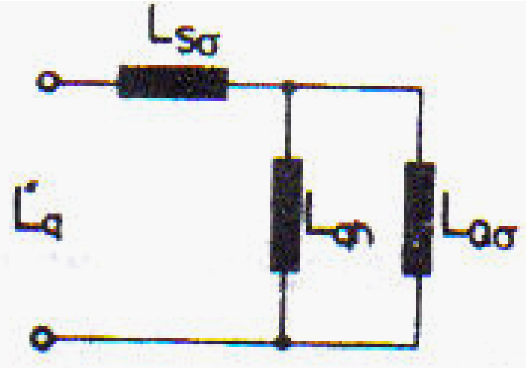


Fig. 5. Sub transient reactance of q axis

Computing these relations, we obtain:

$$(7) \Rightarrow L_d h = L_d - L_{s\sigma} \Rightarrow x_{dh} = x_d - x_{s\sigma} \quad (9)$$

$$(8) \Rightarrow L_{E\sigma} = \frac{L_{dh}(L'_d - L_{s\sigma})}{L_d - L'_d} \Rightarrow$$

$$x_{E\sigma} = \frac{x_{dh}(x'_d - x_{s\sigma})}{x_d - x'_d} \quad (10)$$

$$(9) \Rightarrow L_{Dd\sigma} = \frac{1}{\frac{1}{L''_d - L_{s\sigma}} - \frac{1}{L_{dh}} - \frac{1}{L_{E\sigma}}} \Rightarrow$$

$$x_{Dd\sigma} = \frac{1}{\frac{1}{x''_d - L_{s\sigma}} - \frac{1}{x_{dh}} - \frac{1}{x_{E\sigma}}} \quad (11)$$

$$(10) \Rightarrow L_{qh} = L_q - L_{s\sigma} \Rightarrow x_{qh} = x_q - x_{s\sigma} \quad (12)$$

$$(11) \Rightarrow L_{Qq\sigma} = \frac{L_{qh}(L''_q - L_{s\sigma})}{L_q - L''_q} \Rightarrow$$

$$x_{Qq\sigma} = \frac{x_{qh}(x''_q - x_{s\sigma})}{x_q - x''_q} \quad (13)$$

The time constants are:

$$T_E = \frac{L_E}{R_E}; T_D = \frac{L_D}{R_D}; T'_{d0} = \frac{x_{E\sigma} + x_{dh}}{\omega_0 \bullet R_E};$$

$$T''_{d0} = \frac{x_{Dd\sigma} + x_{dh} \,||\, x_{E\sigma}}{\omega_0 \bullet R_D}; \quad (14)$$

where:

$$R_E = \frac{x_{E\sigma} + x_{dh}}{\omega_0 \bullet T'_{d0}}; R_D = \frac{x_{Dd\sigma} + x_{dh} \,||\, x_{E\sigma}}{\omega_0 \bullet T''_{d0}};$$

$$R_{Qq} = \frac{x_{Qq\sigma} + x_{qh}}{\omega_0 \bullet T''_{q0}} \quad . \quad (15)$$

The notation is the usual in literature [10] and we are implemented in Matlab the symbolic algorithm to compute the parameters of the synchronous machine.

3 Problem Solution

The aim of this part is to compute, with GUIDE of Matlab [11], the parameters of a synchronous machine that had given the following parameters, expressed in per-unit:

- inertial constant (J);
- armature time constant:
- (T_a); power factor angle (ψ);
- base (rating) power (P_N);
- base (rating) voltage (U_N);
- stator leakage inductance ($x_{s\sigma}$);
- synchronous, d-axis reactance (x_d);
- transient d- axis reactance (x'_d);
- sub-transient transient d- axis reactance (x''_d);
- transient open-circuit time constant (T'_{d0});
- sub-transient open-circuit time constant (T''_{d0});
- synchronous, q-axis reactance (x_q);
- sub-transient q- axis reactance (x''_q);
- sub-transient open-circuit time constant (T''_{q0}).

The equal mutual parameters, transient and sub-transient time constant are computing using the 7's to 17 expressions. These expressions are implemented in two M-File applied by another M-File, using the facilities of GUIDE of Matlab.

GUIDE, the MATLAB Graphical User Interface development environment, provides a set of tools for creating GUIs. These tools greatly simplify the process of laying out and programming a GUI.

A graphical user interface (GUI) is a user interface built with graphical objects (the components of the GUI) such as buttons, text fields, sliders, and menus.

GUIDE, the MATLAB Graphical User Interface development environment, provides a set of tools for creating GUIs. These tools greatly simplify the process of laying out and programming a GUI [12],[13].

GUIDE is a set of layout tools and also generates an M-file that contains code to handle the initialization and launching of the GUI. This M-file provides a framework for the implementation of the callbacks (the functions that execute when users activate components in the GUI).

Applications that provide GUIs are generally easier to learn and use since the person using the application does not need to know what commands are available or how they work.

The action that results from a particular user action can be made clear by the design of the interface.

Creating a GUI involves two basic tasks:

- Laying out the GUI components
- Programming the GUI components.

A GUI is an arborescent structure like in figure 6.

The model was applied on a synchronous generator [3] with: S_N=440MVA, U_N=6300V, n_1=1000rpm, f_1=50Hz, m=3, p=3, cosφ_N=0.8 ind., U_{eE}=3928v.

Machine's parameters in phase A are (in r.u.) [3]:

- synchronous d axis reactance $x_d = 1.4$;
- synchronous d axis reactance $x_q = 0.8$;
- transient d axis reactance x_d'=0.303;
- subtransient d axis reactance x_d'' =0.16;
- subtransient d axis reactance x_q''=0.135;
- transient open circuit time constant T_{d0}=8s;
- subtransient open circuit time constant T_{do}'' =0.00682s;
- subtransient open circuit time constant T_{qo}'' =0.00682s;
- inertial constant J=4;
- armature time constant T_a=0.182.

A model of interface for this subject (Parameters of the synchronous machine) is illustrated in figure 8. This interface could be improved with other elements necessary to illustrate this theme [14].

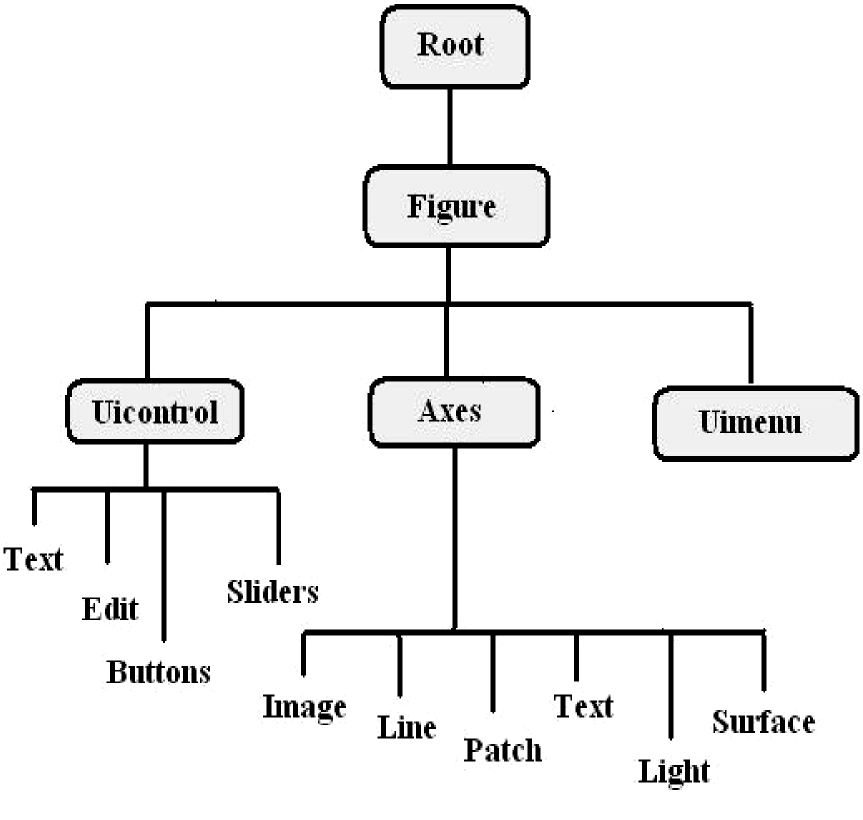


Fig.6. Basic structure of a GUI

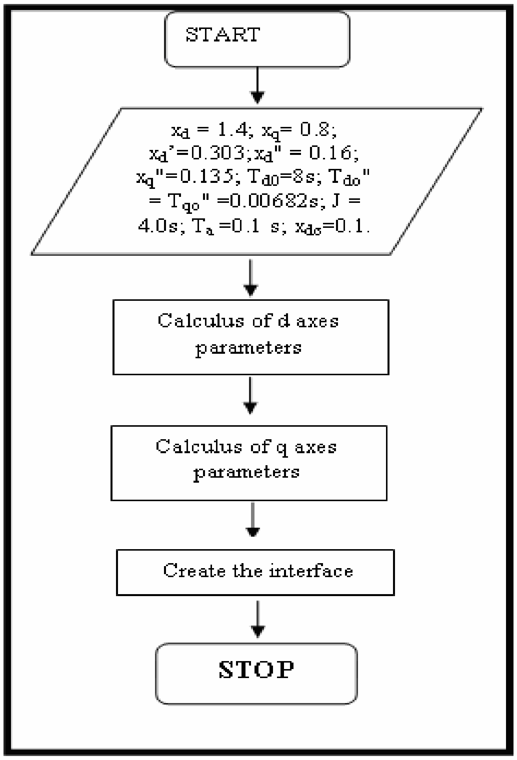
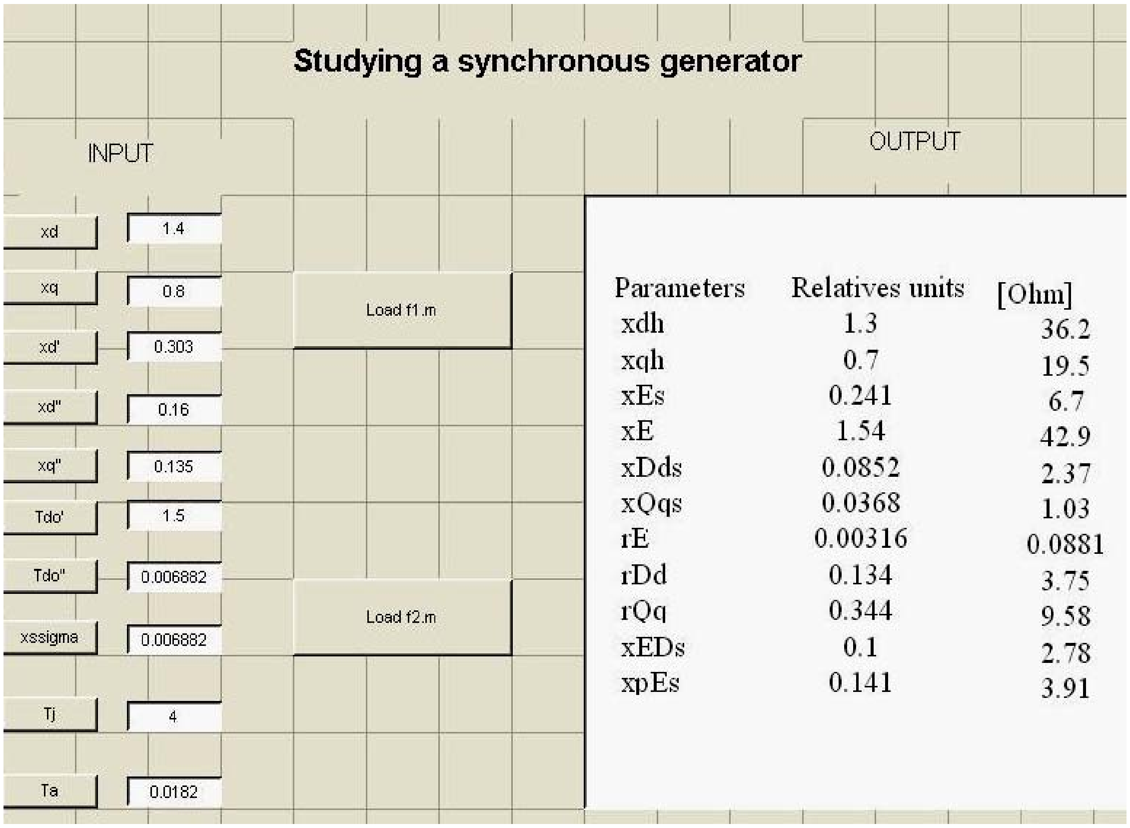


Fig. 7. Logical scheme



Studying a synchronous generator

INPUT

xd 1.4
xq 0.8
xd' 0.303
xd" 0.16
xq" 0.135
Tdo' 1.5
Tdo" 0.006882
xssigma 0.006882
Tj 4
Ta 0.0182

OUTPUT

Parameters	Relatives units	[Ohm]
xdh	1.3	36.2
xqh	0.7	19.5
xEs	0.241	6.7
xE	1.54	42.9
xDds	0.0852	2.37
xQqs	0.0368	1.03
rE	0.00316	0.0881
rDd	0.134	3.75
rQq	0.344	9.58
xEDs	0.1	2.78
xpEs	0.141	3.91

Figure 8. Graphical interface to study the parameters of the synchronous machine

4 Conclusion

This application could be a starting point for creates a virtual laboratory to present the basic information about the synchronous machine.

This application is also, a useful tool to improve the understanding in many of basic concepts, about electromechanical transient processes in synchronous machine.

It's a difference between two categories of parameters: in permanent regime and in transient regime. The parameters of the permanent regime (non saturated) are the resistances and the reactance. The transient parameters for the d, q models are the times constants: $T_d^{'}, T_d^{''}, T_{d0}^{'}, T_{d0}^{''}, T_q^{''}, T_{q0}^{''}$ or the times constants $T_d^{'}, T_d^{''}, T_q^{''}$ and the reactances $X_d^{''}, X_q^{''}, X'$. The reactance X' of the d,q model isn't the same with the transient reactance $X_d^{'}$ of the machine without of damping windings.

(d,q) model is used to the identification of the parameters of the machine, in the case of the assumptions of a quasi stationary regime. Time constants are founded through the numerical analyze of the transient responses in the short circuit tests under load. The precision of the results is affected not only by the approximations of the quasi sinusoidal regime, but also by the errors appeared at the separation of the non periodical components and also at the numerical analyze made to find the six time constants.

The paper is also the starting point to study the behavior of synchronous machine and the parameter's influences on its operation.

Further works will be directed towards a graphical interface which allows the study of the transient behavior of the synchronous machine.

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