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Educational application based on MATLAB for the analysis of transient stability of power systems

Aplicación educativa basada en MATLAB para el análisis de la estabilidad transitoria de sistemas de potencia

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Abstract

This paper presents an educational computer implementation for transient stability analysis of power systems. The transient stability is formulated by considering the One-Machine Infinite Bus model and by solving a unified way the Differential Equations System by combining the Implicit Trapezoidal Rule and Newton-Raphson method. The proposed implementation is developed by using the visual programming environment GUIDE of Matlab, and it has a friendly user interface, intuitive and very easy to handle; it is also computationally efficient and numerically stable for use in all subjects related to computer-assisted analysis of power systems, either in workshop environment or distance learning courses. The implementation avoids the integration of a numerical method for solving the OMIB model, which greatly reduces development time and obtaining results,

Educational implementation, MATLAB, Transient Stability, One-Machine Infinite Bus

Resumen

Este trabajo presenta una implementación informática educativa para el análisis de la estabilidad transitoria de los sistemas de potencia. La estabilidad transitoria se formula considerando el modelo de bus infinito de una máquina y resolviendo de forma unificada el sistema de ecuaciones diferenciales mediante la combinación de la regla trapezoidal implícita y el método de Newton-Raphson. La implementación propuesta se desarrolla utilizando el entorno de programación visual GUIDE de Matlab, y cuenta con una interfaz de usuario amigable, intuitiva y muy fácil de manejar; además es computacionalmente eficiente y numéricamente estable para su uso en todas las asignaturas relacionadas con el análisis asistido por ordenador de sistemas de potencia, ya sea en entorno de taller o en cursos a distancia. La implementación evita la integración de un método numérico para la resolución del modelo OMIB, lo que reduce en gran medida el tiempo de desarrollo y la obtención de resultados,

Implementación educativa, MATLAB, Estabilidad transitoria, Bus infinito de una máquina

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Introduction

Stability has been recognized as an important problem for the safe operation of Electric Power Systems (EPS) since 1920 (Steinmetz, 1920; AIEE-SISF, 1926). Most major outages or failures in electric power systems have illustrated the importance of studying this phenomenon (Vassell, 1991). Historically, transient instability has been the dominant stability problem in SEPs and has been a topic of attention of many of the generating companies, consumers and researchers around the world (Kundur et al, 2004). The principles of transient stability analysis are studied in the later subjects of electrical engineering and related programs, since the study of this phenomenon is complex and it is desirable that students possess well-grounded prior technical knowledge.

Electrical engineering education has been a topic of extensive debate and discussion in the political and educational arena in the last decade (Omer & Idowu, 2011). Corderoy et al. (2003) and Singh (2001) highlight in their reports the need to modernize curricular programs to respond to major changes in technology, educational policy, and industry. Most scholars of electrical engineering programs agree that one of the main approaches to reform teaching in these educational programs is through newer educational tools (Omer & Idowu, 2011), which allow students to acquire and apply knowledge in solving real problems to develop in turn the competencies for handling work situations.

This characteristic in electrical engineering students is very important, since the technical personnel who design, operate and control power systems must possess vast technical knowledge, in addition to their practical thinking and problem solving skills, so people who will work in the electrical sector must acquire practical and theoretical knowledge (Güney et al, 2014). The analysis of power systems is very complex and mostly requires the implementation of computational algorithms for the solution of models, which takes considerable time to develop and obtain results.

In recent years and thanks to the rapid development of computational systems and packages, many applications and computer programs have been developed to assist in the teaching of electrical engineering programs around the world (Güney et al, 2014; Acarnley, 2005; Omer & Idowu, 2011; Levi & Nedic, 2001; Islam & Chowdhury, 2001; Shin et al, 1999; Lee et al, 2001; Overbye et al, 1995; Larsson, 2004; Vournas et al, 2004; Ayasun et al, 2006).

It is important to mention that most of these computational tools are executable and users do not have access to the source code, which translates into a disadvantage because modifications cannot be made and students are confined to the implicit solution methods of the programs.

In the above context, this paper presents the development of a computational application based on Matlab (MathWorks, 2015) to assist teachers in teaching the study of Transient Stability of SEPs.

Whose source code is provided to electrical engineering or related students so that they can perceive the operation of the tool and can integrate their own methods and models or make the modifications that they consider pertinent in the application, with the purpose that the students acquire the knowledge and the competence of analysis and application of the same. This is possible because the proposed application is very flexible and is designed to be easily extended to other power system applications or even to other applications outside electrical engineering. applications outside electrical engineering.

The Implicit Trapezoidal Rule

The formulation of the ET problem with the OMIB model is represented by a system of system, which can be solved by different numerical integration numerical integration methods, such as the Euler's method, Modified Euler's method, Runge Kutta Methods (second and fourth order) or order) or Implicit Integration Methods. In this work the RTI is used to solve the ED system because it is a very ED system because it is a very numerically numerically very stable.

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The RTI is an method of implicit integration with which the differential equations are differential equations are integrated implicitly implicitly and converted into algebraic equations algebraic equations, so it is necessary to apply a method for is necessary to apply a solution method for these equations during each equations during each time interval (Rafian et al, 1987), in the present work we use the Newton-Raphson Newton-Raphson method is used for this purpose. method is used for this purpose. To illustrate the application of this method to RTI for the solution of differential equations differential equations, the following system is considered of n DEs.

$$\frac{dY}{dt} = f(Y) \tag{1}$$

Where f(Y) is a vector of n nonlinear algebraic expressions, while Y is a vector of n system state variables.

By applying the RTI to Equation 1) we:

$$Y_t = Y_{t-\Delta t} + \frac{\Delta t}{2}\left(f(Y_t) + f(Y_{t-\Delta t})\right) \tag{2}$$

In (2) Δt is the integration step, so the subscripts t and t-Δt indicate the evaluation of f (Y) and Y at the current time and at the previous integration step, respectively. Ordering the above equation to expand the in the Taylor series around the neighborhoods of the point Yt, truncating the higher order terms and iteratively obtaining the solution in iterative form that equation, the following expression for the Newton-Raphson method results:

$$-F(Y_t)^k = \nabla F(Y_t)^k \, \Delta Y_t^k \tag{3}$$

Where ∇F(Yt) and F(Yt) are given as follows:

In (3) the superscript k indicates the iteration number and in the gradient expression c is Δt/2. The terms F(Yt)k and ∇F(Yt)k are the evaluation of Equation (2) and the gradient of that equation, respectively, both evaluated at the kth iteration. The update of Yt:

$$\nabla F(Y_t) = \begin{bmatrix} 1 + c\frac{df_1(Y_t)}{dy_{1t}} & c\frac{df_1(Y_t)}{dy_{2t}} & \cdots & c\frac{df_1(Y_t)}{dy_{nt}} \\ c\frac{df_2(Y_t)}{dy_{1t}} & 1 + c\frac{df_2(Y_t)}{dy_{2t}} & \cdots & c\frac{df_2(Y_t)}{dy_{nt}} \\ \vdots & \vdots & \ddots & \vdots \\ c\frac{df_n(Y_t)}{dy_{1t}} & c\frac{df_n(Y_t)}{dy_{2t}} & \cdots & 1 + c\frac{df_n(Y_t)}{dy_{nt}} \end{bmatrix}$$

$$F(Y_t) = \begin{bmatrix} y_{1t} - \frac{\Delta t}{2} f_1(Y_t) \\ \vdots \\ y_{nt} - \frac{\Delta t}{2} f_n(Y_t) \end{bmatrix} - \begin{bmatrix} y_{1(t-\Delta t)} + \frac{\Delta t}{2} f_1(Y_{t-\Delta t}) \\ \vdots \\ y_{n(t-\Delta t)} + \frac{\Delta t}{2} f_n(Y_{t-\Delta t}) \end{bmatrix}$$

k and k is performed as follows:

$$Y_t^{k+1} = Y_t^k + \Delta Y_t^k \qquad k = k+1 \tag{4}$$

The oscillation equation

Under the occurrence of a disturbance, the magnetic axis of the generator rotor will accelerate or decelerate with respect to the synchronous speed of the stator rotational magnetic field axis, and a relative motion will start between both axes. The equation describing this relative motion is known as the oscillation equation and is given by Expression (5) (Kundur, 1994; Saadat, 2010).

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{m(pu)} - P_{e(pu)} \tag{5}$$

Where H is the inertia constant in MJ/MVA, ωs represents the electrical angular velocity, δ is the power angle of the synchronous machine measured in radians, while Pm and Pe are the mechanical and electrical power in pu, respectively. When considering the classical generator model, the expression for the electrical power in 5) depends on the transfer reactance and the angle between the internal voltage of the machine and the infinite bus, and is given as follows (Saadat, 2010):

$$P_e = \frac{EV}{X_s}\sin\delta = P_{max}\sin\delta \tag{6}$$

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In most disturbances, the oscillations are of such magnitude that linearization is not permissible and the nonlinear oscillation equation must be solved. The following section illustrates the numerical solution of Equation (5) as an effective method to determine the Transient Stability of power systems.

Numerical solution of the oscillation equation using RTI

The evaluation of the Transient Stability is performed with the oscillation equation, which can be expressed in terms of two first order differential equations as follows:

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(P_m - P_{max}\sin\delta) \tag{7}$$

$$\frac{d\delta}{dt} = \omega_s \Delta\omega \tag{8}$$

In Equation (7), three values are defined for the Pmax, which correspond to the for the Pmax, which correspond to the electrical power power supplied by the generator in pre-fault, fault and post-fault in pre-fault, fault and post-fault states. The above system of differential equations is converted into a system of nonlinear algebraic equations by applying the RTI and solved iteratively with the Newton-Raphson method as shown below:

$$\begin{vmatrix} 1 & \frac{\Delta t}{4H} P_{max}\cos\delta_t \\ -\frac{\Delta t}{2}\omega_s & 1 \end{vmatrix}^k \begin{vmatrix} \Delta(\Delta\omega_t) \\ \Delta(\delta_t) \end{vmatrix}^k = \begin{vmatrix} \Delta\omega_t - \frac{\Delta t}{4H}(P_m - P_{max}\sin\delta_t) \\ \delta_t - \frac{\Delta t}{2}\omega_s\Delta\omega_t \end{vmatrix}^k - \begin{vmatrix} \Delta\omega_{t-\Delta t} - \frac{\Delta t}{4H}(P_m - P_{max}\sin\delta_{t-\Delta t}) \\ \delta_{t-\Delta t} - \frac{\Delta t}{2}\omega_s\Delta\omega_{t-\Delta t} \end{vmatrix} \tag{9}$$

The updates of the status variables are performed as follows:

$$\Delta\omega^{k+1} = \Delta\omega^k + \Delta(\Delta\omega)^k \tag{10}$$

$$\Delta\delta^{k+1} = \Delta\delta^k + \Delta(\delta)^k \tag{11}$$

$$k = k+1 \tag{12}$$

As mentioned, in this case, RTI is being used to RTI is being used to solve the OMIB model OMIB model, however, following a similar similar methodology the student can implement his own student can implement his own numerical solution method. numerical solution method.

Practical implementation of the proposed educational application

The educational application proposed in this article was designed based on the five dimensions of knowledge: attitudes and perceptions, knowledge acquisition, deepening knowledge, meaningful use of knowledge and mental habits (Marzano et al, 1993), with the purpose of making the student easily understand the handling and root operation of the application, thus achieving a real understanding of how the tool solves the ET problem, that is, in order to teach students to process in a grandiloquent way the information.

Considering the above, the OMIB model with the combination of the RTI and the Newton-Raphson method is implemented in a computational algorithm. In order to facilitate data management and interpretation of results in such algorithm, a Matlab Graphical User Interface (GUI) is designed and developed using a visual programming environment offered by such package known as GUIDE (MathWorks, 2015). The input data for the ET simulation, Table 1, are handled through a data entry element known as edit text, while the condition or property of each input data is indicated to the user through text elements known as static text. Two types of buttons are also used, the push button and the radio button, which are buttons on which the instructions or code to be executed to solve the ET problem are programmed. For the output data, Table 2, the static text elements are selected to program on them the result of the angle and critical time calculation, while to display the graphs the axes element is selected giving the desired size to the print window.

The input data, initial conditions, graphs and results have been grouped by panels to have a better organization of the environment, as shown in Figure 1. It should be noted that the "calculate" button only has action in the results panel, which is located between the results and the input data of the right column.

In Figure 1 it is clear that the interface clearly and directly prompts the user for the input data and displays all the variables of interest when performing a TE study by means of three graphs and three boxes.

Dato	Descripción	Dato	Descripción
f	Frecuencia eléctrica (Hz)	P_{e1} P_{e2} P_{e3}	Potencia eléctrica del generador en estado de pre-falla, falla y post-falla (pu).
Δt	Paso de integración (segundos).	t_i t_f	Tiempo de inicio y final de simulación (segundos).
H	Constante de inercia (MJ/MVA).	t_{if} t_{lf}	Tiempo de inicio y liberación de la falla (segundos).
P_m	Potencia mecánica (pu).	δ_0 $\Delta\omega_0$	Condición inicial del ángulo de potencia y cambio de velocidad inicial (rad, rad/seg).

Table 1 Input data proposed educational application

Dato	Descripción	Dato	Descripción
t_c	Tiempo de liberación crítico (segundos).	δ_c δ_{max}	Ángulo de liberación crítico y máximo (radianes).

Table 2 Output data of the proposed educational application

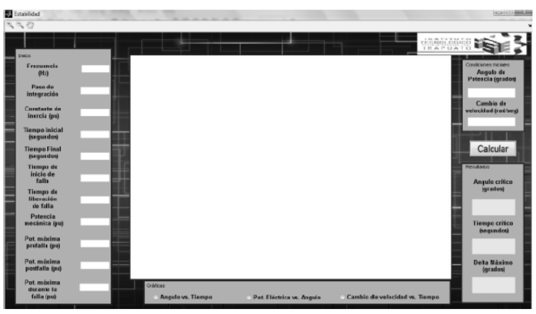

Figure 1 Environment of the proposed educational application

The graphs are controlled from the graphing panel made up of three radio button radio button selection elements, showing the first one the oscillation graph of the power angle with respect to time power angle versus time, the second the power second the behavior of the electrical power vs. the second one the behavior of the electrical power vs. its angle under fault conditions. conditions and finally the third element shows the graph of the graph of the change of synchronous speed versus time. with respect to time. These elements are located in the lower central part of the interface and the space for the and the space for the display of the graphs is the predominant predominant part of the interface. In the upper left part of the interface, zoom and manual scrolling tools have been added to facilitate the handling of the graphs.

To facilitate the handling of the graphs. In case the fault release time exceeds the critical time, a loss of synchronism warning window will be displayed, which implies that the system will lose stability.

With the introduction of the competency-based curriculum model in Mexico (Gutiérrez, 2007), educational instructions have given great importance to the development of competencies of being, knowing and knowing how to do, since it is necessary that these become permanent resources that allow students to perform adequately in the changing world of work. In this sense, the application described above tries to help to give a turn to the education in electrical engineering in a dimensional way, trying that the student understands what it does and the way in which the tool solves the problem, in order to manipulate this tool from the source code, allowing the complete understanding of the ET phenomenon of power systems, as well as the acquisition of knowledge and the application of the same in this area, with which the change in the traditional teaching is achieved and the competences for the handling of the labor situations are developed.

Use of the proposed educational application for the ET analysis of SEPs

In order to illustrate how to use the proposed application, its reliability and application is used, as well as its reliability and and usefulness, the TE of a four-unit thermoelectric thermoelectric power plant is examined, 24 KV, 60 Hz power plant supplying power to an infinite bus through two infinite bus through two transmission lines, as shown in transmission lines, as shown in Figure 2 (Kundur, 1994). (Kundur, 1994).

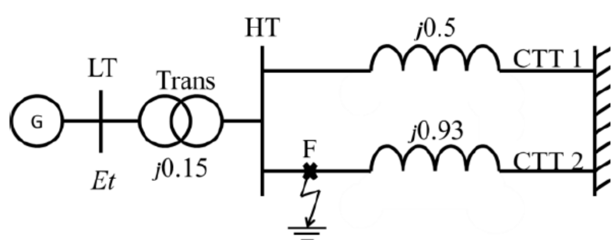

Figure 2 Infinite machine-bus power system

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The initial condition of the system with quantities expressed in pu on a 2220 MVA and 24 kV basis are: Pm = Pe = 0.9, Q=0.436 (over-excited), Et =1.028.34º and EB 0.900810º . The equivalent generator of the system has a transient reactance of 0.3 pu and an inertia constant of 3.5 MJ/MVA without damping. The maximum pre-fault, fault and post-fault electrical powers are 1.351 pu, 0 pu and 1.1024 pu, respectively.

The simulation is performed for a period of 5 s with an integration step of 0.001 s, a fault application time of 1 s, and three fault release times of 0.07, 0.086, and 0.087 s.

Obviously, these input data are entered at their corresponding position on the left side of the graphical interface environment. The initial conditions of the power angle the initial conditions of the power angle and angular velocity change are 41.77 º and 0 rad/s, which are entered in the upper right panel. the upper right panel.

Once all the simulation data have been entered, the calculate button is pressed to present the results in the panel with this name and to obtain any of the three graphs offered by the application, selecting the one required. The results obtained from the simulation are presented and compared with those reported in the open literature in Table 3, while in Figure 3 and 4 the plots of the power angle as a function of time for the three fault release times and the plots of the electrical power as a function of the delta angle are presented, respectively.

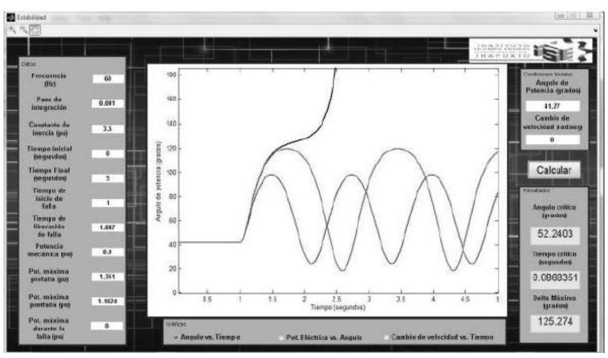

Figure 3 Power angle response for different values of fault release time

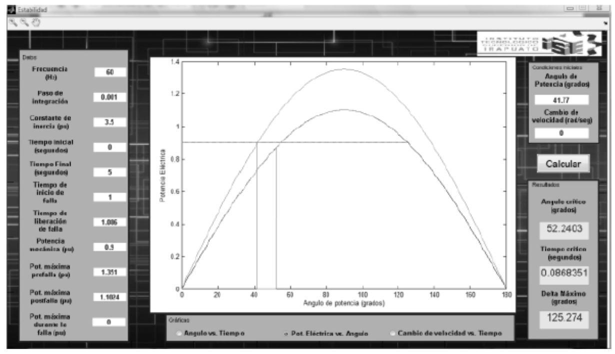

Figure 4 Electrical power diagram as a function of rotor angle

Table 3 shows that the implementation proposed in this work is reliable to carry out the TE analysis of SEPs, since the data obtained by such implementation are very similar to those reported in (Kundur, 1994).

In addition, it is shown that the critical release time is 0.0868351 s, so that with any fault release time greater than the above the system will lose stability. In Figure 3, the lowest and highest amplitude curve corresponds to the fault release times of 0.07 s and 0.086 s, respectively, while the curve that does not have sinusoidal behavior is 0.087 s, respectively. In this figure it is observed that the system is unstable or loses synchronism for the case in which the fault release time is 0.087 s, which confirms the above, while for the other two cases the electrical system maintains stability. It is important to mention that the power angle oscillates around the new operating point of the machine because damping windings are not being considered, see Figure 4.

It should be emphasized that this section has only shown how the application is used and has not illustrated how the code is modified, since this topic is too broad to be explained here, however, it is clear that electrical engineering teachers and students should not have problems to carry out such modifications because they are familiar with Matlab programming codes. In practice, excellent student performance has been observed when the teacher teaches various numerical integration methods before using the ET educational application, so it is recommended to do this to increase the educational effect that the proposed application has.

Conclusions

An educational computational application for the analysis of Transient Stability of electrical power systems has been presented. The proposed application was designed based on the five dimensions of knowledge and was developed as a Graphical User Interface in Matlab using a visual programming environment known as GUIDE offered by that package. The RTI combined with the Newton-Raphson method was used for the numerical solution of the DE system associated with the TE model, however, students have an excellent performance when the teacher teaches various numerical integration methods before using the TE educational application, so it is recommended to do this to increase the educational effect that the proposed application has.

The article illustrated how to use the proposed application, which has a friendly, intuitive and easy to handle user interface. This feature gives it the potential to be used in classroom or even in distance education courses of all subjects related to computer aided analysis of power systems. With the use of the tool, results are obtained in a short time, but thanks to its flexibility students can integrate their own solution methods, so that students not only acquire cognition, but also the competence of analysis and application of knowledge. Therefore, with the use of novel tools, such as the one presented in this work, it is possible to change in a dimensional way the traditional teaching of engineering education, since students acquire knowledge in a simpler way and learn to apply it in the innovative solution of problems, developing competencies for the management of work situations.

Finally, it should be mentioned that the proposed educational application is free to use and is open to any modification or improvement, so it is possible to acquire the tool by the person who wants it, whether student or teacher. To do so, it is necessary for the interested person to contact any of the authors of this work or through the web page of the authors' institution of origin www.itesi.edu.mx, where he/she will receive the appropriate attention.

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