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Algorithm development for analyzing transient stability in Matlab

Desarrollo del algoritmo para el análisis de estabilidad transitoria en Matlab

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Abstract

The electrical energy supply quality of the supply company is of great importance for both the supply company as the end users. This is because it is convenient for the supply company to bill all the electrical energy generated at that moment, and the end users can thus benefit from the supplied energy to perform the day-to-day chores. However, the electrical energy supply quality can be discontinued due to electrical faults caused by natural phenomena (thunderstorm, snow etc.) or by human operation errors. Therefore, due to the possible electrical fault occurrences in the different location of power system, transient stability analysis is required to determine the power system capacity to remain stable in presence of electrical disturbances.

Electrical Disturbances, Electrical Power System, Transient Stability

Resumen

La calidad de suministro de energía eléctrica de la empresa suministradora es de suma importancia tanto para la empresa como para los usuarios finales. Debido a que la empresa suministradora le conviene facturar toda la energía eléctrica generada en el momento y los usuarios finales les convienen tener energía eléctrica para desarrollar los quehaceres de la vida día a día. Sin embargo, la calidad de suministro de energía eléctrica puede ser discontinuado por fallas eléctricas ocasionados por fenómenos naturales (tormenta, nieve etc.) o por errores de operaciones humanas. Por lo tanto, ante las posibles ocurrencias de fallas eléctricas en las diversas partes del sistema eléctrico, se requiere hacer estudios de estabilidad transitoria para determinar la capacidad del sistema eléctrico de permanecerse estable ante disturbios eléctricos.

Disturbios Eléctricos, Estabilidad Transitoria, Sistema Eléctrico de Potencia

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Introduction

The quality of the power supply of the utility is of utmost importance for both the utility and the end-users. Because it is in the interest of the utility to bill for all the electricity generated at the time and it is in the interest of the end-users to have electricity at all times to carry out their day-to-day tasks. However, the quality of power supply can be interrupted by power failures caused by natural phenomena (storm, snow etc.) (Blackburn & Domin 2006), human operational errors or normal system operations. Therefore, in view of the possible occurrence of power failures in the various parts of the power system, transient stability studies are required to determine the ability of the power system to remain stable in the face of electrical disturbances.

In an electrical power system, transient stability is the analysis performed to determine the ability of the system to remain in synchronism in the event of a large electrical fault or disturbance (Kundur 1994). This analysis is carried out in the form of a numerical simulation of an electrical power system to determine the dynamic response of the system to electrical disturbances. The aim is to obtain information on the dynamic response of the system for the scenarios before, during and after a fault or disturbance.

Background

A system is said to be in steady state when there is an equilibrium between the mechanical torque of the turbine and the electromagnetic torque of the synchronous machine. However, if the equilibrium between the torques is lost by some large disturbance, then the system is said to be in an unstable condition. The condition is unstable when the synchronous machines in the system manifest oscillations that grow as a function of time and thus lose synchronism.

The rotational speed of the synchronous machines is the key to synchronism between the set of machines in the electrical power system. When there is a disturbance, the rotational speed of the rotor will be affected by the event and eventually presents acceleration or deceleration effects. The acceleration or deceleration effect will cause the rotor angle of at least one synchronous machine to move away from the other machine or machines in the system.

For a scenario where the synchronous machine is accelerated, this endangers the mechanical components of the machine and possible failure of the machine.

Disturbances that can cause acceleration or deceleration of rotor rotation can be from day-to-day system operation such as: changes in generation levels, loads, topology and capacitor switchover. On the other hand, electrical disturbances or faults can also be caused by natural environmental phenomena such as lightning, storms, snow, earthquakes.

The electrical power transfer of an electrical system can be expressed in Figure 1 where it can be seen that the electrical power transferred is a function of the rotor angle.

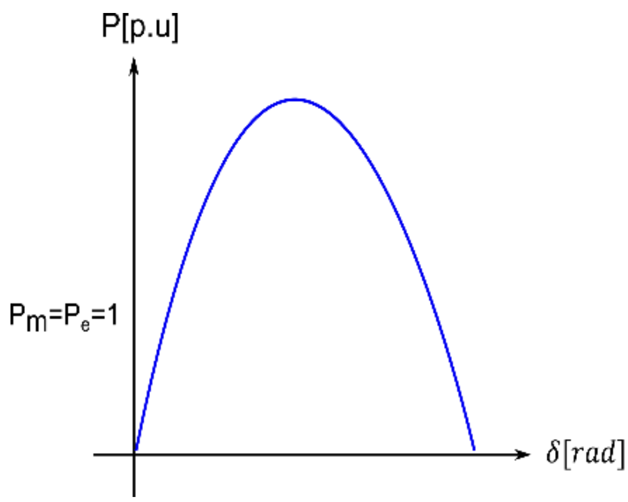

Figure 1 Power transfer
Own Elaboration

Justification

Overhead transmission lines are the most prone to power failures due to natural phenomena because of the long distances exposed to the elements. Therefore, in order to offer a good power supply service while minimising the energy discontinuity caused by wide-area blackouts, which is a consequence of loss of synchronism of the machines, supply companies choose to analyse the transient stability of a system for various disturbance scenarios, considering pre-, during and post-events.

For a small system of a single synchronous machine connected to the infinite bus, the solution is simpler and more intuitive with the criterion of equal areas (Anderson & Fouad 2002).

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In which it is analysed whether two areas called acceleration area (A1) and deceleration area (A2) that can be calculated and presented in Figure 1 are equal. So, if A1 ≤ A2 the system has the ability to remain stable for a given disturbance. Otherwise, if A1 > A2 the system will accelerate and will have no braking capacity to return to the original steady state or synchronism. In this case, the system loses stability.

However, due to the size, complexity and the nature of the non-linearity of the electrical power system, the study of the transient stability of multi-machines is performed with the support of specialised software such as: ETAP, Power World, PSS/E, ATP, PSCAD, PSAT and not the equal area criterion. Another way to perform transient stability is to program it specifically in a programming language such as Matlab (Anderson & Fouad 2002). The latter is desired for the undergraduate students so that they can know the conditions and modelling for such a study of the Selected Topics in Power course.

Objective

To develop computationally in Matlab the modelling and considerations of the classical model for the study of transient stability of multi-machines in an electrical power system. With the aspiration that the undergraduate students understand the concepts of stability, the preparation of input data, the modelling of the oscillation equation and the resolution of the analysis by means of numerical integration supported by the ode45 function in Matlab.

Classical Modelling of Transient Stability Analysis of Multi Machines

Some considerations are made for the multi-machine system in the classical model:

The mechanical power is constant during the study.

The damping is negligible.

A constant voltage source is considered after the transient reactance for the synchronous machine model.

The loads are represented as passive impedances.

The oscillation equation can be decomposed into two parts and is given in equations 1 and 2.

$$\frac{2H_i}{\omega_s}\frac{d}{dt}\omega_i = Pm_i - Pe_i \quad (1)$$

$$\frac{d}{dt}\delta_i = \omega_i - \omega_s \quad (2)$$

Where H_i is the inertia constant of the i-th machine, ω_i is the speed of the i-th machine, Pm_i is the mechanical power of the i-th machine, Pe_i is the electrical power of the i-th machine, δ_i is the angular displacement of the rotor of the i-th machine and ω_s es the reference speed or synchronous speed of the machine.

The calculation of Pe_i is expressed in equation 3, which is the same equation that is used to calculate active power in polar form in power flows using Newton Raphson (Grainger & Stevenson 2005).

$$Pe_i = \left[{E_i}^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \right] \quad (3)$$

Where E_i y E_j are the nodal voltage magnitudes of nodes i and j respectively, Y_{ij} is the magnitude of the off-diagonal elements the Ybus, θ_{ij} is the angle in degrees of the off-diagonal elements the Ybus, δ_i and δ_j are the angles in degrees of the node nodal voltages of the nodes$i$ and j respectively.

Note that under initial or pre-disturbance conditions $Pm_i = Pe_i$ po r that there is an electrical energy balance, where the generation power satisfies the load power.

All per unit data must be expressed on the same basis. For example, over 100 MVA all.

The passively modelled load equivalents as shunt admittance are presented in equation 4.

$$Y_L = \left(P_L/{V_L}^2\right) - j\left(Q_L/{V_L}^2\right) \quad (4)$$

Where Y_L is load modelling in passive form as shunt admittance, P_L y Q_L are the active and reactive powers of loads, V_L es is the power flow solution nodal voltage result.

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The initial condition internal voltages $E_i\angle\delta_{i0}$ of generator in classical model is calculated from power flows. The angles of internal voltages can be calculated from the terminal voltages.$V\angle\alpha$ a nts of failure. This is presented in equation 5.

$$E\angle\delta' = (V + Q\, x'd/V) + j(P\, x'd/V) \qquad (5)$$

The initial angle of the generator δ_0 is obtained by adding up the pre-transient voltage angle α a δ'. This is presented in equation 6.

$$\delta_0 = \delta' + \alpha \qquad (6)$$

The admittance matrix Ybus must be reduced to an equivalent to the number of synchronous machines in the system using Kron's reduction to Ybus. The Ybus is partitioned into four sub-matrices as shown in equation 7.

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{bmatrix} \begin{bmatrix} V_n \\ V_r \end{bmatrix} \qquad (7)$$

Where the subscripts n represents number of generators and r represents the number of remaining nodes.

The Kron reduction is applied to the Ybus as presented in equation 8. This results in a reduced Ybus having matrix dimension (n*n) where n represents number of generators.

$$Ybus_{kron} = (Y_{nn} - Y_{nr}{Y_{rr}}^{-1}Y_{rn}) \qquad (8)$$

This Kron reduction is applied to the three Ybus de topologies for the three times of the disturbance event. Pre-fault, during-fault and post-fault.

9-Bus System Description

The classical transient stability study will be performed for a 9-bus power system (Anderson & Fouad 2002). The data of the transmission lines, as well as the loads, operating voltages and shunt admittances are presented in Figure 2.

Parameters	G1	G2	G3
MVA	247.5	192	128
kV	16.5	18	13.8
Pf	1.0	0.85	0.85
Type	hidro	vapor	vapor
[r/min]	180	3600	3600
X'd	0.0608	0.1198	0.1813
Stored kinetic energy at rated speed [MW*s]	2364	640	301

[1]**Table 1** Generator Data. Source: Anderson & Fouad 2002.

The disturbance is simulated as a solid three-phase fault on the section of line 5-7 close to bus 7. Therefore, it is considered as if the fault was on bus 7. The fault is released 5 cycles (0.083s) later by opening line 5-7. This study is carried out for 2 seconds.

The data for the three generators is presented in Table 1.

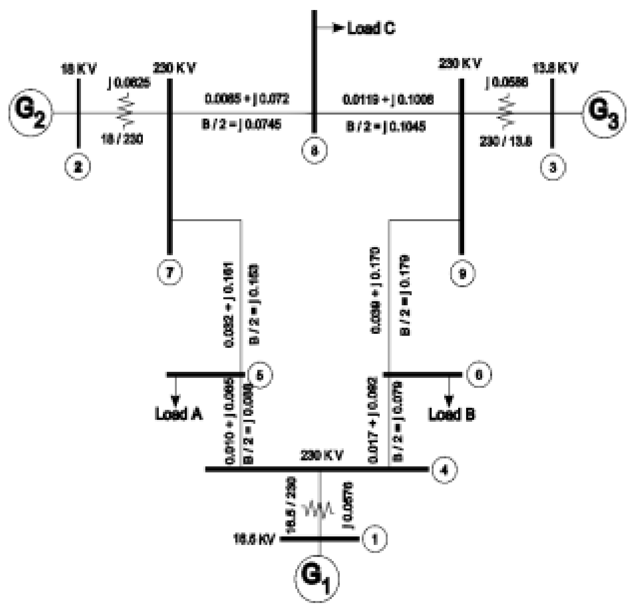

Figure 2 Single-line diagram of the 9-bus system with line data in pu expressed at 100 MVA base
Own Elaboration

The results of power flows by the Newton Raphson method are shown in Figure 3 in steady state. This shows the nodal voltages of each bus, and the active and reactive power of each line in both directions.

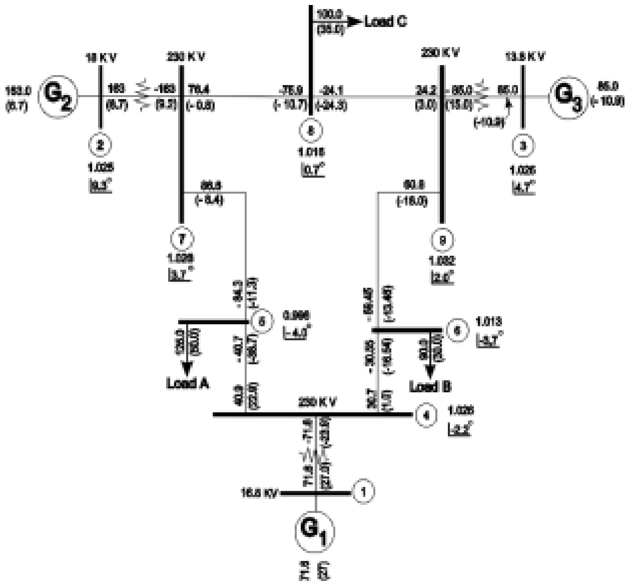

Figure 3 Results of Power Flows of the 9-bus system
Own Elaboration

Simulation and Results

First of all, the power flow analysis must be carried out in order to know the nodal voltages in steady state. This process was carried out with the Newton Raphson iterative method in Matlab. The results of the voltages at each bus are shown in Figure 4, which coincides with the results presented in Figure 3. In Figure 4, the first column corresponds to number of buses, second and third column presents the magnitude and angle of the voltage.

```
------------------------------
-----Voltage in Polar Form-----
------------------------------
  Nodes     |V|      Delta
  1.0000   1.0400        0
  2.0000   1.0250   9.2388
  3.0000   1.0250   4.6283
  4.0000   1.0258  -2.2299
  5.0000   0.9957  -4.0109
  6.0000   1.0127  -3.7083
  7.0000   1.0258   3.6826
  8.0000   1.0159   0.6913
  9.0000   1.0324   1.9338
```

Figure 4 Results of the voltages on each bus
Own Elaboration

The results of the internal voltages of each generator are shown in Figure 5 by performing equations 5 and 6.

Therefore, the angles shown in the third column are already angles in degrees for the initial condition of the transient stability analysis.

```
-----------------------------------
-----Voltage in Polar Form----------
-----------------------------------
  Nodes     |E|     Initial Delta
  1.0000   1.0566     2.2852
  2.0000   1.0502    19.6908
  3.0000   1.0169    13.1302
```

Figure 5 Results of the internal voltages of each generator
Own Elaboration

We proceed to find the three matrices of admittance Ybus reduced by Kron, before fault, during fault and after fault, and they are presented below in Figures 6, 7 and 8:

```
------------------------------------------------------
--------------------Y_bus_preF_Kron--------------------
------------------------------------------------------
  0.8454 - 2.9882i   0.2871 + 1.5130i   0.2096 + 1.2256i
  0.2871 + 1.5130i   0.4200 - 2.7239i   0.2133 + 1.0879i
  0.2096 + 1.2256i   0.2133 + 1.0879i   0.2770 - 2.3681i
```

Figure 6 Results of Ybus prefalla Kron
Own Elaboration

```
------------------------------------------------------
--------------------Y_bus_durF_Kron--------------------
------------------------------------------------------
  0.6568 - 3.8160i   0.0000 + 0.0000i   0.0701 + 0.6306i
  0.0000 + 0.0000i   0.0000 - 5.4855i   0.0000 + 0.0000i
  0.0701 + 0.6306i   0.0000 + 0.0000i   0.1740 - 2.7959i
```

Figure 7 Results of Ybus during the Kron fault
Own Elaboration

```
------------------------------------------------------
--------------------Y_bus_posF_Kron--------------------
------------------------------------------------------
  1.1813 - 2.2287i   0.1376 + 0.7264i   0.1910 + 1.0794i
  0.1376 + 0.7264i   0.3886 - 1.9526i   0.1988 + 1.2293i
  0.1910 + 1.0794i   0.1988 + 1.2293i   0.2727 - 2.3423i
```

Figure 8 Results of Ybus post-failure Kron
Own Elaboration

The simultaneous equations 1 and 2 are solved using the Runge-Kutta method with the Matlab function ode45.

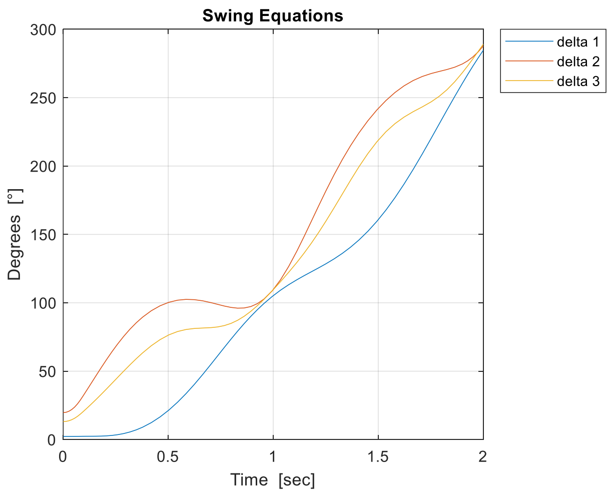

Figure 9 Results of angles δ over time
Own Elaboration

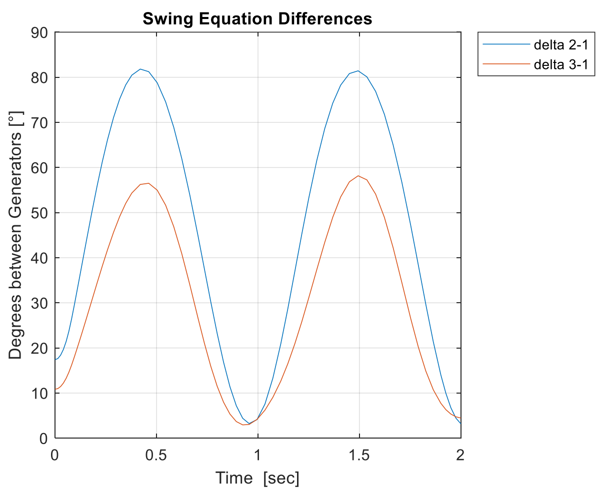

Figure 10 Results for differences of angles δ over time. δ_{21}y δ_{31}
Own Elaboration

Figure 9 shows the graphs of the δ angles of the three synchronous machines over time. Figure 10 shows the graphs of the differences of the angles δ of the three synchronous machines over time, taking machine one as a reference., δ_{21}y δ_{31}.

It is observed that the angles δ in Figure 9 of the three machines increase and then decrease. And it is also seen in Figure 10 that the differences of the angles increase and decrease. In neither figure do the angles increase infinitely because, if it does, then at least one machine will go out of synchronism, and the system will be unstable. Therefore, it is concluded that the system is stable for this study.

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Conclusions

It can be concluded from the results obtained that the system will maintain synchronism despite the disturbance of a three-phase fault on line 5-7 near bus 7. The fault duration was 5 cycles and is released when the protections are activated and line 5-7 is opened.

The development of the algorithm in Matlab of this study is intended to facilitate the undergraduate students to move the parameters of the system and to enable them to see the different scenarios. Such as to observe the effect and importance of inertia constant H of synchronous machines, location of fault, time of fault duration etc. So that students can interpret the result graphs and determine when it remains in steady state and when it becomes unstable for a given fault condition.

Finally, the algorithm is developed in a general way. By changing the input data of the system, the stability analysis can be performed for another given system. This does not limit students to study only one system but any system.

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