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Simulation Techniques of Electrical Power System Stability Studies by Using Matlab

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***Abstract*—The stability of an electric power system is a term in electrical power engineering that represents the ability of the system to return to the normal state of operation (at the default voltage and frequency) after a disturbance. The integrity of the system is preserved when practically the entire power system remains intact with no tripping of generators or loads, except for those disconnected by isolation of the faulted elements or intentionally tripped to preserve the continuity of operation of the rest of the system. Several methods are used for that purpose like an equal area criterion and transient stability margin (TSM). In this study, the calculation will be made on one and multi machines connected to an infinite bus, steady state and transient stability using Matlab to achieve a stable system.**

Keywords—Frequency, Swing Equation, Steady State Stability, Transient Stability

I. INTRODUCTION

As electrical power systems have been evolved during the past couple of years, the instability of the system have also been involved in this evolution. To keep dealing with problems, such as faults and disturbances; new technologies and methods of analysis were invented, in order to supply the loads and keep the system secured. However, power system stability is known as the capability of an electric power system, for a given starting operating conditions, to recover a state of operating balance after being subjected to a physical disorder, with most system variables enclosed so that basically the entire system remains unharmed. The system will fail to regain equilibrium if it is unstable. Instability exists in many kinds in modern power systems, such as voltage and frequency; accordingly, there are different methods used to solve them. The stabilization processes basically works by compensating the causes of instability [1].

II. CLASSIFICATION OF POWER STABILITY

Rotor Angular or Synchronous Stability: The rotor angle stability issue includes the investigation of electromechanical oscillations inalienable in power systems. A critical factor in this problem is how the power outputs of synchronous machines fluctuate as their rotor angles change. In case when the system is irritated, this balance is disturbed, which results in speeding up or deceleration of the machine's rotors as indicated by the laws of movement of a turning body. In case if one generator incidentally runs faster than the other one, the angular position of its rotor with respect to that of the slower machine will progress. Past a specific point of confinement, an expansion in the precise partition is joined by a diminishing in power exchange; this builds the angular division further and prompts to instability. It ought to be noticed that loss of synchronism can happen between one machine and whatever remains of the system, or between groups of machines, probably with synchronism preserved within each group after untying from each other [4],[5].

Frequency Stability: Frequency stability is subjected to the ability of a power system to hold steady frequency following a brutal system upset resulting in a significant difference between generation and load. It depends on the ability to keep up/re-establish the balance between system generation and load, with the least unexpected loss of load. The instability that may occur as a result of managed frequency swings, which results in stumbling of creating units or potentially loads. Extreme system disturbance results in huge trips of frequency, power flow, voltage, and other system variables, accordingly summoning the activities of procedures, controls, and protection that are not displayed in routine transient stability or voltage stability studies. In large interconnected power systems, this sort of circumstance is most regularly connected with conditions taking after part of systems into islands. Stability for this situation is an issue of regardless of whether every island will achieve a condition of equilibrium with insignificant inadvertent loss of load. For the most part, frequency stability issues are connected with deficiencies in hardware reactions, poor coordination of control and protection equipment, or lacking generation reserve [6,][7].

Voltage Stability: When it comes to reactive power balance, the circumstance is not as clear and straightforward as concerning active power. There is dependably a harmony amongst the "delivered" and "expended" reactive power in each hub of a network. This is an immediate result of the Kirchhoff's first current law. When one discusses irregularity in this setting, it will imply that the infused reactive power is such, typically too little, that the voltage in the hub cannot be kept to adequate qualities. (At low load the infused reactive power could be high bringing about a too high voltage, conceivably higher than the hardware may be intended for. This is obviously not desirable, but rather it could ordinarily be controlled in a manner that no instabilities develop.) When discussing imbalance for this situation, the infused reactive power contrasts from the coveted infused reactive power, expected to keep the desired voltage. In the event that this imbalance gets too high, the voltages surpass the satisfactory range [8],[9].

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III. EQUATIONS

Study Over One Machine Connected to an Infinite bus: First of all, an infinite bus is characterized by a constant terminal voltage, constant frequency and small synchronous impedance. In this case, the generator is presented by constant voltage behind the direct axis transient reactance $X_d^{/}$ .The purpose of the study is to get the power angle variation curve with respect to electrical power variation. The following circuit in Fig.1. describes the study [10].

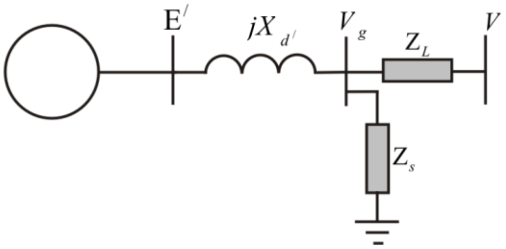

Fig. 1. Single Machine Connected to an Infinite Bus.

To perform the study, the admittance formulas are derived from the circuit and are as follow:

$$\left.\begin{aligned} y_{10} &= \frac{Z_L}{jX_d^{/}Z_S + jX_d^{/}Z_L + Z_SZ_L} \\ y_{20} &= \frac{jX_d^{/}}{jX_d^{/}Z_S + jX_d^{/}Z_L + Z_SZ_L} \\ y_{30} &= \frac{Z_S}{jX_d^{/}Z_S + jX_d^{/}Z_L + Z_SZ_L} \end{aligned}\right\} \tag{1}$$

Then an equivalent circuit with an infinite bus connecting two nodes is considered in Fig.3 [10].

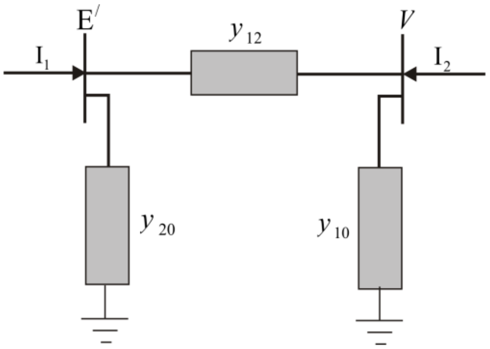

Fig. 2. Equivalent Circuit for a Machine Connected to an Infinite Bus

The following current equations derived from the circuit can be presented in a matrix form:

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} E^{/} \\ V \end{pmatrix} \tag{2}$$

Where:

$$\left.\begin{aligned} Y_{11} &= y_{10} + y_{12} \\ Y_{22} &= y_{20} + y_{12} \\ Y_{12} &= Y_{21} = -y_{12} \end{aligned}\right\} \tag{3}$$

$$P_e = \left|E^{/}\right|^2 \left|Y_{11}\right| \cos\theta_{11} + \left|E^{/}\right|\left|V\right|\left|Y_{12}\right| \cos(\delta - \theta_{12}) \tag{4}$$

In most systems, Z_L and Z_S are predominantly inductive; hence $\theta_{11} = -\theta_{12} = 90^o$ so the electrical power equation become

$$P_e = \frac{\left|E^{/}\right|\left|V\right|}{X_{12}} \sin\delta$$

The variation of the power angle (δ) allows the variation of the power and plotted on the curve in Fig.4.

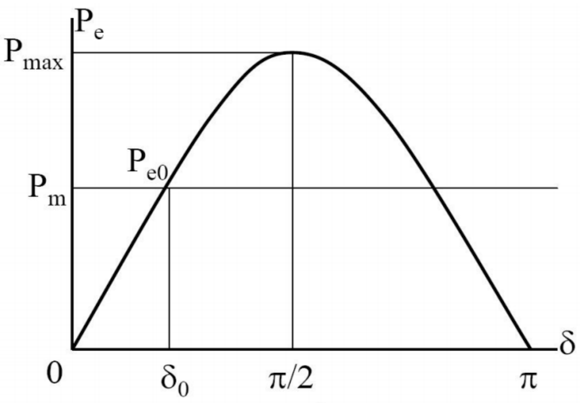

Fig. 3. Power Angle Curve

In case of maximum power:

$$P_{max} = \frac{\left|E^{/}\right|\left|V\right|}{X_{12}}$$

If an attempt was made to advance the power angle further and further, the maximum power will drain back and decrease. And the machine will accelerate causing loss of synchronism with the infinite bus.

The power equation can be expressed as:

$$P_e = P_{max} \sin\delta \tag{7}$$

For transient stability problems, the machine is represented by the voltage $(E^{/})$ behind the reactance $(X_d^{/})$; where the current during the transient period is limited with transient reactance $(X_d^{/})$ if the generator is suddenly short-circuited.

The voltage is governed with this equation:

$$E' = V_g + jX'_d I_a \tag{8}$$

Where (V_g) stands for the generator terminal voltage and (I_a) stands for pre-fault steady state generator current. Note that the transient power-angle curve has the same general form of the steady-state curve; however, it attains a larger peak compared to the steady-state peak value [11].

A. Swing Equation:

Once a disturbance occurs, the rotor's speed may speed up or down with respect to the air gap. To monitor this disturbance many parameters were determined and derived to a final form and can be monitored through an equation called swing equation. Swing equation concerns the rotor's motion with respect to synchronously rotating air gap "magnetomotive force", and brings the rotor's speed back to synchronous speed. In terms of electrical radians [12]:

$$P_m - P_e = \frac{d^2.\delta.H}{\pi.f_0.dt^2} \tag{9}$$

B. Steady State Stability –Small Disturbances:

The ability of the power system stability to regain its synchronism when subjected to small disturbances is referred to as steady-state stability. The motion of the system is free, and stability is assured if the system returns to its original state. This result can be attained by finding the characteristic equation of the system. One-machine system connected an infinite bus is considered again to illustrate the steady-state stability problem. If the electrical power is substituted in the swing equation, the result will be [13]:

$$\frac{d^2.\delta.H}{\pi.f_0.dt^2} = P_m - P_{\max}\sin\delta \tag{10}$$

Motion of the rotor relative field in electrical radian becomes:

$$\delta = \delta_0 + \frac{\pi.f_0.\Delta P}{H.\omega_n^2}\left[1 - \frac{1}{\sqrt{1-\zeta^2}}.e^{-\zeta\omega_n t}\sin(\omega_d t + \theta)\right] \tag{7}$$

C. Transient Stability with Equal-Area Criterion:

Equal-area criterion, which is a method used for a quick prediction of stability, is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance.

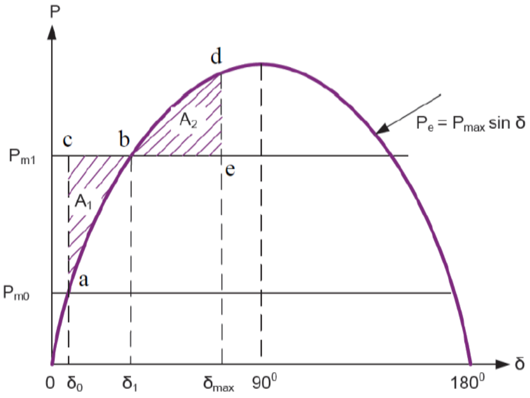

Fig. 4. Equal Area Criterion with Sudden Change in Load

In Fig.5. |area A1|=|area A2|, and the rotor swings to point b and the angle $\delta_{\max}$. This is known as equal-area criterion where the rotor angle would oscillate back and forth between δ_0 and $\delta_{\max}$ the damping will cause these oscillations to subside and the new steady state operation would be established at b [14].

D. Numerical Solution of the Swing Equation:

It should consider a generator connected to an infinite bus through parallel lines as see in Fig.6 [15].

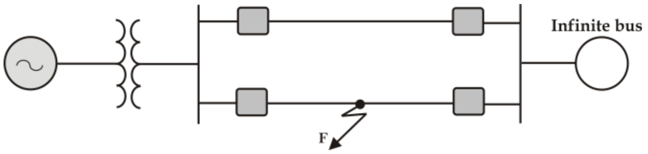

Fig. 5. Generator Connected to Infinite Bus through Parallel Lines

The numerical solution of the swing equation is given by [16]:

$$\delta_{i+1}^c = \delta_i + \left(\frac{\left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{i+1}^p}}{2}\right).\Delta t \tag{12}$$

$$\Delta\omega_{i+1}^c = \Delta\omega_i + \left(\frac{\left.\frac{d\Delta\omega}{dt}\right|_{\delta_i} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{i+1}^p}}{2}\right).\Delta t \tag{13}$$

E. Euler's Method:

Given the first order differential equation as:

$$\frac{dx}{dt} = f(x) \tag{14}$$

one simple integration technique is Euler's method as shown in Fig.7. The integration step size is Δt [1].

First, by applying Euler's method, calculate machine frequency ω and power angle δ. Next, the slope at $\tilde{\delta}$ and $\tilde{\omega}$ are calculated [17]:

$$\frac{d\tilde{\omega}}{dt} = \frac{\tilde{P}_{ap.u}\,.\omega_s}{2H\,\tilde{\omega}_{p.u}} \qquad (15)$$

$\tilde{P}_{ap.u}$:is the per-unit accelerating power calculated at $\delta = \tilde{\delta}$ and $\tilde{\omega}_{p.u,} = \frac{\tilde{\omega}}{\omega_s}$.

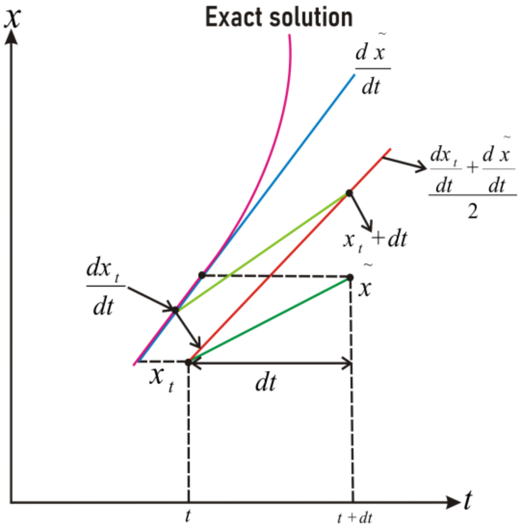

Fig. 6. Illustration of Modified Euler's Method

$$\delta_{t+\Delta t} = \delta_t + \frac{\left(\frac{d\delta_t}{dt} + \frac{d\tilde{\delta}}{dt}\right)}{2}\Delta t \qquad (16)$$

$$\omega_{t+\Delta t} = \omega_t + \frac{\left(\frac{d\omega_t}{dt} + \frac{d\tilde{\omega}}{dt}\right)}{2}\Delta t \qquad (17)$$

IV. ONE MACHINE STABILITY FLOW CHART

One machine stability is classified into four cases: damping, Euler's, Equal area criteria with and without fault.

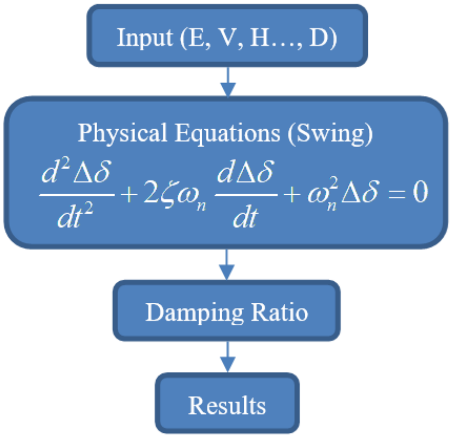

Fig. 7. Damping case flow chart

Euler's method tends to know the accelerated power angle and speed by estimating the slope of the power. After loading the 11-column data, the program is run and the results will show power angle and frequency variation numerically and in figures.

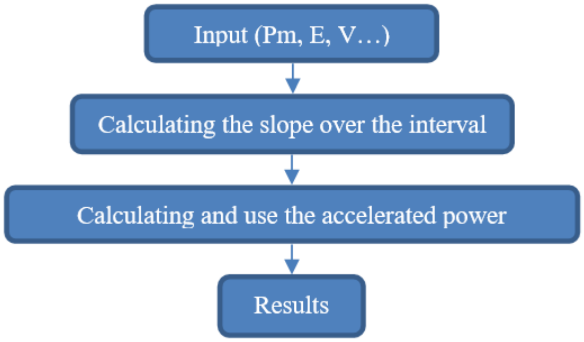

Fig. 8. Euler method flow chart

Equal are criteria flow chart without and with fault:

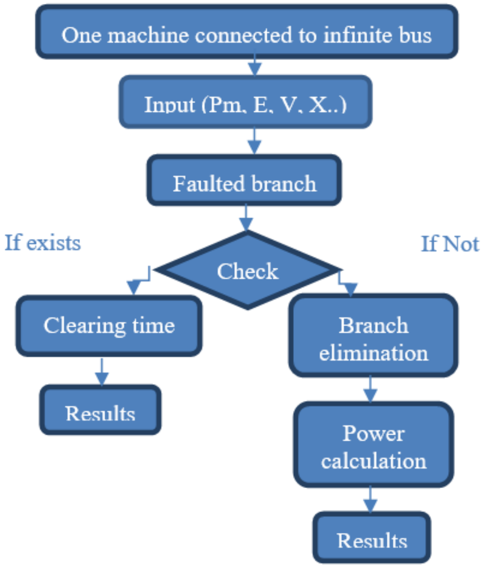

Fig. 9. Equal area criterion flow chart

In this methodology, the power system got defined so that the program can continue its process, then the input data are entered and the branch number that is predicted to be faulted is entered and check for fault, if it detects a fault, then calculations are performed to check the time needed to eliminate the fault and the results are displayed. While if no fault is detected, then the branch will get eliminated from the study and power calculations are carried out to obtain the results.

V. CASE STUDY

The case study is made for Deir Ali power plant in Damascus-Syria. Data were taken as the inputs, and implemented using Graphical User Interface (GUI). Results are shown to display the most severe fault case. Methods for one machine are applied below, (Damped, Euler, Equal area without or with fault).

A. *One Machine in Case of Damping:*

For inputs per unit

$$E = 1.6, V_{Load} = 1, H = 1.52, \ P_m = 1, \ X = 2.3, f = 50[Hz]$$

When the generator deviates from its synchronous speed of 3000 rpm, frequency is modified to 50Hz to include a damping torque of 0.35 pu.

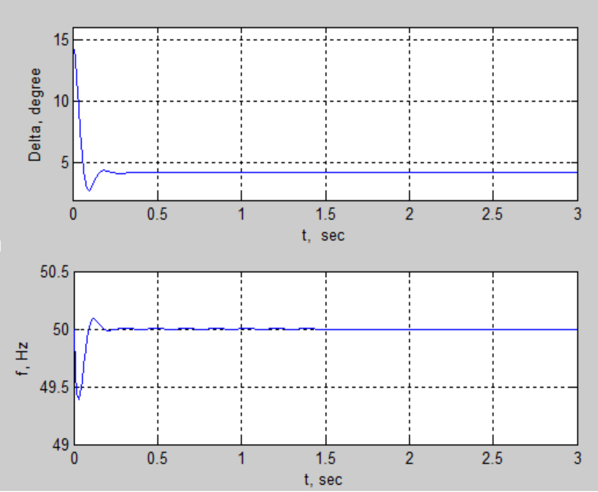

Fig. 10. Relationship between the power angle Delta and frequency obtained using damping theory.

B. *One Machine Euler's Method:*

After applying two derivation on swing equation, with Pm reference:

$$E = 1.6, V = 1, X_1 = 2, X_2 = 0.5, X_3 = 0.94, H = 1.52$$
$$f = 50[Hz], T_c = 0.4[sec], T_f = 1[sec], T_{step} = 0.002[sec]$$

At 0.4s the average power angle and frequency are decreased.

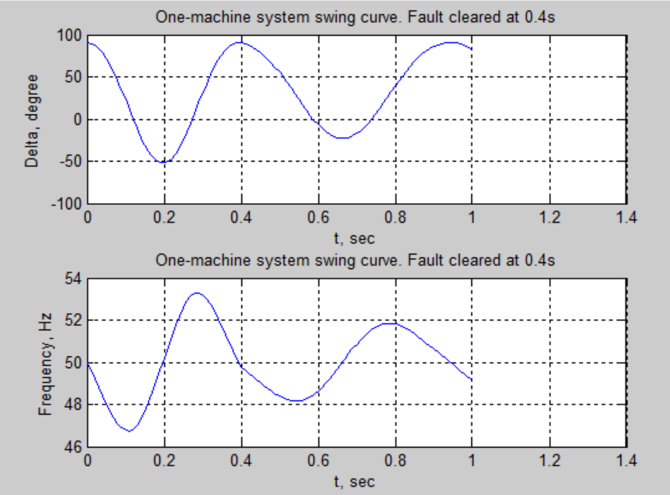

Fig. 11. Relationship between the power angle Delta and frequency obtained using the Euler's method.

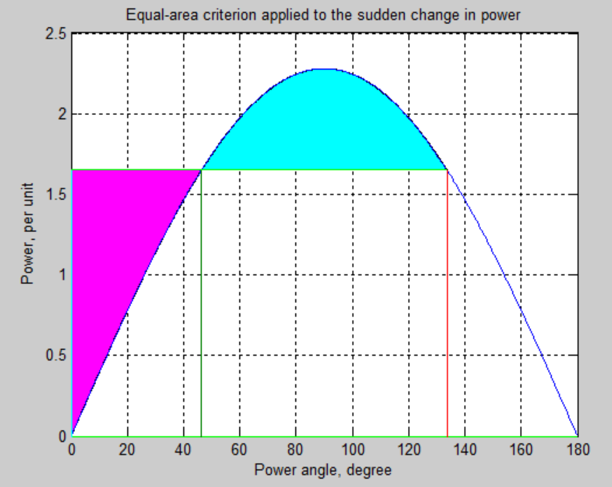

Fig. 12. Relationship between the power angle Delta and frequency obtained using the Equal Area Theory.

VI. CONCLUSION

According to the presented data, the following specs should be taken into consideration in order to keep the power system stable:

- Increment of the inertia constant of the generators. This makes the rotors harder to accelerate regarding faults, and the hazard for losing synchronism is lessened. As a rule, this is an extremely costly means, and just in unique cases, it can be connected, e.g. by introducing a flywheel on a little hydro unit [9].
- Increment of system voltage. This build $P_{e\max}$, and for a given power P_m the stability margins are expanded [18],[19].
- Decrease of the transfer reactance X_e. This will likewise increase $P_{e\max}$ as in the past case. This can be accomplished by building parallel lines, or by introducing series capacitors on existing lines or new

lines. By introducing series capacitors, the effective reactance of the line is decreased. This strategy has been utilized broadly throughout the years [20],[21].

- Establishment of quick securities and quick breakers. Along these lines, the time with a fault associated can be lessened and in this manner the time during which the generator rotors are quickened. The capability for the system to decelerate the rotor swings is increased [16].

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