Transient Stability Analysis of Synchronous Generator in Electrical Network

Fetissi Selwa, Labed Djamel

Abstract— The stability analysis is an important and complex part in the energy systems design. It is essential during electrical faults, that the system remains stable for not having to face a blackout that would compromise service to customers. This article studies the transient stability of electrical system based on the stability of the rotor angle while a three-phase fault, to determine the number of lines to be built under a voltage of 1200 kV and to transport a power of 9000 MW. The simulation is performed using MATLAB/ Simulink software.

Index Terms— Transient stability, three phase fault, stability of the rotor angle.

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1 INTRODUCTION

THe mains objectives of electricity networks operate is to ensur the foctionning of a system in good condition and keep it in a stable state when it is subjected to a sudden disturbance, as it is the case of lines separation or electric generators.

According to IEEE / CIGRE definition: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [1].

The stability of the power system is divided into three groups: the stability of the rotor angle, the voltage and frequency. In this paper we are interested in the stability study of the rotor angle.

In the other side; defining the stability of the rotor angle as: the capacity of a synchronous interconnected power system to remain in synchronism following disturbance machines. It depends on the ability to maintain a restored equilibrium between electromagnetic and mechanical torques acting on the rotor of each synchronous machine in the system [2]. In other words, a system is unstable if the angle difference between two interconnected generators increases indefinitely or transient oscillation caused by a disturbance, is not sufficiently damped in the evaluation time [3]. The instability typically occurs as increasingly swings angle generators leading to some loss of synchronism with other generators [4]. It is divided into two types: angular stability to large disturbances (transient stability) and angular stability to small perturbations (dynamic stability).

After a sudden disturbance in a power system, each of: the rotational speed of the generator, its angular position and the transmitted power are exposed to rapid changes, its nature and its value depend on the kind of disturbance.

During a large disturbances such as short circuits, the difference between the rotation angles of the generators increase indefinitely, resulting a synchronization loss of one or more generators, so-called phenomenon of the transient stability that occurs on the nearest generator to the location of disturbance. Then it is necessary in all stability studies to determine the effects of faults on the transient stability, which may occur in the electrical system and allow it to return to operating conditions stable.

This article will be conducted on the analysis of a power system by studying the stability of the rotor angle transient, and focuses on the most severe among all types fault which is the three-phase fault, to determine the number of lines to be built to transport 9000 MW that we propose to transport and ensure the stability of our network. The simulation is performed using the MATLAB / Simulink software.

2 TRANSIENT STATE STABILITY

2.1 Transient State Stability

It is the ability of the feed system to maintain the synchronization when it is subjected to serious disturbances [5], [6] as a short circuit on a transmission line. The resulting system response involves large variations of angles of the rotor and is not influenced by the linear power-angle relationship.

The transient stability depends not only on the amplitude of the disturbance and the starting point of operation but also it depends on the dynamic characteristics of the system. It manifests in the short term as a widening gap a periodically certain angles of the rotor [2].

2.2 The relationship (P, δ)

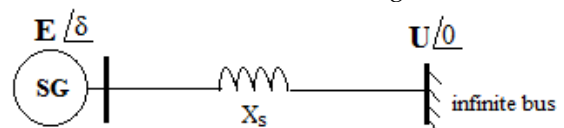We take a simple power system consisting of a synchronous generator connected to an infinite bar, Fig.1.

Fig.1. Synchronous machine connected to an infinite bar

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The power transmitted along the transmission line is calculated by the following formula:

$$P_e = \frac{E.U}{X_s}.\sin\delta \tag{1}$$

Where:

δ: angle of the rotor, it is the phase difference between the internal voltage E of the generator and the voltage of infinite bar U.

Any changes affecting the electrical power will cause a variation of the electrical angle δ. Equation (1) is plotted in Fig.2.
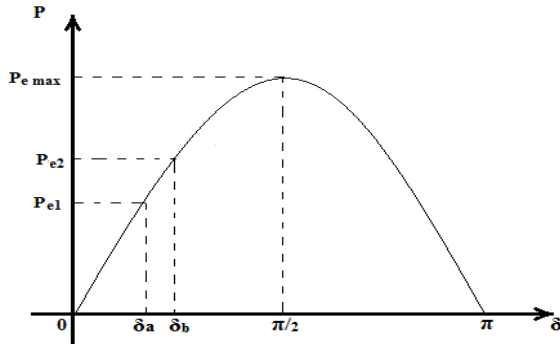

Fig.2. Relationship between the power - angle rotor.

For the case of a generator, we have:

$$P_e = P_m - P_a \tag{2}$$

P_e: Electrical power transmitted in the line.

P_m: mechanical power obtained from the generator.

P_a: power of acceleration, which stores the rotational kinetic energy.

In steady state, $P_a = 0$ and there is no acceleration, the system operates at the equilibrium point, the electric power P_{e1} is equal to the mechanical power applied to the corresponding angle $δ_a$.

A sudden change on the generator load results a variation of the mechanical power, and so the electrical power, e.g. of P_{e1} to P_{e2}, Fig.2. The rotor will then accelerate so that the power angle increases of $δ_a$ to $δ_b$, in order to provide an additional power to the load. Also, although the power developed for $δ_b$ is sufficient for the load, the rotor will exceed the angle $δ_b$ until sufficient torque opposite is developed to stop the acceleration. The extra energy will cause the rotor slowing and the angle decrease of the power [2], [7].

2.2 Swing equation of rotor

In practice cases, for determining the stability of a system, it comes to the variation graph of the angle δ in time Fig.3. If this curve shows that the angle δ begins to increase after passing through a maximum, it is generally accepted that the system will remain stable (case1: Fig.3). And if the curve does not pass through a maximum, it indicates that the generator will become unstable and losing synchronism with the network (cas2: Fig.3).

3 SECTIONS

As demonstrated in this document, the numbering for sections upper case Arabic numerals, then upper case Arabic numerals, separated by periods. Initial paragraphs after the section title are not indented. Only the initial, introductory paragraph has a drop cap.
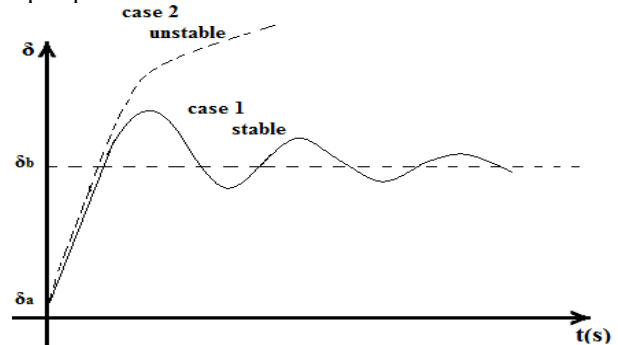

Fig.3. Rotor angle variation.

The equation we are going to use is called "swing equation". It expresses the acceleration or deceleration of the rotor generator according to the load variations.

This equation is as follows:

$$M\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{3}$$

Such that:

$$M = \frac{2H}{w_s}$$

Where:

M: the angular momentum.

H: the constant inertia.

The solution of this equation gives the oscillation curve of the angle δ with respect to time variation. To do this, we used the step method in the simulation.

Numerically we must calculate the following equations:

$$\delta_n = \delta_{n-1} + \Delta\delta_n \tag{4}$$

$$\Delta\delta_n = \Delta\delta_{n-1} + \frac{P_{a(n-1)}}{M}(\Delta t^2) \tag{5}$$

It comes to apply the equation (3) for the different situations on the network.

3 SIMULATION AND RESULTS

Test network

Fig.4 shows the model of power system used in the simulation analysis. A group of plants 9000 MW connected to a set of infinite bar through the two transformers and feeds a transmission line of 965 km at a voltage of 1200 kV.
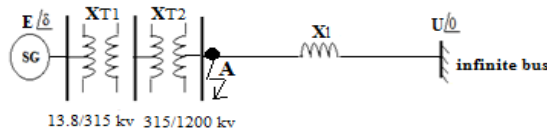
Fig.4. Power system model.

TABLE 2
Parameter elements of the system.

Electrical system parameters		
GS	X_d' (pu)	0.25
	H (MJ/MVA)	3
	P (MW)	9000
TR1	X_{T1} (pu)	0.12
TR2	X_{T2} (pu)	0.15
Ligne	X_l (pu)	1.875
	Y/2 (pu)	0.382
	R_c (Ω)	250
Power Base: 9000MVA (60 Hz)		
Voltage Base: 1200 KV		
Impedance Base: 160 Ω		

Calculating the naturel power of a line:

$$P = \frac{V^2}{R_c} \qquad (6)$$

$$P = \frac{1200^2}{250} = 5760 MW$$

5 EQUATIONS

We are now able to proceed with the study of the stability for a symmetrical three-phase fault in order to determine the number of rows to build and ensure the stability of our network. The complete system has been represented in terms of Simulink blocks in a single model Fig.5. These values may be defined using a m-file program or can be directly provided to the Simulink model.

The fault is assumed to the input line (Fig.4: point A). We can consider in the case of three-phase symmetrical fault steady state and also the voltage at the terminals of the alternator is kept constant because of its excitation system. This fact allows us to consider the unit voltage U for calcu-lations (X_d' =0).

The simulation is done for a period of 2s and the fault is cleared at t = 0.1s (6 cycles).
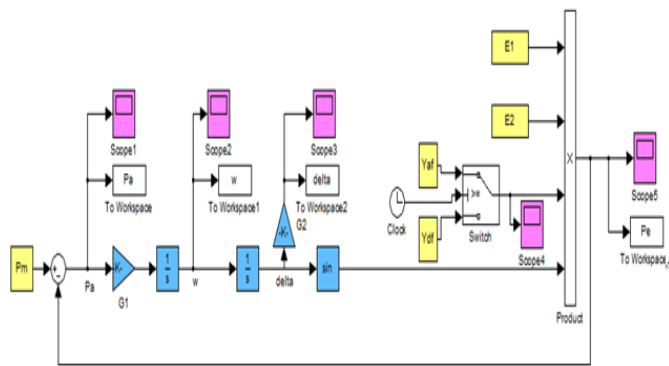

Fig.5. Simulation block diagram of the system in MATLAB / SIMULINK.

6.1 First hypothesis: four lines

We have already calculated the natural line power at 1200 KV. This power is about 5760 MW. Considering this power, it seems that two lines would be sufficient to carry the 9000 MW that we proposed to carry. However; in this case, it is very unlikely that two lines are sufficient. A more realistic hypothesis would be to consider four lines Fig.6.
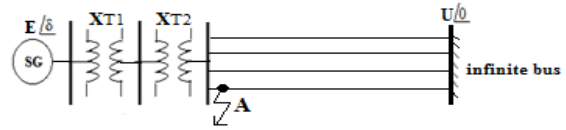

Fig.6. Power system model with four lines.

The transmitted power before the fault is unitary; it is possible to determine the initial electric angle δ_0.
At the default phase, there is no transmitted power so $P_e = 0$. Such as:

$$P_a = P_m - P_e$$

And Pm is considered constant and unitary so P_a becomes unitary also.

After 6 cycles (0.1 second), the default is removed and we find ourselves in the same situation as before, except that δ has not the same value as δ_0. So the power is not unitary, the generator will continue to oscillate as we explained earlier.
It is now possible to construct the variation table of the angle δ in time. To construct this table, it is noted that during sudden changes of situation, it is necessary to calculate the average acceleration power for the variation of the angle δ.

TABLE 2
Angle variation δ in time for four lines.

t (sec)	Pe (pu)	Pa (pu)	[(Δt²)/M] Pa (deg)	Δδ$_n$ (deg)	δ$_n$ (deg)
0⁻	1.00	0.00	0.00	0.00	47.62
0⁺	0.00	1.00	0.00	0.00	47.62
0$_{avg}$	0.00	0.50	4.5	4.5	47.62
0.05	0.00	1.00	9.00	13.5	52.12
0.1⁻	0.00	1.00	0.00	0.00	65.62
0.1⁺	1.23	-0.23	0.00	0.00	65.62
0.1$_{avg}$	0.00	0.38	3.42	16.92	65.62
0.15	1.34	-0.34	-3.06	13.86	82.36
0.20	1.34	-0.34	-3.06	10.80	96.14
0.25	1.29	-0.29	-2.61	8.19	106.86
0.30	1.22	-0.22	-1.98	6.21	114.95
0.35	1.15	-0.15	-1.35	4.86	121.02
0.40	1.09	-0.09	-0.81	4.05	125.66
0.45	1.04	-0.04	-0.36	3.69	129.41
0.50	0.99	0.008	0.072	3.76	132.77
0.55	0.93	0.06	0.54	4.30	136.19
0.60	....	....	....	....	140.20

As results of simulation, we obtained the following curves showing us the system responses:

(a). The internal angle δ of the generator.

(b). The angular speed of the generator.

(c). Electric power of the generator.

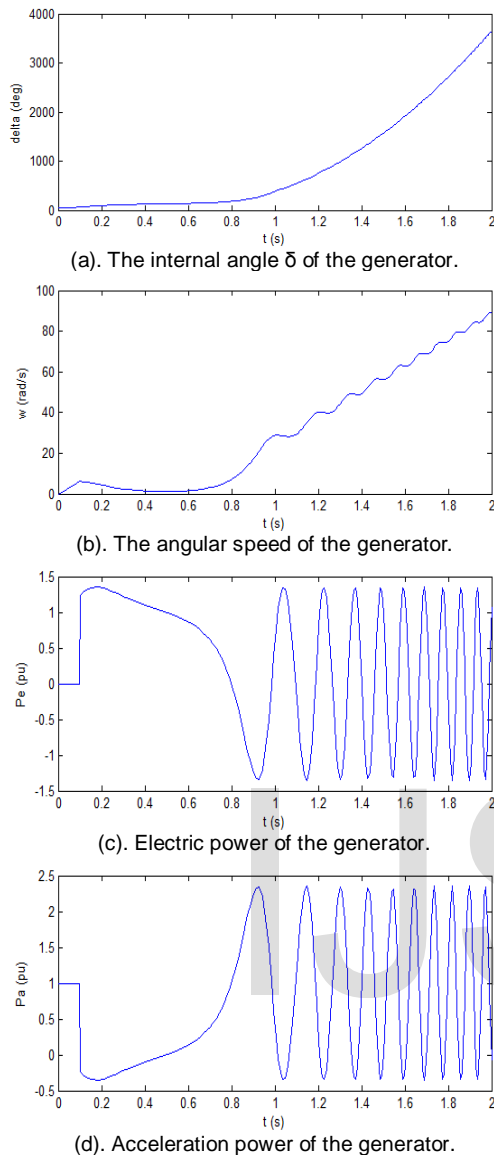(d). Acceleration power of the generator.
Fig.7. Simulation results of the system with four lines for a three-phase fault.

Fig.7 (a) and (b) are showing the variation of the angle δ and the angular velocity of the rotor, while Fig.7 (c) and (d) show the variations of the electrical power and acceleration of the generator in time for the system with four lines.

From Fig.7 (a) and Table 2, we find that the angle δ of the rotor continues to increase following an increasing pace; it does not pass through a maximum and increases indefinitely. As is the case in Fig.7 (b), there is a rapid increase in the angular speed of the generator on a continuous basis.

At the default, the electrical power drops to zero, the rotor accelerates and the generation is getting greater than the power (Fig.7.c). We can also note from (Fig.7.d) that the power storing the kinetic energy of rotation continues to oscillate rapidly and indefinite way, this can be easily explained by the fact that the mechanical torque is higher than the electrical torque. Then a large amount of energy has been accumulated by the generator what put the rotor in over speed after elimination of the fault.

The simulation results indicate that the system is unstable with four lines. We can say that the generator does not come back in to synchronization with the network, so it is impossible to return to stability after the fault clearance and the four lines are not sufficient to ensure the stability of our system in the case of a symmetrical three-phase fault.

6.2 Second hypothesis: five lines

We consider the system with five lines Fig.8. Similarly as in the case for four lines, it is possible to determine the initial electric angle δ_0 before the fault, and the power being transmitted before the unit fault.
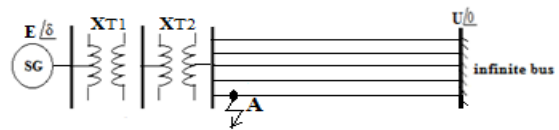

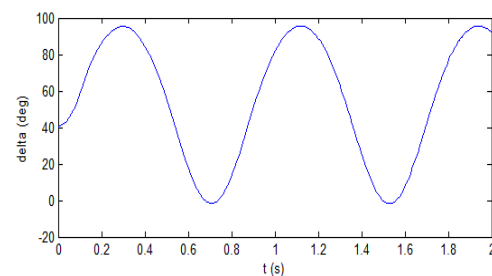Fig.8. Power system model with five lines.

And after elimination of the fault, we find ourselves in the same situation as before except that δ has not the same value as δ_0.

It is now possible to construct the table of variation of the angle δ in time.

Table 3
Angle variation δ in time for five lines.

t (sec)	Pe (pu)	Pa (pu)	[(Δt²)/M] Pa (deg)	Δδₙ (deg)	δₙ (deg)
0-	1.00	0.00	0.00	0.00	40.2
0+	0.00	1.00	0.00	0.00	40.2
0avg	0.00	0.50	4.5	4.5	40.2
0.05	0.00	1.00	9.00	13.5	44.7
0.1-	0.00	1.00	0.00	0.00	58.2
0.1+	1.32	-0.32	0.00	0.00	58.2
0.1avg	0.00	0.34	3.06	16.56	58.2
0.15	1.49	-0.49	-4.41	12.15	74.44
0.20	1.54	-0.54	-4.86	7.29	86.34
0.25	1.54	-0.54	-4.86	2.43	93.25
0.30	1.54	-0.54	-4.86	-2.43	95.44
0.35	1.54	-0.54	-4.86	-7.29	92.62
0.40	1.54	-0.54	-4.86	-12.15	84.87
0.45	1.47	-0.47	-4.23	-16.38	72.27
0.50	1.27	-0.27	-2.43	-18.81	55.48
0.55	0.91	0.08	0.72	-18.09	36.32
0.60	....	....	....	....	14.44

And from the simulation we obtained the following curves showing us the system responses:

(a). The internal angle δ of the generator.

(b). The angular speed of the generator.

(c). Electric power of the generator.
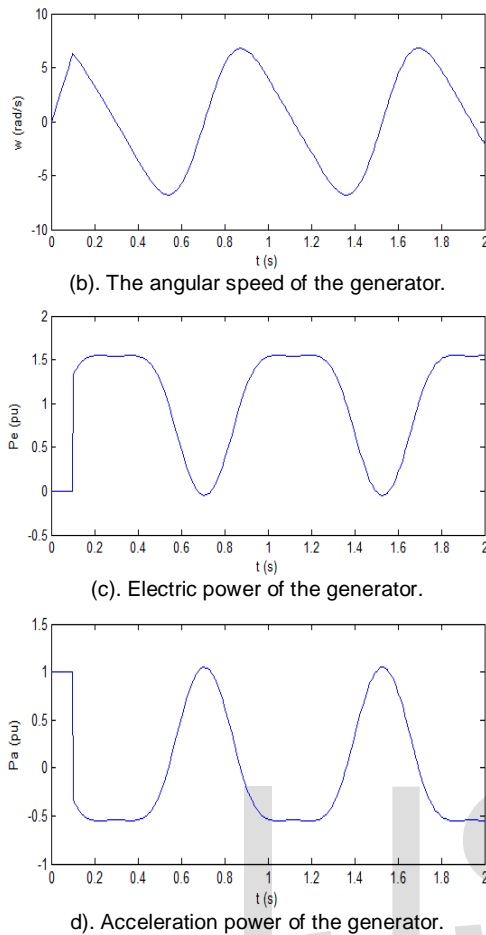

d). Acceleration power of the generator.
Fig.7. Simulation results of the system with five lines for a three-phase fault.

Fig.9 (a) and (b) show the variations of the angle δ and the angular velocity of the rotor, while in Figures 9 (c) and (d) show the variations of the electrical power and acceleration of the generator over time, for the five lines system.

From fig.9 (a) and Table 3, we find that the rotor angle δ varies according to a damped oscillatory pace with time around an equilibrium point δ_{max} = 95.44 °. As it is the case in Fig.9 (b).

After elimination of the fault, the generator keeps oscillating continuously in the same way and operating in the same speed.

It is also evident to note the cushioning system for the electric power in Fig.9 (c) and the acceleration power Fig.9 (d). In fact the rotor oscillates around the equilibrium point.

Simulation results indicate that the system is stable. We can say that the generator maintains its stability after fault clearance and is synchronized with the network.

Five lines are sufficient to ensure the stability of our net-work in the case of a symmetrical three-phase fault.

7 CONCLUSION

In the first case, the rotor acceleration causes an exceeding of the balance point; and the generator loses its synchronization with the network. By cons in the second case the generator retains its synchronization with the network after the removal of the defect.

We can say that four lines are not sufficient to ensure the stability of our network but in the other side five lines are sufficient

to ensure the stability of the system.

This work makes us concluding that the stability of a power system depends on its total impedance X_{total} and duration of the fault clearing time (opening time of the circuit breaker) to avoid the risk of overspeed in case of short circuiting.

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