ISSN No:-2456-2165

Transitory Stability Analysis for a System Composed of Asynchronous and Synchronous Generators Connected to a SMIB

SOLOFO Andrianjakaniaina Basilide
ESPA Electrical Machines Laboratory
University of Antsiranana
ANTSIRANANA, MADAGASCAR

RABE Tsirobaka
ESPA Electrical Machines Laboratory
University of Antsiranana
ANTSIRANANA, MADAGASCAR

ANDRIANANTENAINA Max Richard
ESPA Electrical Machines Laboratory
University of Antsiranana
ANTSIRANANA, MADAGASCAR

RAZAFINJAKA Nirinarison Jean
ESPA Automatic Laboratory
University of Antsiranana
ANTSIRANANA, MADAGASCAR

Abstract:- In this article, we studied the transient stability for a system composed asynchronous generators and synchronous connecting to a power network infinite using the method of Lyapunov. The idea is researching the possibility of using the Hamiltonian energy function as a Lyapunov function one by one for our generators. After having verified the three criteria of Lyapunov's method, we have the possibility for using Hamiltonian energy as a Lyapunov function. According to the results of the simulations on matlab software plus these three criteria, we could affirm that the two machines as well as the complete system, synchronous generator with asynchronous generator connected to a SMIB network are stable in the sense of Lyapunov. In addition, the simulation results show us that all the saddle knots point are on the positive side of the axis, except one which is on the negative side; the latter situation is due to the absence of the wind (case of an asynchronous generator driven by a wind turbine).

Keywords:- *Transient Stability, Hamiltonian Energy, Wind, Lyapunov Function.*

I. INTRODUCTION

One of the most important problem when studying an Electric Power Grid (R.E.E) complex is a stability. This is due to the significant development of networks in recent years. Thus, the objective of this study is to examine the behavior for a system composed of a small power synchronous generator driven by a motor, and a high-power asynchronous generator driven by a wind turbine; these two generators are connected to an infinite power network (SMIB) and subjected to weak or significant disturbances. Continuous load variations are examples of small disturbances, faults such as short circuits and loss of synchronism to the high-power generator are examples of large disturbances. These disturbances are at the origin of the appearance of a difference between mechanical power (production) and electrical power (consumption). This gap must be absorbed in the form of energy. The presence of this gap in terms of power results in change in the rotational speed of the alternator or, in other words, in variations in its speed around the synchronous speed. After elimination of the disturbance, the network will be stable if the average value of the speed differences is zero. In this case, the network continues to operate in satisfying its operating limits and supplying consumers. In this work, we propose to study the stability based on the Lyapunov function for each of the generators, then the complete system. In this case the Hamiltonian energy is used as a Lyapunov function. Figure 1 shows the complete study system.

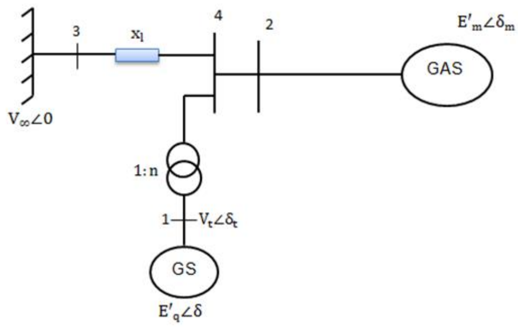


Fig 1: Representation of the complete system

II. DETERMINATION OF HAMILTONIAN FUNCTION

The determination of a Hamilton function is a necessary phase for the transient stability study because it represents an energy function for system studied. This energy is a quadratic scalar function. Moreover, Lyapunov's theory is essentially based on the existence of a scalar function (Lyapunov energy) which establishes sufficient stability of the function with the conditions of the dynamic system in question. In addition, the properties of the Lyapunov function and its derivative provide auxiliary information about the region of attraction from equilibrium point [1,2]

A. Hamiltonian function of synchronous generator

The equation of state with a synchronous generator is given by relations (1). With some assumptions, the synchronous generator provided with a voltage regulator can be modeled by the following differential equations [3]:

ISSN No:-2456-2165

$$\begin{cases} \dfrac{d\delta}{dt} = \omega_0 \omega \\ \dfrac{d\omega}{dt} = \dfrac{1}{2H}\left(T_m - \dfrac{E_q^{'} v_t \sin\delta}{x_d^{'}} - D\omega \right) \\ \dfrac{dE_q^{'}}{dt} = \dfrac{\left(x_d - x_d^{'}\right)}{T_{d0}^{'}} \left(\dfrac{E_{fd} - E_q^{'}}{x_d - x_d^{'}} - \dfrac{E_q^{'} - v_t}{x_d - x_d^{'}} \right) \end{cases} \tag{1}$$

Consider the third equation of our system; as the variation of the mechanical phenomenon is very slow compared to that of the electrical phenomenon, we can assume that: $\dfrac{dE_q^{'}}{dt} = 0$.

We then get the expression from E_{fd} :

$$E_{fd} = E_q^{'} + \left(x_d - x_d^{'}\right) i_d \tag{2}$$

With,

$$i_d = \frac{E_q^{'} - v_t}{x_d - x_d^{'}} \tag{3}$$

By carrying (3) in (2), we have:

$$E_{fd} = E_q^{'} \left(\frac{2x_d - x_d^{'}}{x_d^{'}} - \frac{2x_d - x_d^{'}}{x_d^{'}} v_t \right) \tag{4}$$

$$E_q^{'} = v_t \left(1 + \cos\delta\right) \tag{5}$$

By replacing $E_q^{'}$ the second equation of our system by its expression:

$$\begin{cases} \dfrac{d\delta}{dt} = \omega_0 \omega \\ \dfrac{d\omega}{dt} = \dfrac{1}{2H}\left(T_m - \dfrac{v_t^2 \sin\delta}{x_d^{'}} - \dfrac{v_t^2 \sin 2\delta}{x_d^{'}} - D\omega \right) \end{cases} \tag{6}$$

The Hamiltonian system given by (6) constitute a very important class of differential equations whose Hamiltonian H is always a first integral (i.e., is a constant along solutions) [4] as shown in Figure's phase plan. We can pose:

$$\begin{cases} \dfrac{d\delta}{dt} = \dfrac{\partial H_{m1}}{\partial \omega} \\ \dfrac{d\omega}{dt} = -\dfrac{\partial H_{m1}}{\partial \delta} \end{cases} \tag{7}$$

Where H_{m1} is the Hamiltonian function.
Therefore,

$$\begin{cases} \dfrac{\partial H_{m1}}{\partial \omega} = \omega_0 \omega \\ \dfrac{\partial H_{m1}}{\partial \delta} = -\dfrac{1}{2H}\left(T_m - \dfrac{v_t^2 \sin\delta}{x_d^{'}} - \dfrac{v_t^2 \sin 2\delta}{x_d^{'}} - D\omega \right) \end{cases} \tag{8}$$

The simulation (8) allows for the phase diagram given in Figure 2.

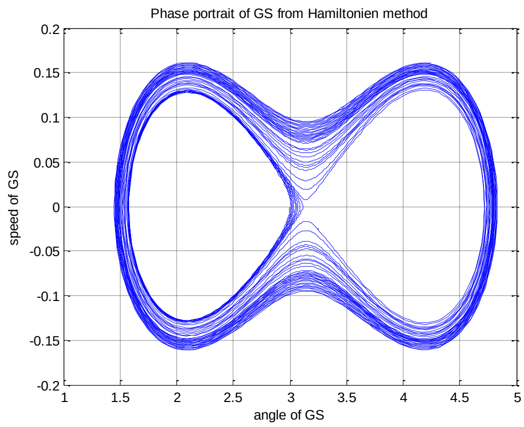


Fig 2: The phase portrait for the synchronous generator

By successive integrations of the second term (8), we finally expression of the Hamilton function as follows:

$$H_{m1} = \frac{1}{2H}\left(-T_m\delta - \frac{v_t^2 \cos\delta}{x_d^{'}} - \frac{v_t^2 \cos 2\delta}{2x_d^{'}} + \frac{D\omega^2}{2} \right) + H_0 \tag{9}$$

This function has the dimension of energy. Indeed, the first term $(\frac{T_m\delta}{2H})$ represents the energy expended by the mechanical torque of the system, the second term $\frac{vt^2 cos\delta}{2HX_d'} + \frac{vt^2 cos2\delta}{2HX_d'}$ is the potential energy, and the third term $\frac{D\omega^2}{4H}$ is the kinetic energy. Figure 3 shows the Hamiltonian energy level curves of synchronous generator.

ISSN No:-2456-2165

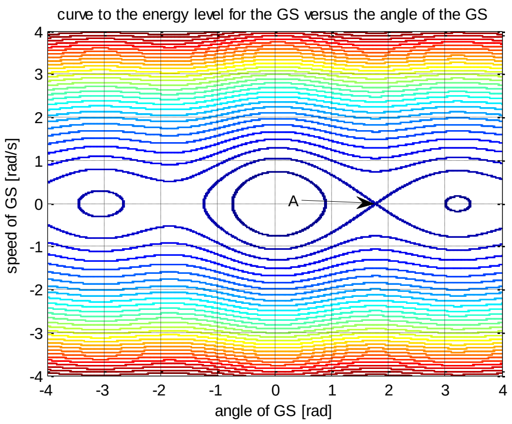


Fig 3: Curve to the energy level for the synchronous generator

By simulating the Lyapunov function for different initial conditions for (δ, ω), we obtain the curves of the speed relative to the position δ. Clearly some curves exhibit a circular path and curl around a periodic trajectory. This system therefore has attractive points of equilibrium, point A (1.75, 0) is an example; it is also the saddle knot point. In addition, there is a closed orbit which is attractive: this is called a limit cycle [5].

B. Determination a critical point of the synchronous generator

By definition, the critical points are the points where the derivatives are zero [6,7, 8, 9, 10, 11]. In our case, we have:

$$\begin{cases} \dfrac{\partial H_{m1}}{\partial \omega} = 0 \\ \dfrac{\partial H_{m1}}{\partial \delta} = 0 \end{cases} \qquad (10)$$

The first expressions (8) and (10) gives that: $\omega = 0$. Therefore, the second expressions of (8) and (10) are equivalent to:

$$T_m - \frac{v_t^2 \sin\delta}{x_d^{'}} - \frac{v_t^2 \sin 2\delta}{x_d^{'}} = 0 \qquad (11)$$

For a small angle δ, sin δ = δ; $\sin 2\delta = 2\delta\left(1 - \dfrac{\delta^2}{2}\right)$.

These trigonometric relationships allow us to write the equation (11) in the form:

$$T_m - \frac{v_t^2}{x_d^{'}}\delta - 2\frac{v_t^2}{x_d^{'}}\delta\left(1 - \frac{\delta^2}{2}\right) = 0 \qquad (12)$$

If we ask:

$$\begin{cases} p = -3 \\ q = \dfrac{T_m x_d^{'}}{v_t^2} \end{cases}$$

Equation (12) becomes:

$$\delta^3 + p\delta + q = 0 \qquad (13)\ .$$

Cardan's method solves all third-degree equations. This method makes it possible to set up formulas called Cardan formulas giving, as a function of p and q, the solutions of equation (13) [12]. The solution is of the form:

$$\delta = \mu + \upsilon \qquad (14)$$

With,

$$\begin{cases} \mu = \sqrt[3]{\dfrac{-q + \sqrt{\Delta}}{2}} \\ \upsilon = \sqrt[3]{\dfrac{-q - \sqrt{\Delta}}{2}} \\ \Delta = q^2 + \dfrac{4}{27}p^3 \end{cases} \qquad (15)$$

C. Search the Lyapunov function for the synchronous generator

Lyapunov functions are a mathematical generalization of the concept of dispersive energy physics. The Lyapunov functions are the centerpiece stability theory of Lyapunov for dynamic systems in general. Here, we present a simple method to check the validity of a quadratic Lyapunov function that is built for the linearization of a nonlinear system [16]. Since the function in question is based on a function of energy, we will then see if the Hamilton function can meet the conditions of stability in the sense of Lyapunov. The stability conditions within the meaning of Lyapunov [6,13,14,15] are:

The thirst condition: $V(xs) = 0$, xs being the equilibrium point

The second condition: $V(x) > 0$, Lyapunov function

The third condition: $\dfrac{dV(x)}{dt} \le 0$

The derivative of the Hamiltonian function given by (9) with respect to time, leads us to:

$$\frac{\partial H_{m1}}{dt} = \frac{\partial H_{m1}}{\partial \delta}\frac{\partial \delta}{dt} + \frac{\partial H_{m1}}{\partial \omega}\frac{\partial \omega}{dt} \qquad (16)$$

Which is equivalent to:

$$\frac{\partial H_{m1}}{dt} = -\frac{1}{2H}\omega_0\omega\left(T_m - \frac{v_t^2 \sin\delta}{x_d^{'}} - \frac{v_t^2 \sin 2\delta}{x_d^{'}}\right) + \omega_0\omega\frac{1}{2H}\left(T_m - \frac{v_t^2 \sin\delta}{x_d^{'}} - \frac{v_t^2 \sin 2\delta}{x_d^{'}} - D\omega\right)$$

(17)

$$\frac{\partial H_{m1}}{dt} = -\frac{D\omega_0}{2H}\omega^2 \le 0 \qquad (18)$$

For δ infinitely small:

$$-\frac{v_t^2\cos\delta}{x_d^{'}}-\frac{v_t^2\cos 2\delta}{2x_d^{'}} \ll 1$$

or T_m and ω are proportional quantities which implies $-T_m\delta \ll \frac{D\omega^2}{2}$

Finally:

$$H_{m1}=\frac{1}{2H}\left(-T_m\delta-\frac{v_t^2\cos\delta}{x_d^{'}}-\frac{v_t^2\cos 2\delta}{2x_d^{'}}+\frac{D\omega^2}{2}\right)>0 \quad (19)$$

As we have seen that the Hamiltonian energy function is always positive, these three conditions met and enable us to say that we can determine the Lyapunov function from a Hamiltonian function and also confirm that our system is stable in the Lyapunov senses.

D. Hamiltonian function of asynchronous generator

For this type of generator, the state equations can be written as follows:

$$\begin{cases}\frac{d\phi}{dt}=\frac{1}{E_m^{'}T_0^{'}}\left(T_0^{'}\left(\omega_r-\omega_s\right)E_m^{'}-\frac{x_s-x^{'}}{x^{'}}v_s\sin\left(\delta_m+\theta\right)\right)\\ \frac{d\omega_r}{dt}=\frac{p_m}{2H}-\frac{E_m^{'}}{2Hx^{'}}\sin\left(\delta_m+\theta\right)\\ \frac{dE_m^{'}}{dt}=\frac{1}{T_0^{'}}\left[-\frac{x_s}{x^{'}}E_m^{'}+\frac{x_s-x^{'}}{x^{'}}v_s\cos\left(\delta_m+\theta\right)\right]\end{cases} \quad (20)$$

The principles of the calculations are the same as before, but for the determination of the Lyapunov function, we adopt the real case, that is to say that there is a friction torque when a machine is subjected to a load. Let us denote by: $D_a=\frac{T_f}{M}$ this friction torque.

To simplify the calculations, let's set:

$$\eta_1=\frac{x_s-x^{'}}{T_0^{'}x^{'}}v_s\ ;\ \eta_2=\frac{p_m}{2H}\ ;\ \eta_3=\frac{v_s}{2Hx^{'}}\ ;\ \eta_4=\frac{x_s}{T_0^{'}x^{'}}\ ;$$

et $\phi=\delta_m+\theta$

The system of our state equation reduces to:

$$\begin{cases}\frac{d\phi}{dt}=\omega_1-\frac{\eta_1}{E_m^{'}}\sin\phi\\ \frac{d\omega_1}{dt}=\eta_2-\eta_3E_m^{'}\sin\phi-D_a\omega_1\\ \frac{dE_m^{'}}{dt}=-\eta_4E_m^{'}+\eta_1\cos\phi\end{cases} \quad (21)$$

As the variation of mechanical phenomenon is very slow compared to that of the electric phenomenon, we can ask that $\frac{dE_m^{'}}{dt}=0$.

For large values of η4, the internal voltage E (t) is primarily determined by the ratio η1 / η4. According to [17], for typical parameter values of wind turbines in the range 500 kilowatts to 1 MW, the values of η4 are in the range [11.1 ÷28.9 It is recalled that η1 is linearly proportional to the terminal voltage of the asynchronous generator. It can be concluded that the variations of E (t) follow closely the variations in terminal voltage [2].
We then have:

$$E_m^{'}=\frac{\eta_1}{\eta_4}\cos\phi \quad (22)$$

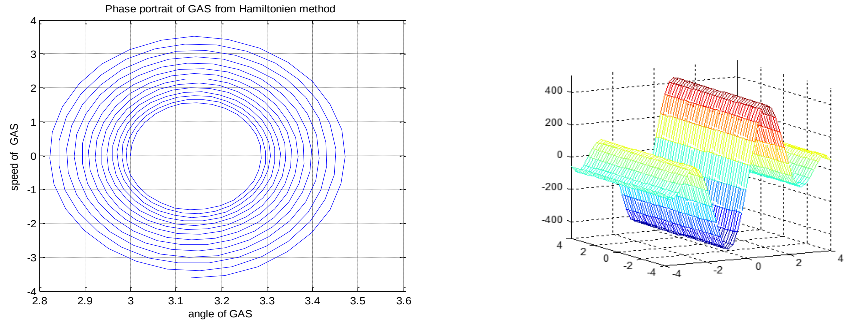
Let us carry the relation (18) in the first two equations of our system:

$$\begin{cases}\frac{d\phi}{dt}=\omega_1-\eta_4\tan\phi\\ \frac{d\omega_1}{dt}=\eta_2-\frac{\eta_3\eta_1}{2\eta_4}\sin 2\phi-D_a\omega_1\end{cases} \quad (23)$$

By analogy of Hamilton function:

$$\begin{cases}\frac{dH_{m2}}{d\omega_1}=\omega_1-\eta_4\tan\phi\\ \frac{dH_{m2}}{d\phi}=-\eta_2+\frac{\eta_3\eta_1}{2\eta_4}\sin 2\phi+D_a\omega_1\end{cases} \quad (24)$$

The corresponding curves are given according to figures 4-a and 4-b.



(a) (b)

Fig 4: Phase portrait of GAS from Hamiltonian method in plan (a) and in the space (b)

The expression of the Hamilton function will be determined by successive integrations and we finally have the following relation

$$H_{m2}(\phi,\omega_1) = -\eta_2\phi - \frac{\eta_3\eta_1}{4\eta_4}\cos 2\phi + \frac{D_a\omega_1^{\,2}}{2} + H_0$$

(25)

where H_0, the value of energy at the instant φ_0 and ω_0

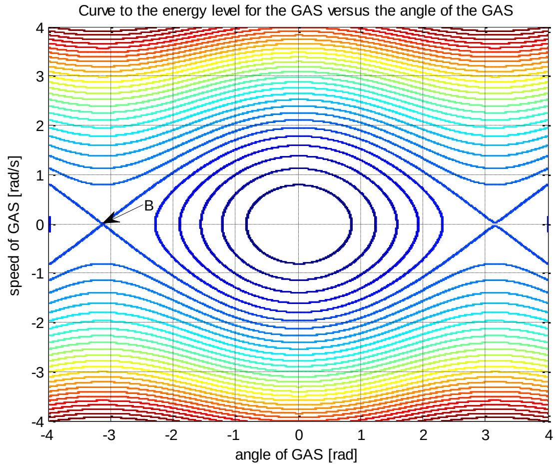


Fig 5: Curve to the energy level for the asynchronous generator

The graph in Figure 5 shows trajectories in the phase plane, that is to say, the Cartesian plane whose coordinate axes are δ_m and ω . Some trajectories revolve around (0, 0) while remaining in a bounded region of the plane (δ_m , ω); this region is also called the region of attraction. Outside this domain, the curves present limit values, i.e., each present a minimum value for ω positive and a maximum value for ω negative. In this figure, point B (-3.15, 0) represents a saddle knot point.

E. Determination a critical point for asynchronous generator

As for the synchronous generator, the critical points are determined by:

$$\begin{cases} \dfrac{\partial H_{m2}}{\partial \omega_1} = 0 \\ \dfrac{\partial H_{m2}}{\partial \phi} = 0 \end{cases} \qquad (26)$$

These relationships allow us to write:

$$\begin{cases} \omega_1 - \eta_4 \tan\phi = 0 \\ -\eta_2 + \dfrac{\eta_3\eta_1}{\eta_4}\sin 2\phi + D_a\omega_1 = 0 \end{cases} \qquad (27)$$

After having linearized the sine and tangent functions, these equations reduce to:

$$\phi^3 - \left(2 + \frac{D_a\eta_4^{\,2}}{\eta_1\eta_3}\right)\phi + \frac{\eta_2\eta_4}{\eta_1\eta_3} = 0 \qquad (28)$$

By applying Cardan's method for this equation, we have the three values ϕ_1, ϕ_2 et ϕ_3, and for the critical points of the asynchronous generator.

F. Stability Lyapunov for asynchronous generator

The three Lyapunov stability conditions must be checked. For this it is necessary that:

$$\frac{dH_{m2}}{dt} \le 0$$

Now calculate the derivative with respect to time as in the previous case:

$$\frac{dH_{m2}}{dt} = \frac{dH_{m2}}{d\omega_1}\frac{d\omega_1}{dt} + \frac{dH_{m2}}{d\phi}\frac{d\phi}{dt}$$

(29)

Which leads us to:

$$\frac{dH_{m2}}{dt} = D_a\omega_1\left(\eta_2 - \frac{\eta_3\eta_1}{2\eta_4}\sin 2\phi - D_a\omega_1\right) + \left(-\eta_2 + \frac{\eta_3\eta_1}{2\eta_4}\sin 2\phi\right)\left(\omega_1 - \eta_4\tan\phi\right)$$

(30)

In the case of a real machine, the study is very complex, which requires us to conduct numerical solutions of problems [2]. For this, we assume that Da = 1. Then equation (30) will be written as follows:

$$\frac{dH_{m2}}{dt} = -\omega_1^2 - \left(-\eta_2\eta_4 + \frac{\eta_3\eta_1}{2}\sin 2\phi\right)\tan\phi \quad (31)$$

And we know that ω_1 and η_2 are proportional, which implies $\omega_1^2 \rangle \eta_2$ and, therefore:

$$\frac{dH_{m2}}{dt} \le 0 \quad (32)$$

For ϕ infinitely small, then

$$\begin{cases} \frac{\eta_3\eta_1}{4\eta_4}\cos 2\phi \ll 1 \\ \eta_2 \text{ et } \omega_1 \text{ are proportional} \\ \eta_2\phi < \frac{D_a\omega_1^2}{2} \end{cases}$$

Consequently,

$$H_{m2}(\phi,\omega_1) = -\eta_2\phi - \frac{\eta_3\eta_1}{4\eta_4}\cos 2\phi + \frac{D_a\omega_1^2}{2} > 0$$

(33)

Finally, we can say that our machine is therefore stable in the sense of Lyapunov.

G. Hamiltonian function of the system composed with a synchronous and asynchronous generator

For our system consisting of a synchronous and asynchronous generator which have been coupled to a infinite network, Hamilton function is determined by the sum of the two generators Hamilton were considered and discussed above, which ultimately gives us the following expression:

$$H_{es} = H_{m1} + H_{m2}$$

(34)

From where:

$$H_{es} = -\frac{1}{2H}\left(T_m\delta + \frac{v_t^2\cos\delta}{x_d'} + \frac{v_t^2\cos 2\delta}{2x_d'} - \frac{D\omega^2}{2}\right) - \eta_2\phi - \frac{\eta_3\eta_1}{4\eta_4}\cos 2\phi + \frac{D_a\omega_1^2}{2} \quad (35)$$

Figures 6 and 7 show the energy level curves of the GAS versus the internal angle of the GS, respectively and the energy level curves of the GS versus the internal angle of the GAS

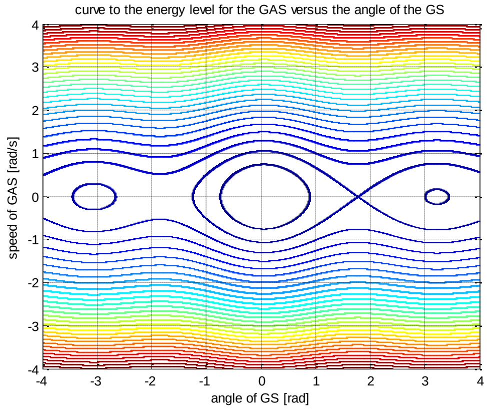


Fig 6: Curve to the energy level of the asynchronous generator versus the angle of the synchronous generator

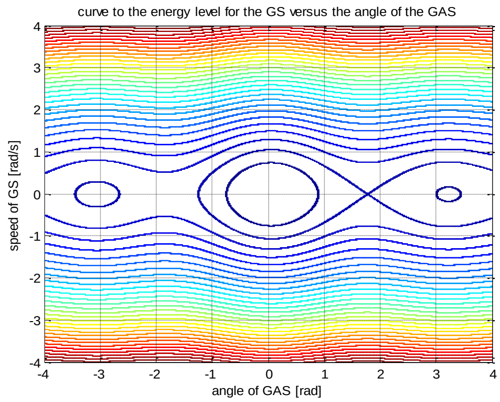


Fig 7: Curve to the energy level of the synchronous generator versus the angle of the asynchronous generator

The function derived from our energy is:

$$\frac{dH_{es}}{dt} = \frac{dH_{m1}}{dt} + \frac{dH_{m2}}{dt} \quad (36)$$

Or: $\frac{dH_{m1}}{dt} \le 0$ et $\frac{dH_{m2}}{dt} \le 0$

so we have:

$$\frac{dH_{es}}{dt} = \frac{dH_{m1}}{dt} + \frac{dH_{m2}}{dt} \le 0 \quad (37)$$

Since the derivative of our function is non-zero, we need to compute the Hessian matrix to find the extremes.

$$H_e = \begin{pmatrix} \frac{v_t^2\cos\delta}{x_d'} + \frac{v_t^2\cos 2\delta}{x_d'} & 0 & 0 & 0 \\ 0 & \frac{\eta_3\eta_1}{\eta_4}\cos 2\phi & 0 & 0 \\ 0 & 0 & D & 0 \\ 0 & 0 & 0 & D_a \end{pmatrix}$$

(38)

The eigenvalues of this matrix are calculated from the following determinant:

$$d\acute{e}t(H_e - \lambda I) = \begin{bmatrix} \left(\frac{v_t^2 \cos\delta}{x_d^{'}} + \frac{v_t^2 \cos 2\delta}{x_d^{'}}\right) - \lambda_1 & 0 & 0 & 0 \\ 0 & \frac{\eta_3\eta_1}{\eta_4}\cos 2\phi - \lambda_2 & 0 & 0 \\ 0 & 0 & D - \lambda_3 & 0 \\ 0 & 0 & 0 & D_a - \lambda_4 \end{bmatrix} \quad (39)$$

Analysis of this key assures us that all eigenvalues are positive, which allows us to say that our function has a minimum.

H. Results interpretation

Equations (8) and (23) physically represent the total energy of the synchronous respectively asynchronous generator. Since the Hamiltonian does not explicitly depend on time, it constitutes a constant of movements. It represents the dynamic behavior of our system. In the case of figures (2, 3, 4, 5, 6, 7), the contour lines for each energy are presented so that the potential and kinetic energies vary inversely in proportion: when one is maximum, the other is minimal. For the case of Figures 3 and 5, the respective points A and B, the potential energy is maximum and the kinetic energy is zero. These points represent the saddle knot points. In figures (3, 6, 7), the saddle knot points are on the positive side of the axis, unlike their position in figure 5, this is due to the absence of wind, that is to say – it's means instead of producing, the asynchronous generator consumes energy. Given the nature of our Hamiltonian, it represents the total energy of the system. For sufficient values of this energy, the trajectory of the system in the state space (δ; ω) is a closed curve to thus translate a stable system and, otherwise, the level lines diverge.

III. CONCLUSION

To conclude, the study for the stability to a system composed of asynchronous and synchronous generators connected together with an infinite network is very complex. Its realization for a multi-machine electrical system is an important phase in ensuring the proper functioning of a network. Such a system requires the determination of the energy function to better explain its behavior. In the present work, the choice is pointed at the Hamilton function as an energy function. In the present case, the energy function taken from the state equation of the system can be used as a Lyapunov function. The Hamiltonian function for the synchronous generator, and then that of the asynchronous generator. On the basis of these two functions, it has been shown that they meet the criteria of Lyapunov functions for the GS, for the GAS and finally for the synchronous generator-asynchronous system connected to the SMIB. The stability Lyapunov are verified which shows the reliability of the emitted proposal.

REFERENCES

[1]. H. Khalil « Nonlinear Systems » Prentice-Hall, Englewood Cliffs NJ, 1996. p. 5-1 (cf. p. 1, 6-8).
[2]. Valerijs Knazkins « Stability of Power Systems with Large Amounts of Distributed Generation » Doctoral Thesis Stockholm, Sweden 2004
[3]. MANASINA RUFFIN "Stabilité transitoire des réseaux électriques multi machines" ; Mémoire pour l'obtention du Diplôme d'Etudes Approfondies (DEA)en électrotechnique à l'Ecole Supérieure Polytechnique Antsiranana.
[4]. Sylvie Benzoni « Equations différentielles ordinaires » 26 mars 2005
[5]. G. Bastin « Modélisation et analyse des systèmes dynamiques » 14 juillet 2013
[6]. Mohammed SAFI « Stabilité de Lyapunov de systèmes couplés impliquant une équation de transport » thèse doctorat de l'université de Toulouse, soutenue 31 octobre 2018.
[7]. Khalil, H.K(1996). Nonlinear Systems. Prentice-Hall, Upper Saddle River.
[8]. Lewis, F.L Abdallah, C.T., and Dawson, DM (1993). Control of robot manipulator. MACMILLAN Publishing company
[9]. Lewis, Dawson, DM., and F.L Abdallah, C.T. (2004). Robot Manipulator Control Theory and Practice. Marcel Dekker, Inc., New York
[10]. Slotine, J.J. and Weipping, L. (1991). Applied Nonlinear Control. Prentice Hall.
[11]. Bachir Bouiadjra Rochdi. Commande robuste des systèmes non linéaires. Thèse doctorat à l'université d'Oran1, 2015.
[12]. M. Bezout "Théorie générale des équations algébriques", Académie Royale des sciences
[13]. H-K. Khalil. « Noninear systems ». In: Prentice-Hall, New Jersey 2.5 (1996), p. 5-1 (cf. p. 1, 6-8).
[14]. H. K. KHALIL: Nonlinear Systems. Prentice Hall, third édn, 2002.
[15]. Emmanuel Moulay « Une étude des systèmes non linéaires en théorie du contrôle par les fonctions de Lyapunov ». HDR en Automatique / Robotique. Université de Poitiers, 2014.
[16]. Skuli Gudmundsson ∗ Sigurdur F. Hafstein « Lyapunov Function Verification : MATLAB Implementation » Reykjavik University, Menntavegur 1, 101 Reykjavik, Iceland.
[17]. Z. Saad-Saoud and N. Jenkins. Simple wind farm dynamic model. IEEE Proc. -Gener. Transm. Distrib., 142(5):545–548, September 1995.