Modelling and Simulation of Synchronous Inductor Machines

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ABSTRACT

This study focuses on the study of the compartment of the synchronous inductor machine with variable speed, fed by a three-phase inverter. Several transients were treated by simulation (start unloading, introducing a torque load, reversing and speed setpoint change). Then engine cushion at both loss and when starting without the damper. In addition, robustness tests on the parametric variation of (MSRB) were also performed. Based on the results of simulations, the control technique studied makes it possible to obtain good dynamic and static performances and has a robustness with respect to the external perturbation and the parametric variation.

I. Introduction

The synchronous machine is an AC machine whose steady state speed of rotation is in close relation with the frequency of the stator winding. If this winding is designed to form pole pairs p and if f denotes the frequency of the stator currents. Consequently, for a given frequency of the stator winding, the speed of rotation of the synchronous machine remains constant and does not depend on the value of the load. Such a definition of the synchronous machine is assumed that the magnetic field in the circuit is created from a DC source. A synchronous machine which operates without excitation current is called reactive synchronous machine [1]. The main field of use of the synchronous machine remains the production of electrical energy. The field of use of synchronous motors is very wide. It goes from band drives, (from a few watts) to high-power drives (pumps, boat propulsion, variable speed generators, traction ..., from a few MW of power) to the servomotors of robotics (robot arm, spindles of machine tools ..., powers ranging from 100W to 10W). Even if the structures of the machines are very varied, their principles of operation and control remain almost identical. The synchronous machine can also be used to improve the power of an electrical network (synchronous compensator) by participating in the regulation of the reactive power of the network [2].

In synchronous machines with salient poles, of which the hydro-alternators are part, the poles are physically separated and on each pole is a coil of excitation dressed on the polar nuclei. This embodiment is feasible for all synchronous rotation speeds (with rare exceptions 3000 rpm). this type of machine often comprises a damper winding (starter) housed in semi-closed circular notches arranged on the surface of the polar expansion. Synchronous compensators are most often manufactured with salient poles for a speed of 750tr / min and powers ranging from 75 to 100MVA. The synchronous engine can not start alone. It always needs a means of starting (external or internal). As an internal means, the use of the induction principle in the rotor (short-circuited rotor brushes) can be cited, and even the damping winding can also be used for launching the synchronous machine by the induction effect. External motors can also be used for starting the synchronous motor, such as coupling the synchronous machine to an asynchronous machine or a dc machine. In the vicinity of the synchronous speed, the excitation winding is supplied by a DC voltage; this creates an additional flow that hooks the rotor to the rotating field of the stator and thus brings the rotor back to synchronous speed. When starting asynchronously, the excitation winding must be short-circuited or closed on a resistor, because in the opposite case (open excitation circuit) a rather high voltage could be induced at its terminals causing the breakdown of the current. isolation and decommissioning of the engine [2].

In this paper, we applied the vector control to the machine for normal mode and flow control, which is based on the classical PI controllers [3, 4].

II. Modelling of synchrounus machine

Much of the electrical energy is currently produced by the synchronous machines of the various power plants. We will give in the following principle of operation and we establish a dynamic model called "complete" and a second said "classic" of this important element of an electrical system. Apart from the production of energy, the role of the synchronous machines is to maintain constant the tensions at the nodes of the network as well as the frequency. To this end, the synchronous machines of the power stations are equipped with voltage and speed regulators.

The state representation of the machine is based on the choice of the reference and state variables for the electrical equations. This representation is not unique but generally linked to objectives to be achieved. In our study, we write the equations in the reference (d, q), because it is the most suitable method to solve our control problems.
The choice of variables depends on the objectives either for the control or for the observation. [5–7]

In this part, we give the model of the inductor MS.The general form of the state representation is as follows:

$$\begin{cases} [\dot{X}] = \frac{d[X]}{dt} = [A] * [X] + [B] * [U] \\ [Y] = [C] * [X] \end{cases} \quad (1)$$

Où

[X] : the state vector.[U] : the control vector.
[A] : the matrix of the state.
[B] : the application matrix commands.
[Y] : the output vector.

The instantaneous electrical power supplied to the rotor and stator electrical circuits is expressed as a function of the axis magnitudes (d q):

$$P_e = U_d i_d + U_q i_q + U_f i_f + U_{kd} i_{kd} + U_{kq i_{kq}} \quad (2)$$

This power is divided into three sets of terms:

- The power dissipated in losses joule:

$$P_1 = R_s\left(i_d^2 + i_q^2\right) + R_f i_f^2 + R_{kd} i_{kd}^2 + R_{kq} i_{kq}^2 \quad (3)$$

- The power representing the exchanges of electromagnetic energy with the sources:

$$P_2 = i_d \frac{d\Psi_d}{dt} + i_q \frac{d\Psi_q}{dt} + i_f \frac{d\Psi_f}{dt} + i_{kd} \frac{d\Psi_{kd}}{dt} + i_{kq} \frac{d\Psi_{kq}}{dt} \quad (4)$$

- The mechanical power regrouping all the terms related to the derivatives of the angular positions:

$$P_3 = \left(\Psi_d i_q - \Psi_q i_d\right) \frac{d\theta}{dt} \quad (5)$$

The instantaneous electromagnetic torque is defined by:

$$C = \frac{3}{2}.P.(\Psi_s \wedge i_s) \qquad (6)$$

$$Ce = \frac{3}{2}P(L_d i_{sq} i_{sd} + M_f i_f i_{sq} + M_{kd} i_{kd} i_{sq} - L_q i_{sd} i_{sq} - M_{kq} i_{kq} \qquad (7)$$

$$J\frac{d\Omega}{dt} = C_e - C_r - F\Omega \qquad (8)$$

and $P\Omega = \omega_r$

Ω: the mechanical rotation speed
J: the moment of inertia of the motor
F: the viscous coefficient of friction
Ce: the electromagnetic torque delivered by the motor
Cr: the resistant or load torque

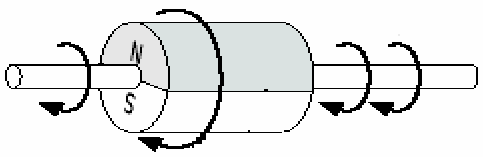


Figure 1. Different torques that act on the rotor [1]

If the synchronous machine has smooth poles, the inductances of the stator winding and the mutual inductances between these windings are constant. Moreover, the constancy of the air gap imposes the equality of the inductances [8].

$L_q = L_d = L_s$: Synchronous machines are generally studied in the reference system. $(\omega_{coor} = \omega_r)$.The following figure (2) shows the electrical model of the synchronous motor[9–16].

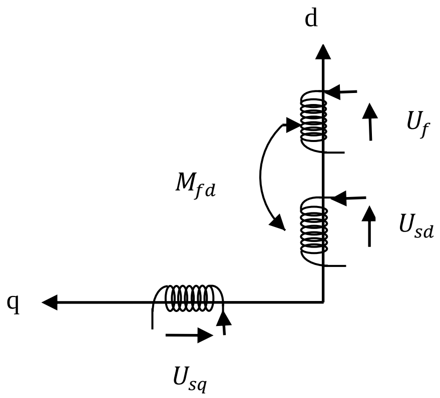


Figure 2. Model of synchronous machine without damper

The voltage Expressions are:

$$\begin{cases} U_{sd} = R_s i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_r \Psi_{sq} \\ U_{sq} = R_s i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_r \Psi_{sd} \\ U_f = R_f\, i_f + \frac{d\Psi_f}{dt} \end{cases} \qquad (9)$$

The magnetic expressions also,

$$\begin{cases} \Psi_{sd} = L_d i_{sd} + M_{df} i_f \\ \Psi_{sq} = L_q i_{sq} \\ \Psi_f = L_f i_f + M_{fd} i_{sd} \end{cases} \quad (10)$$

In matrix form

$$\begin{bmatrix} U_{sd} \\ U_{sq} \\ U_f \end{bmatrix} = \begin{bmatrix} R_s & -\omega_r L_q & 0 \\ \omega_r L_d & R_s & \omega_r M_{fd} \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_d & 0 & M_{fd} \\ 0 & L_q & 0 \\ M_{fd} & 0 & L_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} \quad (11)$$

To solve this system, it must be put in the form of a state equation:

$$[\dot{I}] = [L]^{-1}[U] - [L]^{-1}[R[I]] \quad (12)$$

Where,

$$|L| = \begin{bmatrix} L_d & 0 & M_{fd} \\ 0 & L_q & 0 \\ M_{fd} & 0 & L_f \end{bmatrix}; [R] = \begin{bmatrix} R_s & -\omega_r L_q & 0 \\ \omega_r L_d & R_s & \omega_r M_{fd} \\ 0 & 0 & R_f \end{bmatrix} et [R] = [R_1] + \omega_r [R_2]$$

and,

$$[R_1] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_f \end{bmatrix}; \ [R_2] = \begin{bmatrix} 0 & -L_q & 0 \\ L_d & 0 & M_{fd} \\ 0 & 0 & 0 \end{bmatrix}; \ [Z] = [L]^{-1}$$

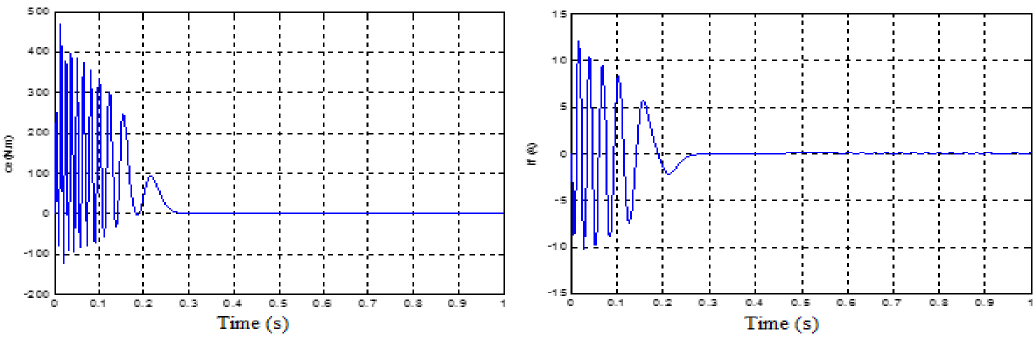
For the three-phase synchronous machine, the electromagnetic torque is expressed by:

$$C_e = \frac{3}{2} p\left[\left(L_d - L_q\right) i_{sd} i_{sq} + M_{fd} i_{sq} i_f\right] \quad (13)$$

The expression of movement by:

$$\frac{j}{p}\frac{d\omega r}{dt} = c_e - c_r - F\Omega \quad (14)$$

Represents the main characteristic of synchronous motor without damper



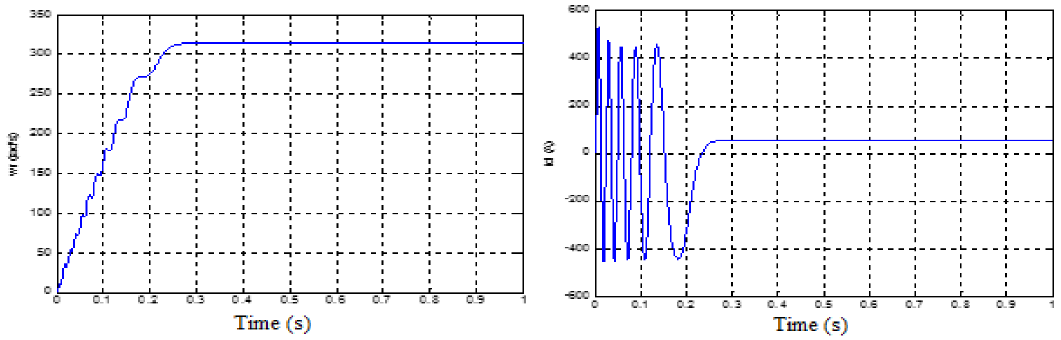


Figure 3. Synchronous motor characteristics.

At very low speeds, the torque is short-lived but high intensity and then fade when the machine picks up speed while remaining oscillatory.the speed undergoes transient variations due to the counter-reaction effect of the rotating masses, which tend to bring the machine back to its initial speed. It constantly presents weak oscillation around synchronism; these are due, among other things, to the absence of the damping circuit. The rotor current undergoes the same law of variation. At low speed, their amplitude is important but stabilizes rapidly as synchronism approaches. It is possible to deepen the simulation work by varying the values of the stator resistorsand excitement, the excitation voltage, the load torque, as well as the moment of inertia.

III. Modeling and simulation of SM with shock absorber

The machines with salient poles have their rotor equipped with dampers made of copper bars housed in notches made in the pole pieces. These bars are interconnected at their ends by two rings or conductor hoops depending on the number of poles. Shock absorbers resist any rapid variation of flow through the rotor. They have a primary role in stabilizing the speed of the machine due to load variations. They have the same mechanical characteristics as cage asynchronous machines. If the speed tends to increase (negative slip) following a sudden drop in the load, the induction effect originates in the damping windings and produces a resistant (negative) torque to the movement of the rotor and slows it down, and the rotor is thus brought back to the synchronous speed.Otherwise, if the speed tends to fall (positive slip) due to a sudden overload of the machine, the induction effect is born and the damping winding produces an additional (positive) torque which is added to the engine torque to bring the rotor back to synchronous speed.

In machines with smooth polesit is the mass part of the rotor iron which plays the role of shock absorber [16]. The figure above shows the model of the synchronous machine with salient poles with dampers.

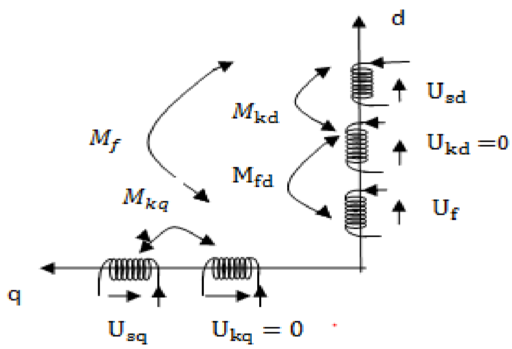


Figure 4. Synchronous machine model with shock absorber

The expression of the voltages and flows are given as follows [15]:

$$\begin{cases} U_{sd} = R_s i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_r \Psi_{sq} \\ U_{sq} = R_s i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_r \Psi_{sd} \\ U_f = R_f i_f + \frac{d\Psi_f}{dt} \\ 0 = U_{kd} = R_{kd} i_{kd} + \frac{d\Psi_{kd}}{dt} \\ 0 = U_{kq} = R_{kq} i_{kq} + \frac{d\Psi_{kq}}{dt} \end{cases} \quad (15)$$

And:

$$\begin{cases} \Psi_{sd} = L_d i_{sd} + M_f i_f + M_{kd} i_{kd} \\ \Psi_{sq} = L_q i_{sq} + M_{kq} i_{kq} \\ \Psi_f = L_f i_f + M_{fd} i_{sd} + M_{fd} i_{kd} \\ \Psi_{kd} = L_{kd} i_{kd} + M_{kd} i_{sd} + M_{fd} i_f \\ \Psi_{kq} = L_{kq} i_{kq} + M_{kq} i_{sq} \end{cases} \quad (16)$$

Taking into account flow expressions, the system of stress equations can be written in the form:

$$\begin{bmatrix} U_{sd} \\ U_{sq} \\ U_f \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + sL_d & -L_q\omega_r & sM_f & sM_{kd} & -\omega_r M_{kq} \\ L_d\omega_r & R_s + sL_q & \omega_r M_f & \omega_r M_{kd} & sM_{kq} \\ sM_f & 0 & R_f + sL_f & sM_{fd} & 0 \\ sM_{kd} & 0 & sM_{fd} & R_{kd} + sL_{kd} & 0 \\ 0 & s\,M_{kq} & 0 & 0 & R_{kq} + sL_{kq} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix} \quad (17)$$

The equation system is put in the form:

$$[L] * \frac{d[I]}{dt} = -[A][I] + [U] \quad (18)$$

$$\frac{d[I]}{dt} = -[L]^{-1}[A][I] + [L]^{-1}[U] \quad (19)$$

With

$$[L] = \begin{bmatrix} L_d & 0 & M_f & M_{kd} & 0 \\ 0 & L_q & 0 & 0 & M_{kq} \\ M_f & 0 & L_f & M_{fd} & 0 \\ M_{kd} & 0 & M_{fd} & L_{kd} & 0 \\ 0 & M_{kq} & 0 & 0 & L_{kq} \end{bmatrix}$$

Ou

$$[Z] = [L]^{-1} et [A] = [A_1] + \omega [A_2]$$

$$[A_1] = \begin{bmatrix} R_s & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \quad [A_2] = \begin{bmatrix} 0 & -L_q & 0 & 0 & -M_{kq} \\ L_d & 0 & M_f & M_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[A] = \begin{bmatrix} R_s \omega_r L_q & 0 & & 0 & -\omega_r M_{kq} \\ & \omega_r L_d R_s \omega_r M_f \omega_r M_{kd} & & 0 & \\ 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix}$$

$$[I] = \left[i_{sd} i_{sq} i_f i_{kd} i_{kq} \right]^t \ ; \ [U] = \left[U_{sd} \ U_{sq} U_f \ 0 \ 0 \right]^t$$

The expression of the electromagnetic torque is:

$$Ce = \frac{3}{2} P(L_d i_{sq} i_{sd} + M_f i_f i_{sq} + M_{kd} i_{kd} i_{sq} - L_q i_{sd} i_{sq} - M_{kq} i_{kq} i_{sd}) \quad (20)$$

Expression of movement is:

$$J \frac{d\Omega}{dt} = C_e - C_r - F\Omega \quad (21)$$

Figures below show the results of simulations:

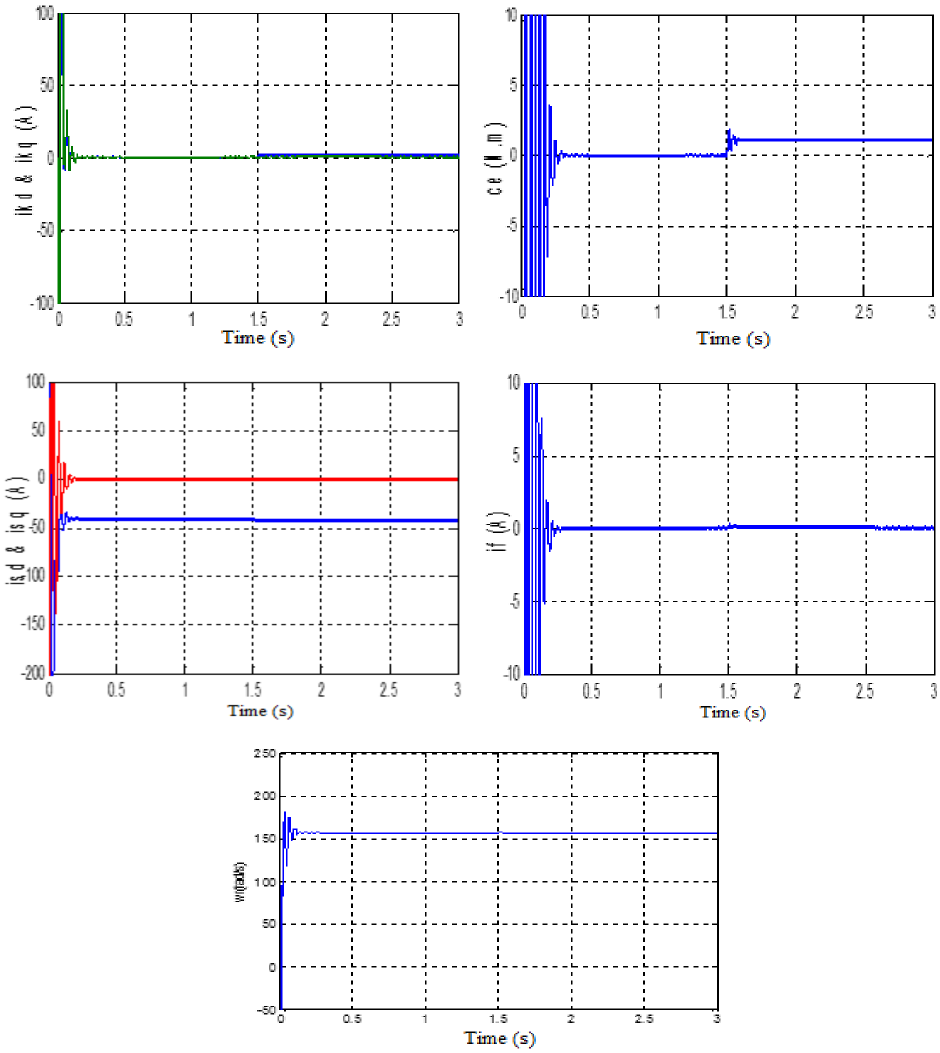


Figure 5. Vacuum start with introduction of a load of 150 Nm at 1.5s. for (f = 50).

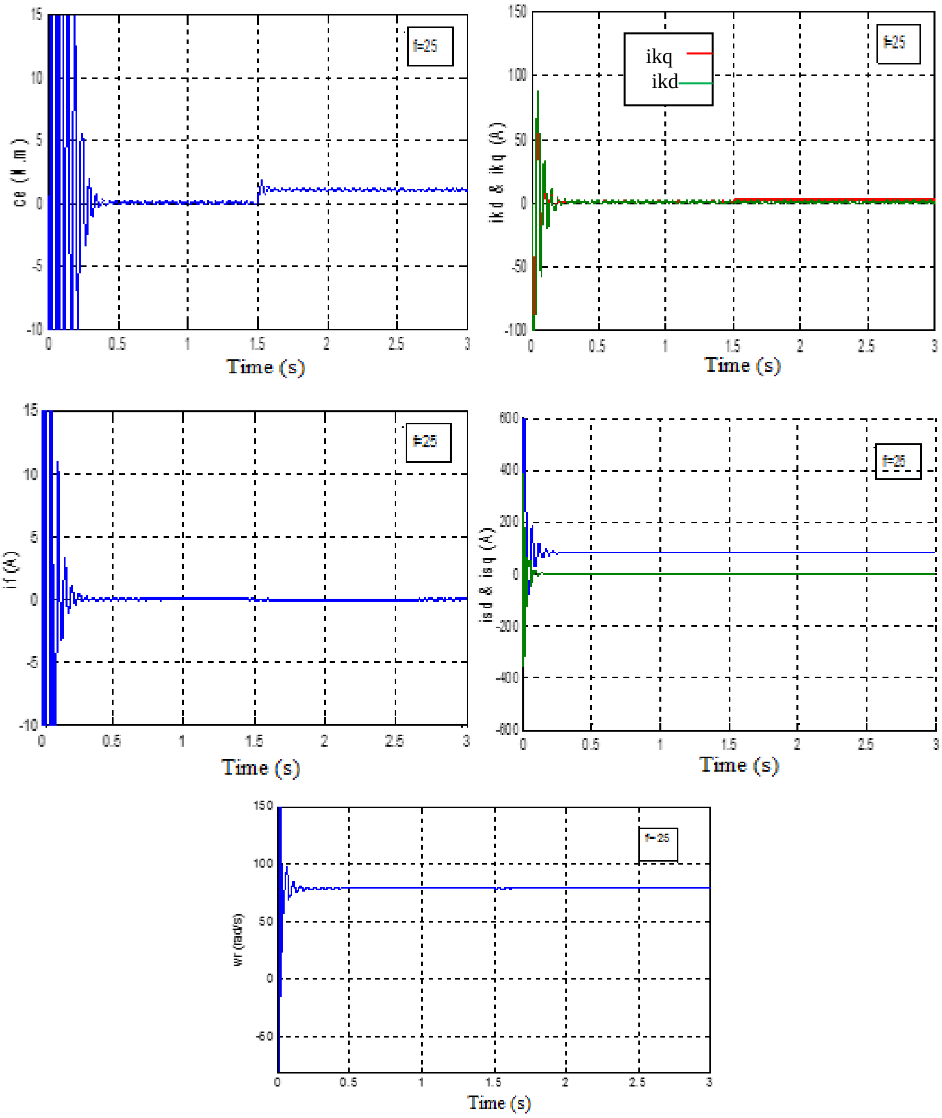


Figure 6. Influence of the variation of the frequency on the parameters of the machine.

Through the various simulation results, we note the absence of oscillations on the speed and torque speeds thanks to the presence of damping windings figures (5 and 6).In the transient interval, the currents i_kd and i_kq are very oscillatory and they cancel each other as soon as the motor reaches the speed of synchronism. They react to any disruption of speed.The stator current isd changes according to the load. When empty, the current isq vanishes at the end of the transient regime. The application of the load at t = 1.5s the engine to a low disturbance due to the presence of dampers.In the case of the variation of the frequency figure (6), its decrease causes the decrease of the speed and the increase of the transient state of all the parameters. The diagram of figure (7), makes it possible to simulate the loss of a phase of the machine, if t = 0 to t = 2s.The simulation results of figure (8), show an instability, practically of all the parameters, characterized by very strong oscillations. The speed drops sharply and continues to oscillate strongly around a rather low value.

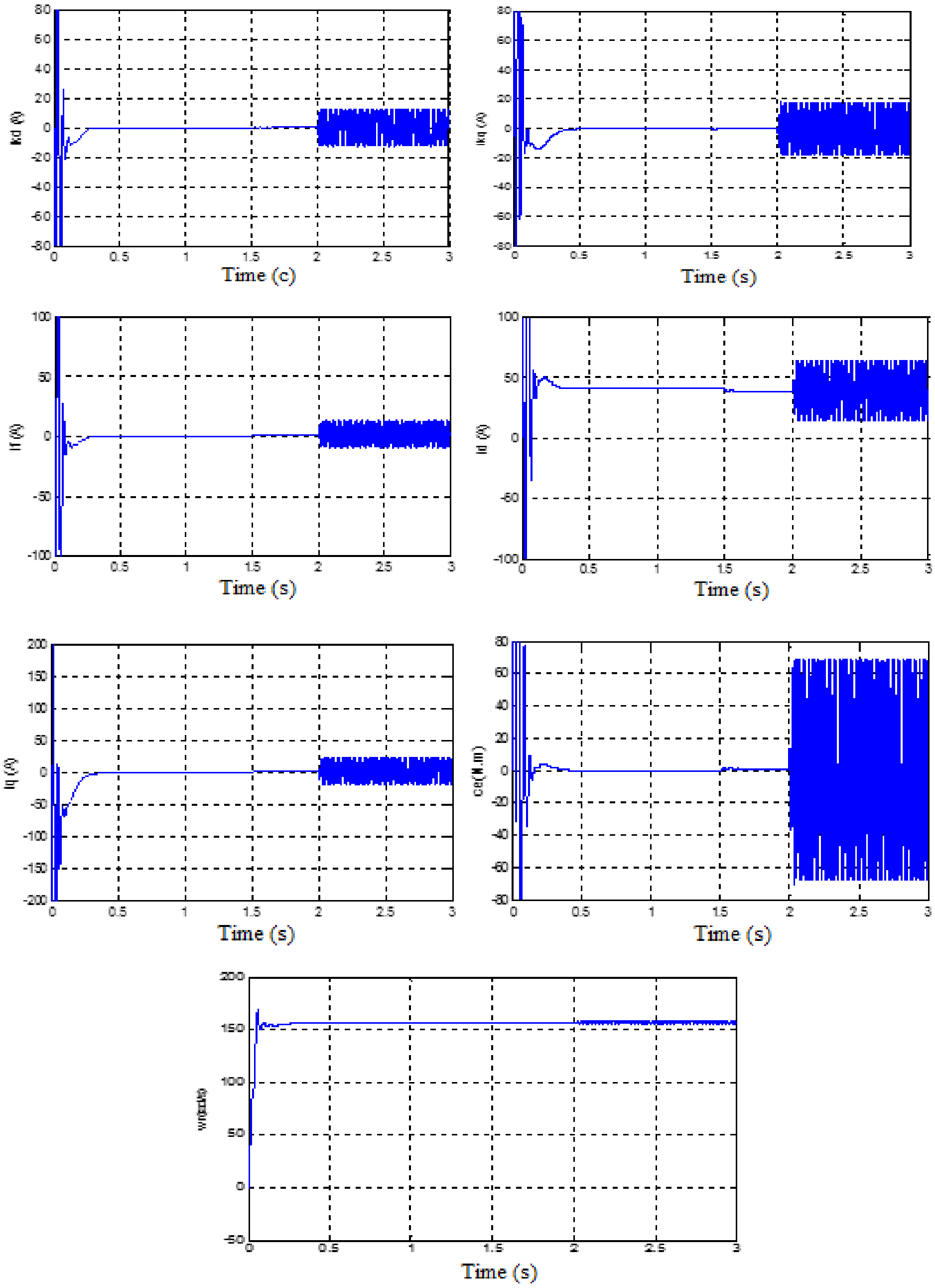
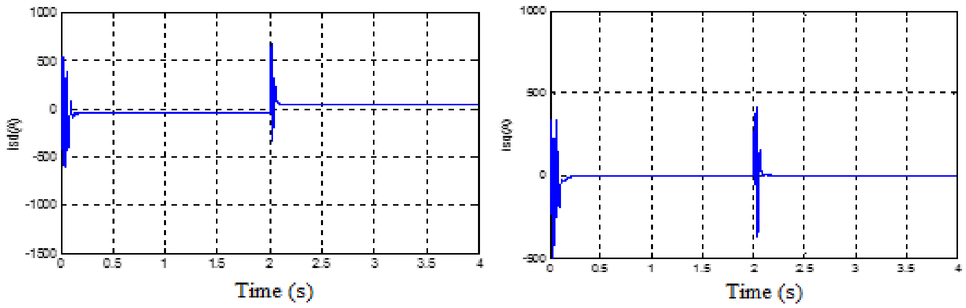


Figure 7. Simulation results when losing a phase.



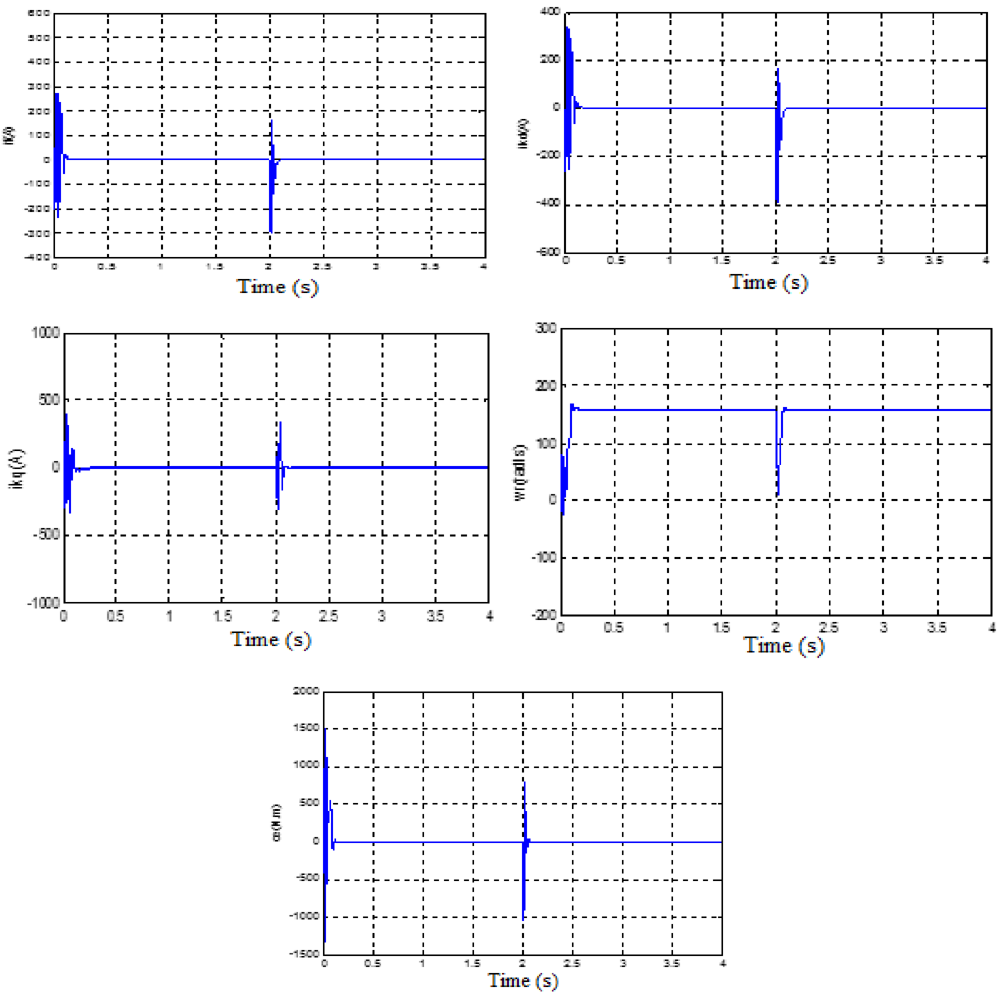


Figure 8. Simulation Results at Excitation Loss

IV. Modeling and simulation of SM without dampers

Consider a synchronous machine with salient poles without dampers (U_kd = U_kq = 0) as shown in the figure (9).

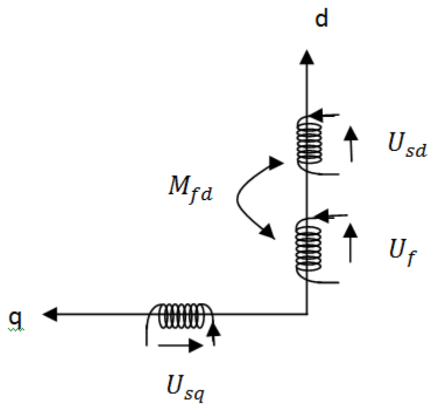


Figure 9. Synchronous generator model.

From the model of the electric machine generalized in the rotor reference, one can write:

$$\begin{cases} -U_{sd} = R_s i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_r \Psi_{sq} \\ -U_{sq} = R_s i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_r \Psi_{sd} \\ U_f = R_f i_f + \frac{d\Psi_f}{dt} \end{cases} \quad (22)$$

Flow expression:

$$\begin{cases} \Psi_{sd} = L_d i_{sd} + M_{fd} i_f \\ \Psi_{sq} = L_q i_{sq} \\ \Psi_f = L_f i_f + M_{fd} i_{sd} \end{cases} \quad (23)$$

Taking into account the system (22) the system of the tensions becomes:

$$\begin{cases} -U_{sd} = R_s i_{sd} + \frac{d(L_d i_{sd} + M_{fd} i_f)}{dt} - \omega_r L_q i_{sq} \\ -U_{sq} = R_s i_{sq} + \frac{d(L_q i_{sq})}{dt} + \omega_r (L_d i_{sd} + M_{fd} i_f) \\ U_f = R_f i_f + \frac{d(L_f i_f + M_{fd} i_{sd})}{dt} \end{cases} \quad (24)$$

Putting, in matrix form:

$$\begin{bmatrix} -U_{sd} \\ -U_{sq} \\ U_f \end{bmatrix} = \begin{bmatrix} R_s & -\omega_r L_q & 0 \\ \omega_r L_d & R_s & \omega_r M_{fd} \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} + \begin{bmatrix} L_d & 0 & M_{fd} \\ 0 & L_q & 0 \\ M_{fd} & 0 & L_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} \quad (25)$$

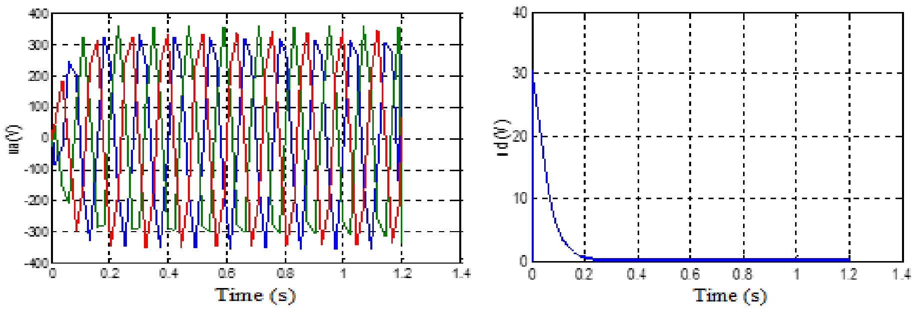
When empty, the currents of the stator phases are zero (i_sd = i_sq = 0), then the system (24) becomes:

$$\begin{cases} -U_{sd} = M_{fd} \frac{di_f}{dt} \\ -U_{sq} = \omega_r M_{fd} i_f \\ U_f = R_f i_f + L_f \frac{di_f}{dt} \end{cases} \quad (26)$$

Thus, there remains only one differential equation representing the state of the synchronous generator operating in a vacuum.

$$\frac{di_f}{dt} = -\frac{R_f}{L_f} i_f + \frac{U_f}{L_f} \quad (27)$$

Simulation result of the synchronous vacuum generator:



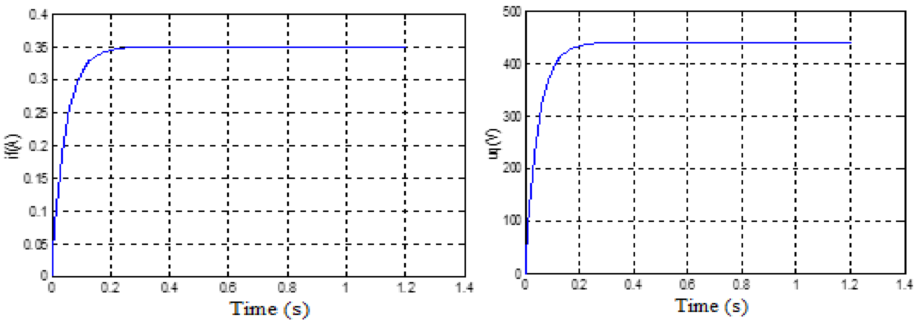


Figure 10. Simulation results of the synchronous with salient poles.

In case the generator supplies a load R_L with an excitation voltage U_f = 220V, the system is the form (26) with:

$$\begin{cases} U_{sd} = R_{ch}\, i_{sd} + L_{ch}\frac{di_{sd}}{dt} \\ U_{sq} = R_{ch}\, i_{sq} + L_{ch}\frac{di_{sq}}{dt} \end{cases} \tag{28}$$

If we replace the expressions U_sq, U_sd in the system (28), we obtain the following system:

$$\begin{bmatrix} 0 \\ 0 \\ U_{sq} \end{bmatrix} = \begin{bmatrix} (R_s + R_{ch}) & -\omega_r L_q & 0 \\ \omega_r L_d & (R_s + R_{ch}) & \omega_r M_{fd} \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} + \begin{bmatrix} (L_d + L_{ch}) & 0 & M_{fd} \\ 0 & (L_q + L_{ch}) & 0 \\ M_{fd} & 0 & L_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} \tag{29}$$

The system (29) can be written as:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} = \begin{bmatrix} (L_d + L_{ch}) & 0 & M_{fd} \\ 0 & (L_q + L_{ch}) & 0 \\ M_{fd} & 0 & L_f \end{bmatrix} . \left(- \begin{bmatrix} (R_s + R_{ch}) & 0 & 0 \\ 0 & (R_s + R_{ch}) & 0 \\ 0 & 0 & R_f \end{bmatrix} - \omega_r \begin{bmatrix} 0 & -L_q & 0 \\ Ld & 0 & M_{df} \\ 0 & 0 & 0 \end{bmatrix} \right) . \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix} + \begin{bmatrix} (L_d + L_{ch}) & 0 & M_{fd} \\ 0 & (L_q + L_{ch}) & 0 \\ M_{fd} & 0 & L_f \end{bmatrix} . \begin{bmatrix} 0 \\ 0 \\ U_f \end{bmatrix} \tag{30}$$

The system (30) is of the form:

$$\frac{d}{dt}[X] = [A] . [X] + [B] . [U] \tag{31}$$

With :

$[A] = -[L]^{-1}[Z]$ et $[B] = [L]^{-1}[X] = \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_f \end{bmatrix}$ And $[U] = \begin{bmatrix} U_{sd} \\ U_{sq} \\ U_f \end{bmatrix}$

$$[Z] = \begin{bmatrix} (R_s + R_{ch}) & 0 & 0 \\ 0 & (R_s + R_{ch}) & 0 \\ 0 & 0 & R_f \end{bmatrix} + \omega_r \begin{bmatrix} 0 & -L_q & 0 \\ L_d & 0 & M_{df} \\ 0 & 0 & 0 \end{bmatrix}$$

$$[L]^{-1}=\begin{bmatrix}(L_d+L_{ch}) & 0 & M_{fd}\\ 0 & (L_q+L_{ch}) & 0\\ M_{fd} & 0 & Lf\end{bmatrix}^{-1}$$

In the case of the absence of damping windings, the expression of the pair is:

$$C_e=\frac{3}{2}p\left((L_d\text{-}L_q)\, i_{sd}\, i_{sq}+M_{fd}\, i_f\, i_{sq}\right) \qquad (32)$$

Simulation result:

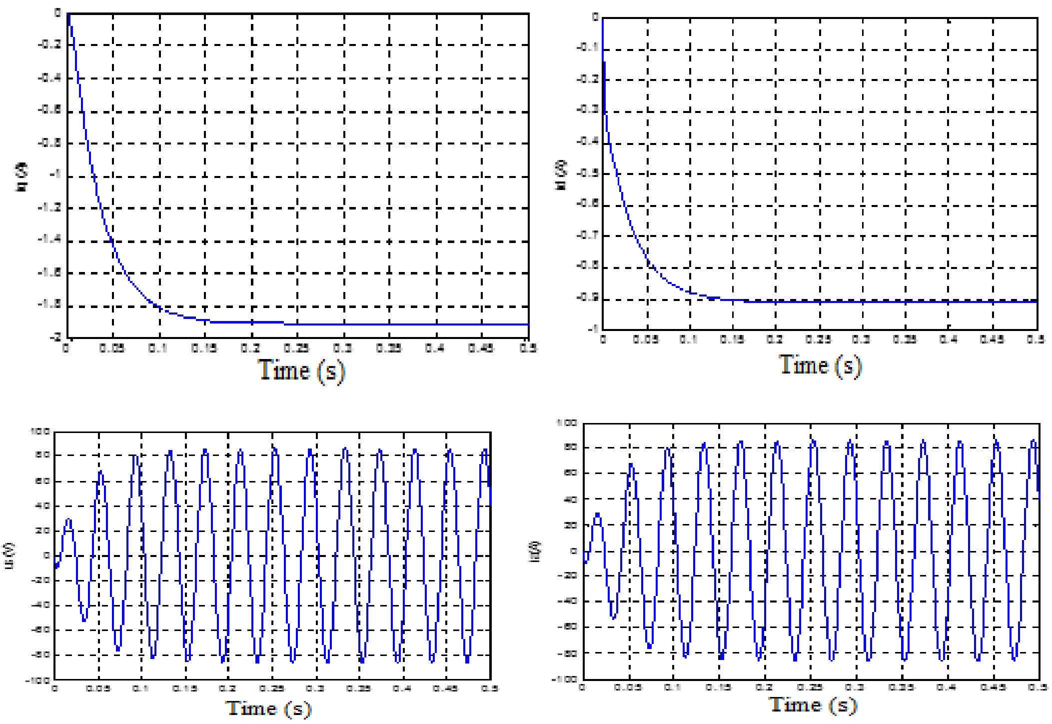


Figure 11. Simulation results of the synchronous machine with salient pole load.

The simulation results presented in Figures (11) show:

For a constant speed = 157 rad / s, the excitation current is established at a value of 0.35A after a transient period of 0.3 s.When empty, it is noted that the voltage Usd, after a peak of 30V, drops to zero at t = 1.2 s; while at time t = 0.3s, Usq reaches an established value of 440V. In load the transient regime has a duration of 0.25s, currentsid and iq take negative values of -0.92A and -1.9A respectively, the current and the voltage at the machine terminals have a sinusoidal value of 2,1A and 105V respectively.

V. Modeling voltage inverters

In the study of the entire inverter control, machine and load, we will only focus on the dynamic behavior of the electrical and mechanical variables of the machine. Modeling can be facilitated and simulation time reduced by modeling the inverter with a set of ideal switches, that is, zero resistance in the on state, infinite resistance in the off state, instantaneous reaction to control signals. This method is most commonly used in the study of the machine inverter assembly [17, 18].

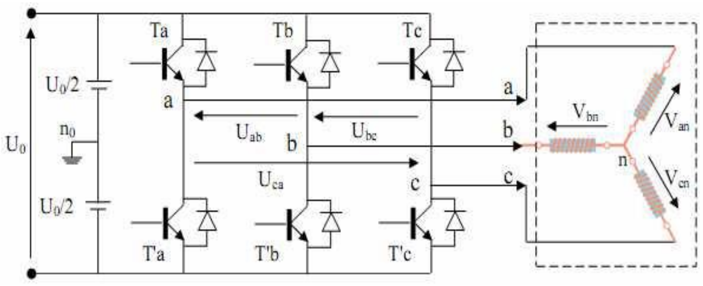


Figure 12. Diagram of the three-phase inverter.

To model the voltage inverter figure (12), we consider its power supplyas a perfect source, supposed to be of two generators of f.e.m equal to U_0 / 2 connected to each other by a point noted n_0.The machine has been modeling from simple voltages that we note$V_{an} V_{bn}$ et V_{cn} ,the inverter is controlled from the logical quantitiesS_1. We call and transistors (supposed ideal switches), we have:

- If S_i=1 So $T_i$is passing And T_i' is open
- If S_i= 0 So T_i is passing And T_i' is open

The simple voltages of the phases of the charge resulting from the compound voltages have a zero sum, therefore:

$$\begin{cases} V_{an} = \left(\frac{1}{3}\right)(U_{ab} - U_{ca}) \\ V_{bn} = \left(\frac{1}{3}\right)(U_{bc} - U_{ab}) \\ V_{cn} = \left(\frac{1}{3}\right)(U_{ca} - U_{bc}) \end{cases} \quad (33)$$

They can be written from the output voltages of the inverter by introducing the neutral voltage of the load in relation to the reference point n_0.

$$\begin{cases} V_{an0} = V_{an} + V_{nn0} \\ V_{bn0} = V_{bn} + V_{nn0} \\ V_{cn0} = V_{cn} + V_{nn0} \end{cases} \quad (34)$$

So we can deduce that:

$$V_{nn0} = (1/3)[V_{an0} + V_{bn0} + V_{cn0}] \quad (35)$$

We have:

$$\begin{cases} V_{an0} = (S_a - 0.5)U_0 \\ V_{bn0} = (S_b - 0.5)U_0 \\ V_{cn0} = (S_c - 0.5)U_0 \end{cases} \quad (36)$$

By replacing (35) in (36), we obtain:

$$\begin{cases} V_{an} = \frac{2}{3}V_{an0} - \frac{1}{3}V_{bn0} - \frac{1}{3}V_{cn0} \\ V_{bn} = \frac{1}{3}V_{an0} + \frac{2}{3}V_{bn0} - \frac{1}{3}V_{cn0} \\ V_{cn} = \frac{1}{3}V_{an0} - \frac{1}{3}V_{bn0} + \frac{2}{3}V_{cn0} \end{cases} \quad (37)$$

Replacing (36) in (37). We obtain

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} U_0 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (38)$$

VI. Simulation of the machine powered on PWM inverter

The general principle is to convert a modulator (reference voltage at the command level), usually sinusoidal, in a voltage in the form of successive slots of variable width (PWM pulse width modulation). The switching angles are calculated to eliminate a certain number of harmonic generated at the output of the inverter (power level). This technique is based on the comparison between two signals the reference signals (sinusoidal) and the carrier signal (triangle).

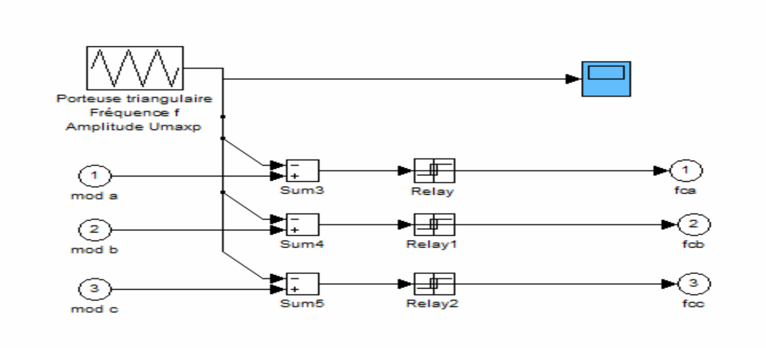


Figure 13. Generation of command signals PWM [18]

Simulation of the model of the machine associated with the inverter

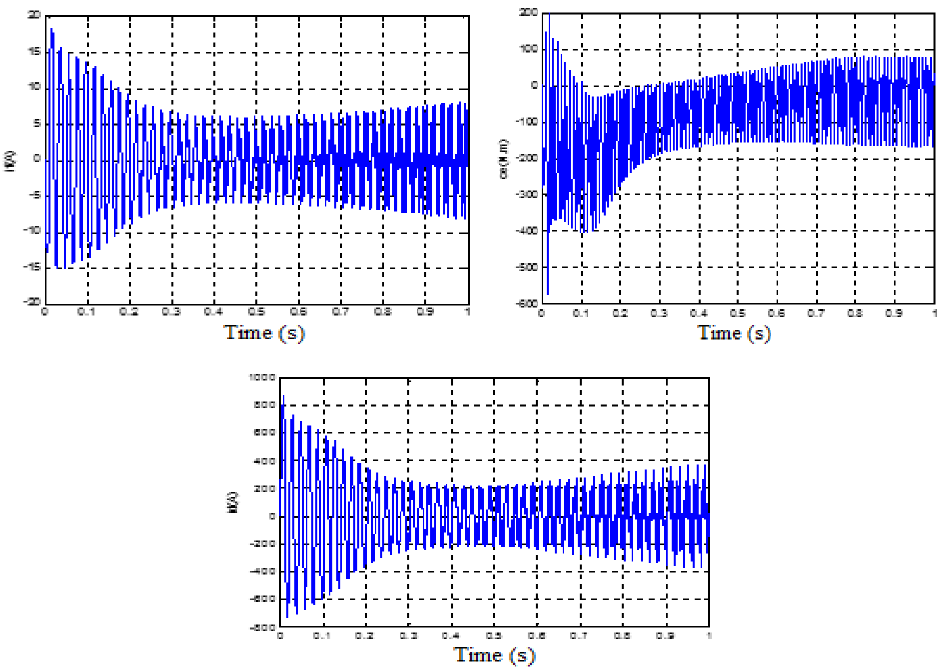


Figure 13. Simulation result of the machine fed to the inverter.

During start-up, we notice that all the signals are strongly pulsating because the machine goes through the transient state and then stabilizes and enters the steady state.For currents id, iq at the beginning of the start, we notice peaks of fairly high current due to the f.e.m. which is due to a low starting speed, after they stabilize at these nominal values.When simulating the model in combination with the PWM inverter, it is noted that the results obtained have the same model but they have oscillations due to harmonics in the voltages delivered by the inverter.

VII. Conclusion

In this paper we presented the modeling of the synchronous machine with inductor and inverter MLI of three-phase voltage, we used the reference of Park to simplify the equations for each case. We presented the simulation on Matlab-Simulink of the different cases of synchronous machine with inductor and inverter PWM. We have described the control of the connection between the machine, the controlled inverter and the load. The law ordering system was also detailed. The results of the various simulations carried out were ordered and allowed to validate the mathematical models of the system.

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