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Mono inverter dual parallel PMSM - Structure and Control strategy

Damien Bidart*, Maria Pietrzak-David*, Pascal Maussion* and Maurice Fadel*
*Université de Toulouse; LAPLACE; CNRS, INPT, UPS
2 rue Camichel, 31071 Toulouse Cedex France

***Abstract*— This paper presents a dual parallel connected PMSM fed by a single power inverter. Both motors have to respect the synchronism even if they have different load torque. The rotor position of the two motors that is to say the load applied on each motor are consequently permanently compared. The motor with the highest load is set as the master one and is auto-piloted. The other one which has the same applied voltage has the same electric pulsation and so the same speed rotation. The change of the master choice is done whereas the load applied on the machine is changing so that oscillations appear during this change. The steady state is however rapidly attained and the synchronism stays always observed.**

I. Introduction

The number of systems fed by power electronics is increasing, specially in domains like aeronautic (flaps and spoiler actuators, braking system,...) or railway propulsion. Among those systems, the synchronous motors is widely used and PMSM have the advantage to be brushless. Those motors are more robust and easier to be produced than DC motors and their performance are good. On the other hand, multi-converter multi-machine systems (MMS) are more and more used for induction machines. Those systems allow to extend the field of the power applications or to increase their flexibility and safety operating. These MMS systems include however a lot of power switches which are quite expensive, heavy and bulky. It is so interesting to reduce their number and consequently their width and volume. Many studies have been done concerning the multi induction motor functioning with a single inverter [1] [2] [3] or double-star synchronous machine [4] or Series-Connected Motors With Induction and Permanent Magnet Machines [5]. The main idea of this paper is to develop a controller for a multi synchronous machine - single inverter system. A few work already exists about this subject [6] [7]. The solution proposed in this study has been developed in a patent to plug the two motors in a parallel configuration [8]. Instead of using six legs for two motors (for a three-phase motor) only three legs are thus necessary. Such a system could be used as a safety system in case of a fault of an inverter leg. The two motors are plugged in parallel so they get exactly the same voltage order. If the two machines are identical and with identical load torque, the motors operate with exactly the same motor velocity.

In the first part of this paper, the structure of the abc control for a self-control PMSM is reminded. The stability of such a machine due to the rotor position is specially pointed out. The second part describes the dual parallel synchronous machines structure. It presents the study of the multi-machine system stability and proposes a switching law of the controls to insure stability for both machines. The third part shows the simulation results under SABER solver to validate PMSM drives performances.

II. Generalities

A. Controlled variables for a single PMSM

The simulated machine is a smooth-air-gap PMSM without any damping circuits in the rotor. The rotor field is constant and created by permanent magnets and the e.m.f are considered as sinusoidal. The principals variables needed for the simulation are the angular position of the rotor θ, the stator currents $i_{s1,s2,s3}$ and the voltages $V_{s1,s2,s3}$ [9].

The simplified electric equation can be written as follows:

$$V_{si} = R.i_{si} + (L_S - M).\frac{di_{si}}{dt} + e_{si} \tag{1}$$

Where R is the stator resistance per phase, L_S the stator inductance, M the mutual inductance and e_{si} the electromagnetic force. $L = L_S - M$ represents the cyclic inductance.

Moreover the mechanical mode is defined by the equations as below

$$J.\frac{d^2\theta}{dt^2} = J.\frac{d\Omega}{dt} = T_{em} - T_L - f_0.\Omega \tag{2}$$

With f_0 the friction, J the total inertia ($Nm.rad^{-1}.s^{-2}$), Ω the rotor rotation speed ($rad.s^{-1}$) and θ the rotor position (rad). T_L represents the load torque and T_{em} the electromagnetic torque (Nm).

In steady state, the currents are considered as sinusoidal and due to its low value, the stator resistance R is not taken into account. This leads to the vector diagram for the machine represented in Fig. 1.

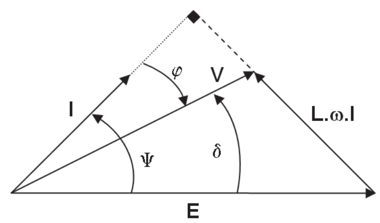


Fig. 1. Vector diagram for a smooth-air-gap PMSM

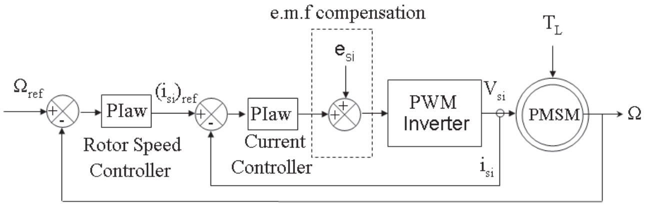


Fig. 2. Block diagram of a rotor speed controlled PMSM

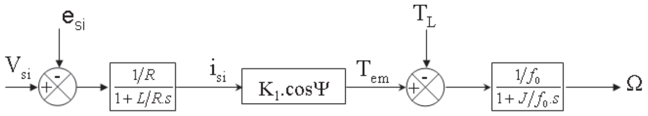


Fig. 3. Block diagram of a PMSM

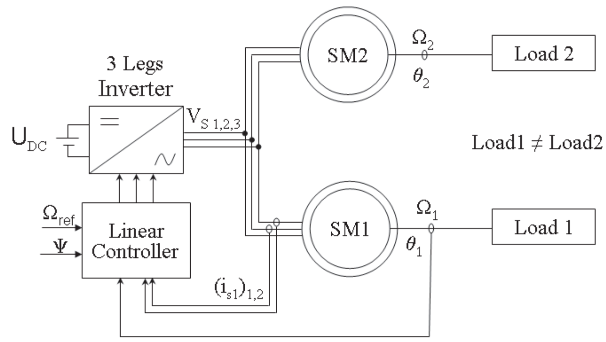


Fig. 4. Master-slave structure for two synchronous motors

In Fig. 1, $\omega = p.\Omega$ is the electric pulsation, p the number of pole pairs and E, I and V respectively represent the RMS values of e_{si}, i_{si} and v_{si}. Moreover, three angles appear: $\Psi = (\overrightarrow{I}; \overrightarrow{E})$, $\varphi = (\overrightarrow{V}; \overrightarrow{I})$ and $\delta = (\overrightarrow{V}; \overrightarrow{E})$.

To control the PMSM, a current or a voltage source can be used to supply the machine [10] [11]. The electromagnetic torque can indeed be calculated as follows:

$$\begin{array}{l} T_{em} = K_1.I.\cos(\Psi) = K_2.\frac{V}{\omega}.\sin(\delta) \\ \text{With } K_1 = 3p.\Phi_M \text{ and } K_2 = 3p.\frac{\Phi_M}{L} \end{array} \quad (3)$$

In (3), Φ_M represents the maximal inductive flux. With a current source, the torque is controlled by imposing the current I and the Ψ angle whereas with a voltage source it is controlled with the voltage V and the δ angle. In the studied case the current control is chosen. Due to the PMSM model (1), the e.m.f e_{si} is added to the control loop. Moreover, to control the amount of power transferred from the inverter to the machine, the PWM technique is used. For this, the voltage reference is compared to a triangle modulation waveform which gives the applied voltage V_{si}. The current loop which has only electrical variables is very fast. As a consequence, it can be included and ignored in the rotation speed loop. The control loop is represented in Fig. 2 . In the studied case, the used controllers are antiwindup PI (PIaw).

The PMSM block diagram represented in Fig. 3 is composed by two blocks representing the electric equation (1) and the mechanical equation (2).

B. Mono-inverter supply

In the case of MMS, the number of power electronic switches can be important. To optimize the volume and the weight of the system, this number can be reduced. Consequently, the machines are connected in parallel configuration. Each inverter leg is thus shared with all the machines. In the studied case, two three-phase PMSM are connected in parallel. The two machines are also linked and exactly the same voltage (frequency and modulus) is applied to them. In such a system, the voltage of the DC bus can not be changed. It implies that the both machines run at the same velocity in steady state. In the studied structure, the two motors are plugged in parallel. This structure is called "master-slave structure" because only the master motor (SM_1) is controlled and auto-piloted. The slave motor (SM_2) is directly plugged to the inverter and is fed by the same voltage than the master. The structure is represented in Fig. 4.

The value of the DC-bus voltage, U_{DC} is considered as constant. The index number corresponds to the machine number. Concerning the currents, they have two index number: the first one is the machine number and the second one is the phase number. As the voltage are the same on the two machines, they are noted only $V_{S\ 1,2,3}$. The study is done in the case when the load applied on the different motors are not necessarily the same and so the reaction of each of the motors depends of the applied load.

C. Instability risks

Such a system has already been developed for induction motors, specially in the railway traction [12] or in the textile [13]. The power part of the system described in Fig. 4 is the same than the one used for induction motor. The problem for PMSM is the stability. For induction motors, the velocity of the rotor depends indeed of the the load torque, even if the load is not the same for the both machines, there is no instability risk. In the case of synchronous machines, the stator and rotor fields have to stay synchronous. This stability is normally assured with the auto-piloting of the two machine. With only one inverter used for the two motors, it is not possible to control both machines. Fig. 5 represents the electromagnetic torque versus the δ angle for a synchronous machine (3).

The evolution of $T_{em}(\delta)$ is sinusoidal. If the load torque is suddenly changed, the rotor does not immediately change contrary to the δ angle (the current loop being fastest than the velocity loop). In the stable operation zone ($\delta < \frac{\pi}{2}$), the increase of the δ angle leads to the increase of the electromagnetic torque. This torque is so again stable with the load torque. However if the δ angle runs over $\frac{\pi}{2}$, there is

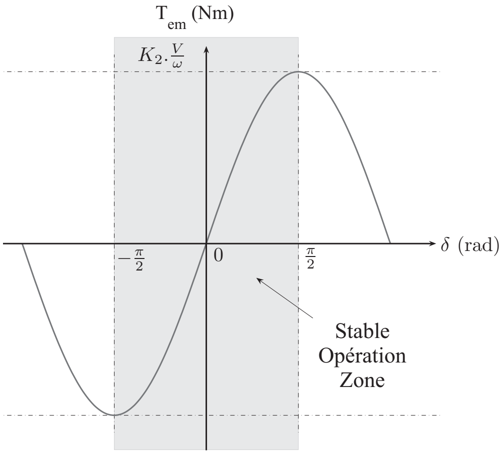


Fig. 5. T_{em} versus δ angle

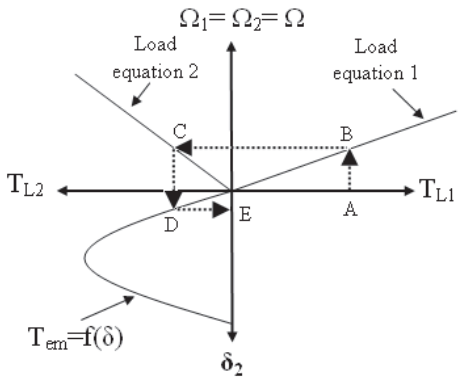


Fig. 6. Velocity versus torque diagram

no more stability. In this case, the increase of the δ angle leads indeed to a decrease of the electromagnetic torque value. It is so necessary to control the δ angle to be sure that its value stays $< \frac{\pi}{2}$

III. The studied structure

A. Cause and effects

In Fig. 6, three curves are drawn: two of them represent the load equations for the both motors in the torque-speed frame and the last one represents the evolution of the δ_2 angle versus the torque T_{L2}. The instability of the system can be easily seen.

To obtain the maximum torque, $\Psi = 0$ is chosen (3). By imposing this angle, the torque becomes directly proportional to the applied current: $T_{em} = K_1.I$

During the steady state, $J.\frac{d\Omega}{dt} = 0 \Longrightarrow T_{emi} = T_{Li}$ (2) so the current fixes the torque (point A on the Fig. 6). The load equation (4) provides the mechanical rotation speed of the master motor (point B). This velocity is proportional to the electrical pulsation of the inverter and consequently the velocity of the slave motor is equal to the velocity of the master one. So in the steady state: $\Omega_1 = \Omega_2 = \Omega$

The imposed velocity of the slave motor and its torque are in relationship through the load equation 2 (point C). The equation (3) gives the value of the δ_2 angle (point D). The stability of the slave motor is assured as long as δ_2 remains lower than $\pi/2$ (point E).

The machine number 1 is auto-piloted so $\delta_1 < \pi/2$. In the studied case, the two motors are identical.

If $T_{L1} = T_{L2}$, $\delta_2 = \delta_1$, so $\delta_2 < \pi/2$,
$\Longrightarrow$ The two motors are stable.
If $T_{L1} > T_{L2}$, $T_{em2} < T_{em1} \Rightarrow \delta_2 < \delta_1$, so $\delta_2 < \pi/2$,
$\Longrightarrow$ the two motors are stable.
If $T_{L1} < T_{L2} \Rightarrow \delta_1 < \delta_2$, so δ_2 can be $> \pi/2$,
$\Longrightarrow$ the stability of the motor is not certified.

B. Vector representation for 2 PMSM

Fig. 7 represents the vectorial diagram with the two motors connected in parallel. For the both diagrams, the value of Ψ_1 is equal to zero. Two cases are represented: $T_{L1} < T_{L2}$ (Fig. 7(a)) and $T_{L1} > T_{L2}$ (Fig. 7(b)).

If $T_{L1} < T_{L2}$, $\Psi_2 < 0$ and the inequality $\delta_1 < \delta_2$ is verified. Concerning the stator current, $I_{S2} > I_{S1}$: the intensity of the current in the slave machine is higher than the intensity ordered in the master motor. However when $T_{L1} > T_{L2}$, $\Psi_2 > 0$ and the inequality $\delta_1 > \delta_2$ is verified. $I_{S2} < I_{S1}$ and the intensity is always lower than its reference value.

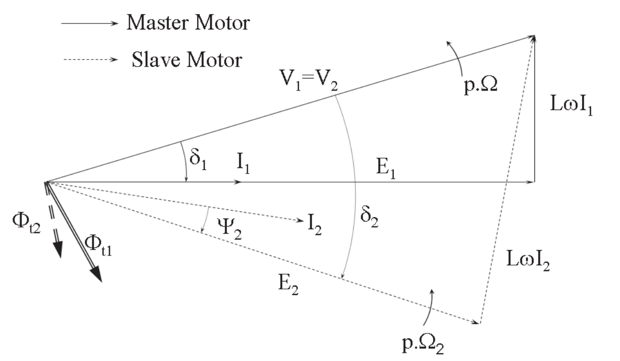
Regarding the magnetic flux Φ_t, it is composed by the rotor flux and the established by induction flux. If $T_{L1} < T_{L2}$, the flux due to the induction reduces the total flux in the slave motor. With $T_{L1} > T_{L2}$ it is the contrary: the motor which is not controlled has the highest total flux. This case is better. The slave machine has thus a magnetic induction effect.

The diagrams are drawn in steady state. A study of the system stability is thus done with a variation of the load torque. If the electrical pulsation $\omega_S = p.\Omega$ increases, the variation of the mechanical speed of the slave machine $\omega_2 = p.\Omega_2$ does not change instantaneously. The mechanical response time is indeed lower than the electrical.

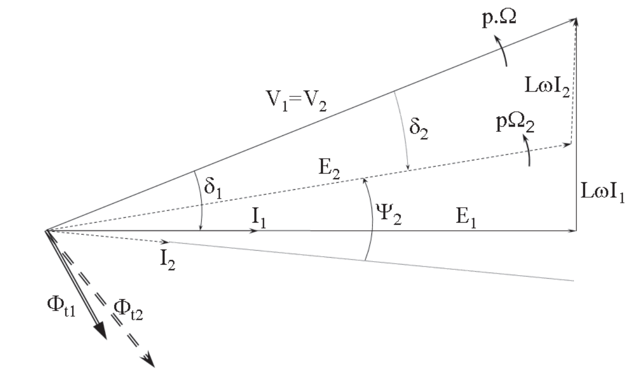
If $T_{L1} < T_{L2}$, the Ψ_2 angle is increasing. The torque of the machine is decreasing and thus the rotor is slowing down. This decrease of the speed involves a growth of the angle between the stator and the rotor. The torque is again decreasing. This phenomena happens until the stall consequently, the mechanism is unstable.

If $T_{L1} > T_{L2}$, the Ψ_2 angle is decreasing. The torque is then increasing and the motor is accelerating. The synchronism can be found again. The mechanism is stable.

The criterions concerning the current, the flux and the stability converge to the same conclusion: to assure the good mechanism it is necessary to control the machine with the highest load torque. It corresponds to the vectorial diagram represented Fig. 7(b)



(a) Case 1 - $T_{L1} < T_{L2}$



(b) Case 2 - $T_{L1} > T_{L2}$

Fig. 7. Vectorial diagram for 2 PMSM plugged in parallel

C. Choice of the master machine

The goal of the proposed strategy is that the controlled machine (the master) is the one which has the highest load torque. It is however necessary to control both machines because the load torques T_{L1} and T_{L2} can vary and are not controlled. It has been previously demonstrated that with $\Psi_1 = 0$, $T_{L1} > T_{L2} \Longrightarrow \delta_1 > \delta_2$. The voltage V is common with the two machines so to compare δ_1 and δ_2 corresponds to compare the two e.m.f angles. Those e.m.f are linked to the magnet, which means that the rotor positions θ_1 and θ_2 can be used to compare the δ angles: $\delta_1 + \theta_1 = \delta_2 + \theta_2$ so when $\delta_1 > \delta_2$; $\theta_1 < \theta_2$. The θ_i rotor positions are already used for the auto-pilotage, so no complementary sensor is needed. Both positions are compared to create a signal called ”Enable”. One of the two PMSM controller is then chosen, depending on the value of this signal. This system is described in Fig. 8.

To create the Enable signal, a simple comparator is used. Both θ_i positions are the majority of the time quite similar so $\theta_2 - \theta_1 \approx 0$. There can be however slight load torque variations. Those variations have not to be considered if they are too slight so an hysteresis is added after the comparator.

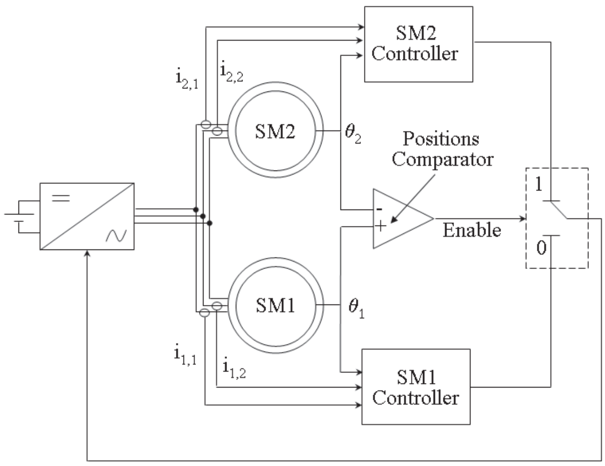


Fig. 8. Principe for the choice of the master machine

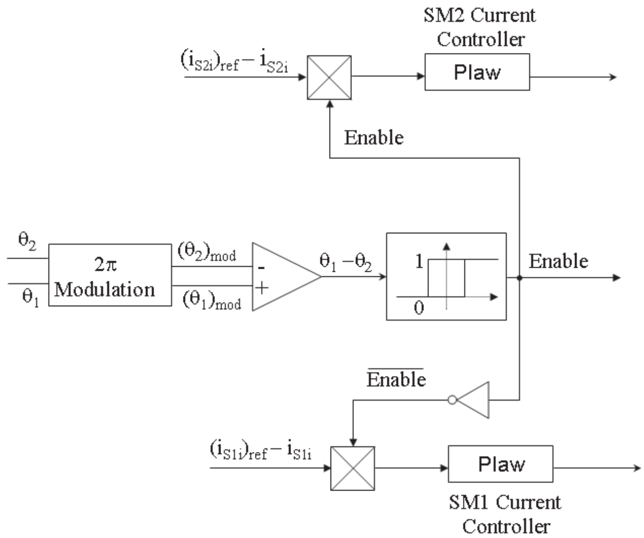


Fig. 9. Detail of the position comparator

After hours of functioning, the θ absolute rotor position can tend to infinite. The positions chosen to compare the θ_i angle is then the ”modulo 2π position”. A logic combination which allows to compare the two positions 2π modulated is integrated in the system. Moreover, with such a system, the control loop for the slave motor is an open-loop so its anti windup is saturated [14]. When the Enable value changes, the slave motor becomes master whereas its regulation value is saturated. Consequently, a current pick happens just after the master-slave change. To avoid this phenomenon the Enable signal cancels the current reference value when its regulation loop is open. This position comparator is depicted in Fig. 9.

D. Simulation

All the simulation are made under the Saber software. Each of the machines is controlled as described in Fig. 2 and the load torque is integrated into the machine model with the load

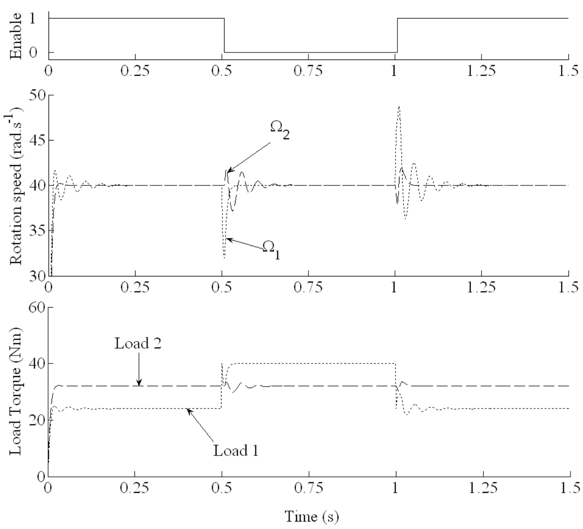


Fig. 10. Speed variation depending on the load torque

equation (4):

$$T_L = a.\Omega + b.c.\Omega \tag{4}$$

where c is a time varying binary value. The load of each machine can then be separately changed depending on the time. The Enable signal depends on the position comparison. If Enable=0, PMSM1 is controlled and if Enable=1, PMSM2 is the master machine.

IV. Simulation Results

A. Speed control

In this case, a change of load is simulated. For PMSM2, the load torque T_{L2} is constant and equal to the nominal torque T_n whereas for PMSM1, the load torque T_{L1} is successively lower higher and lower than this nominal value (the value is $T_n \pm 25\%$). For this, the parameters a et b corresponding to the Ω proportional coefficients have different values. For the PMSM2 this term is constant ($b = 0$) and for the PMSM1 it is changing with the time ($b \neq 0$). According to the chosen control strategy, the machines number 2, 1 and 2 are so controlled in this order.

Fig. 10 represents the variation of the rotation speed for the two motors and Fig. 11 represents the current variation versus the time.

For $t \in [0s; 0.5s]$ $\quad T_{L1} = 0.6\Omega; \quad T_{L2} = 0.8\Omega$
For $t \in [0.5s; 1s]$ $\quad T_{L1} = 1\Omega; \quad T_{L2} = 0.8\Omega$
For $t \in [1s; 1.5s]$ $\quad T_{L1} = 0.6\Omega; \quad T_{L2} = 0.8\Omega$

In Fig. 10, it can be seen that the load variation leads to the change of the enable signal. During the steady state the velocity is exactly the same for the both motors. The oscillations observed specially for the PMSM1 ($\pm 15\%\Omega_n$ with Ω_n the nominal rotation speed) are due to the fact that the load appears suddenly and its change is important ($\pm 50\% T_n$).

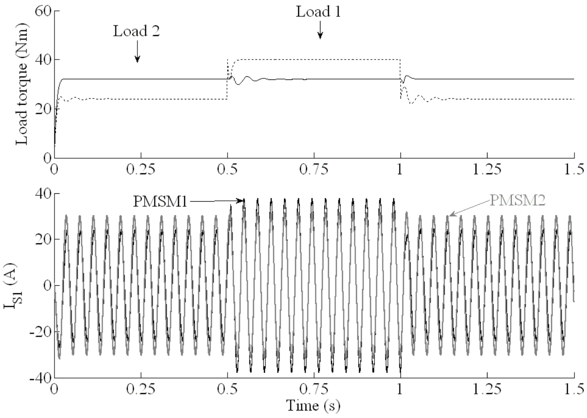


Fig. 11. Current variation depending on the load torque

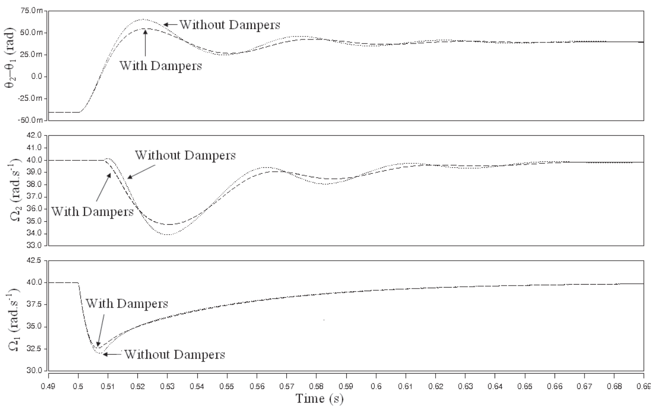


Fig. 12. Dampers effects during the transient state

As it can be seen on Fig. 11, the maximum intensities produced by the machines are directly proportional to the load torque. A torque (i.e current) regulation is obtained with only one machine under control and the master machine is always the one with the highest load torque i.e the one with the highest current. This simulation has been done with a high variation of the nominal torque for PMSM1 so its current variation is important ($\Delta I = 30\% I_n$ with I_n the nominal current value). The load appears only during 0.5s so this high intensity is allowed in the machine.

B. Dampers simulation

The oscillation can be minimized with dampers which create an opposition to the fast flux variation in the rotor. The model of the dampers are established in the (d,q) axes and added in the models of the PMSM [15]. Their effect is represented for the first transition (t=0.5s) in Fig. 12. As depicted in this figure, the oscillations are minimized.

C. Hysteresis influence

To see the hysteresis influence on the position comparison, some simulations are done with different values of this hys-

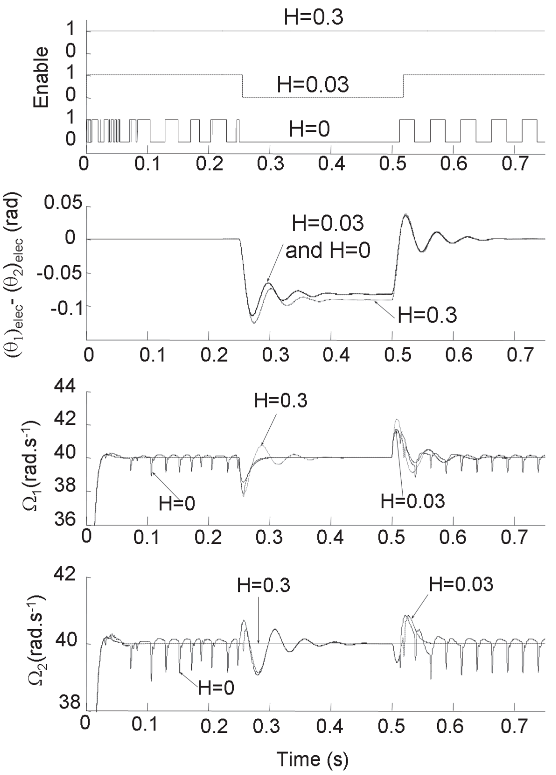


Fig. 13. Hysteresis influence on the position comparison

teresis. The chosen load torque values are quite similar for both machines.

$$\begin{aligned} \text{For } t \in [0s; 0.25s] \quad & T_{L2} = 0.8\Omega = T_n;\ T_{L1} = T_{L2} = T_n \\ \text{For } t \in [0.5s; 1s] \quad & T_{L2} = 0.8\Omega = T_n;\ T_{L1} = 1.25T_n \\ \text{For } t \in [1s; 1.5s] \quad & T_{L2} = 0.8\Omega = T_n;\ T_{L1} = T_{L2} = T_n \end{aligned}$$

The simulations presented in Fig. 13 are done for hysteresis values of H=0; H=0.03 and H=0.3 rad.

As it can be seen on Fig. 13, without hysteresis (H=0), little oscillations appear during the steady state. Those oscillation are due to the fact that the enable signal is continually changing when the load torque are similar i.e $\theta_2 - \theta_1 \approx 0$.

However, when the load changes, the mechanical response is not instantaneous. Consequently, the enable signal does not immediately changes and its transition appears only when $|\theta_2 - \theta_1| > H$. The motor which becomes normally master stays slave before the Enable signal change and its rotation speed consequently decreases. The H value should consequently not be too high but it should also not be too low. A compromise with H=0.03 rad is thus chosen.

V. Conclusion

It is possible to regulate a mono-inverter dual parallel PMSM system. The weight, the volume and the cost of system which use several machines like flaps in aeronautic can consequently be reduced. By comparing the rotor positions, no complementary sensor is needed to choose the master motor. After a transition phase, the choice change of the master motor leads to a steady state which insure the stability for both machines. A fine auto-pilotage is thus needed for the machines because the load is not controlled and can frequently change. The parametric variations in the motor are now studied and a sampled experiment is in progress.

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Appendix

Nominal values for the simulated motors:
$T_n = 32Nm$
$\Omega_n = 40rad.s^{-1}$
$I_n = 30A$
p=4
L=2.6 mH
M=1.105 mH
$R = 0.225\Omega$
$\Phi_M = 0.18Wb$
$f_0 = 3.10^{-3}Nm.s$
J=6.5.10$^{-3}Nm.rad^{-1}.s^{-2}$