Speed control of double stator synchronous machine supplied by two independent voltage source inverters

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Abstract: - In high power applications, power division methods for AC high power converters and machines are used. The rated power of the elementary converters and/or machines becomes lower when the number of converters and/or machines increases. Therefore, power switches with high switching frequency can be used. Then, the current and torque ripples would have theoretically lower amplitude. The speed control of a double stator synchronous machine supplied by two independent voltage source inverters, which is an application of power division, is studied in this paper. After presenting the system under consideration, three strategies of current control are treated. The speed control method is also discussed.

Key-Words: - Multi-converter, double stator machine, power division, current and speed control.

1 Introduction

Electrical propulsion in embarked applications like ships and aircraft requires high power machines with variable speed drives. In this field, AC machines are increasingly used. These machines can be supplied by GTO Voltage-Source Inverter (VSI). The disadvantage is the low commutation frequency of the GTO and consequently the important current and torque ripples. In order to reduce these ripples, it is necessary to use high commutation frequency semi-conductor devices [1],[2]. Several solutions based on power division can be envisaged.

Actually, in high power applications, association of multi-converters with multi-machines is developed. For economic reasons, these electric systems may share some resources in the energizing chain which imply some couplings between the various components. Taking into account these couplings, the system passes by a global approach of the set of the electric components connected to a same supplying source. The global system is defined then by the denomination 'Multi-converter Multi-machine System (MMS)' [3],[4]. It is composed of coupled subsystems which are going to interact between them. This paper treats the case of a magnetic coupling system which is the Double Stator Synchronous Machine (DSSM) supplied by two independent VSI. Switches with reduced power rating and higher switching frequency can therefore be used. The modularity of the used inverters, as well as the possibility of functioning with one or two inverters in service, makes this example attractive.

The paper is organized as follows. Section 2 is devoted to present the open loop control of the DSSM supplied by two VSI. In section 3, three current control strategies are defined. Using these strategies, simulation results of currents and torque waveforms are presented and analyzed in section 4. Section 5 treats the speed control of the system. Finally, conclusions are given in section 6.

2 Open loop control of the DSSM

The studied machine is composed of two stars; each one is formed of three Y connected windings. These stars can be shifted from each other by an electrical angle equal to 'γ' (Fig. 1). Each star is supplied by its own three phase VSI (Fig. 2). The rotor contains permanent magnets [5].

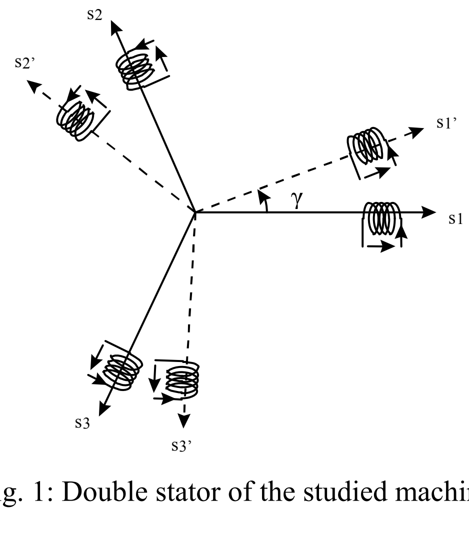

Fig. 1: Double stator of the studied machine.

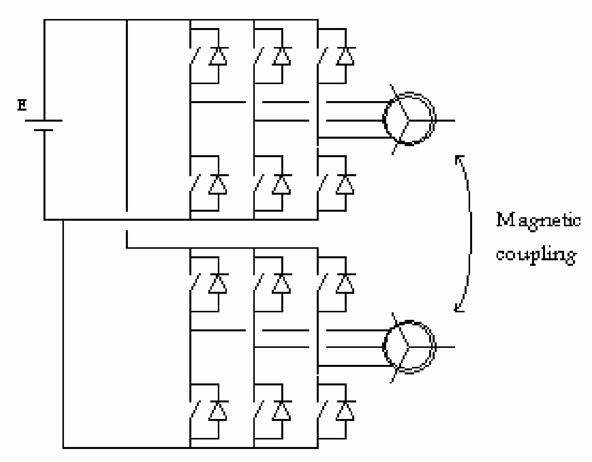

Fig. 2: DSSM supplied by two VSI

To simplify this study, it should be supposed that:
- The used machine is not saturated,
- Iron and all types of losses are neglected,
- The inductances of the machine are constant,
- The coils distributions are sinusoidal.

For the studied machine:

- i_k and i'_k are the currents flowing the k and k' phases of the two stators, with k = 1, 2 or 3,
- v_k and v'_k are the voltage across the k and k' phases of the two stators,
- e_k and e'_k are the emf of the k and k' phases of the two three phase windings, these emf are supposed to be sinusoidal,
- p is the number of pair of poles,
- ls is the coil inductance,
- r is the winding resistance,
- m.cos ξ is the mutual inductance between two windings delayed by an electric angle of ξ. The coefficient m is positive, $[m_{11'} = m.\cos(\gamma)]$.

The expressions of the voltage v_k and v'_k are:

$$\begin{cases} v_k = r.i_k + \dfrac{d\phi_k}{dt} + e_k \\ v'_k = r.i'_k + \dfrac{d\phi'_k}{dt} + e'_k \end{cases} \quad (1)$$

where ϕ_k and ϕ'_k are the generated flux in k and k' phases:

$$\begin{cases} \phi_k = (ls + \dfrac{m}{2}).i_k + \dfrac{3.m}{2}.\cos(\gamma).i'_k \\ \qquad - \dfrac{m.\sqrt{3}}{2}.\sin(\gamma).[i'_{k+1} - i'_{k+2}] \\ \phi'_k = (ls + \dfrac{m}{2}).i'_k + \dfrac{3.m}{2}.\cos(\gamma).i_k \\ \qquad + \dfrac{m.\sqrt{3}}{2}.\sin(\gamma).[i_{k+1} - i_{k+2}] \end{cases} \quad (2)$$

The electromotive force e_k and e'_k take the form:

$$\begin{cases} e_k = E.\sqrt{2}.\sin\left(\omega t - (k-1).\dfrac{2\pi}{3}\right) \\ e'_k = E.\sqrt{2}.\sin\left(\omega t - (k-1).\dfrac{2\pi}{3} - \gamma\right) \end{cases} \quad (3)$$

where ω is the electric speed.

The torque expression of the studied machine is:

$$\Gamma = \frac{p}{\omega}.\left[\sum_{k=1}^{3}(e_k.i_k + e'_k.i'_k)\right] \quad (4)$$

The proposed open loop control method applied to the used VSI is the technical Pulse Width Modulation (PWM) method. Figures 3 and 4 show the influence of the shifted angle on the current waveform. In fact, if the two stars are shifted by 30º, current ripples appear and can be dangerous for the two inverters and for the machine.

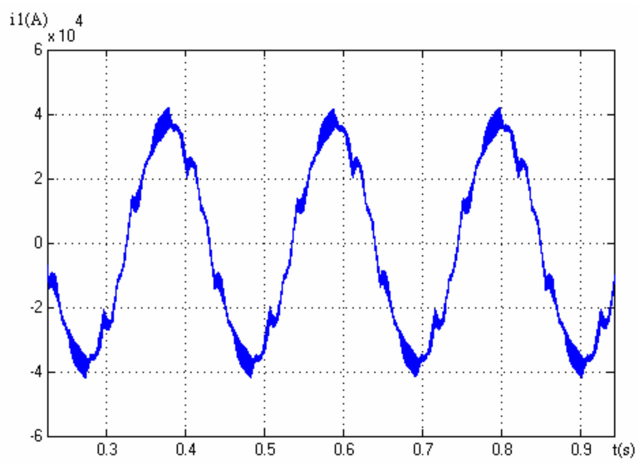

Fig.3: Stator current for non shifted stars.

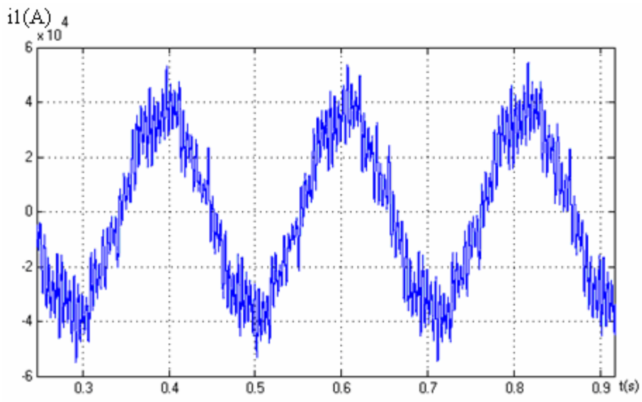

Fig. 4: Stator current for shifted stars.

These ripples, which appear only on the currents, do not affect the machine torque (Fig. 5 and Fig. 6).

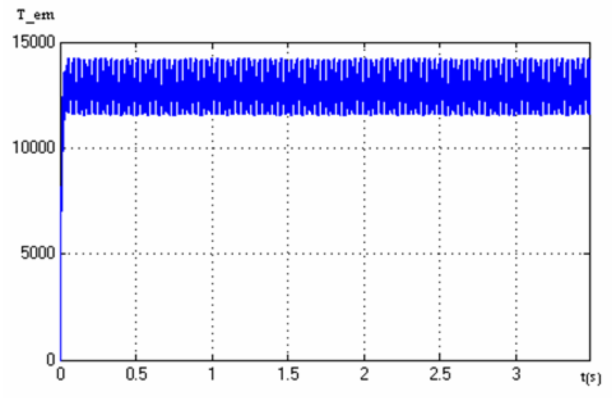

Fig. 5: Torque for non shifted stars.

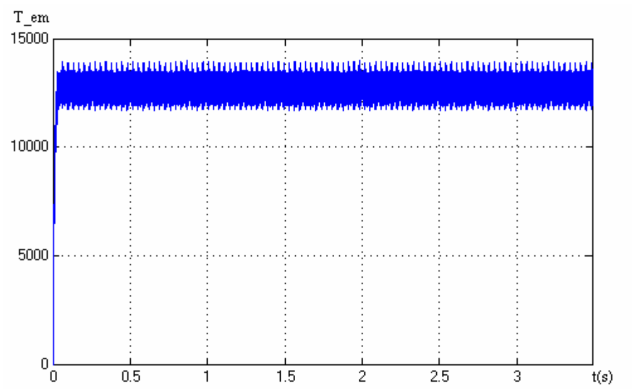

Fig. 6: Torque for shifted stars by 30 degrees

The power division by using multi-star machines supplied by independent PWM VSI can not be applied except if the magnetic coupling between stars is weak [1],[5]. Or in other case, the applied voltages to the homologous phases of the star windings should be instantaneously the same and the star windings should not be shifted [6],[7].

3 Current control strategies

Consider the example of the DSSM supplied by two independent voltage source inverters. To remove or to minimize the phase current ripples which appear when the two star windings are shifted (Fig. 4), it is necessary to apply a control method on the system. The used method is the vector control. Current proportional regulator is used. The principle of this control method is defined according to three strategies:

1. Master-slave current control,
2. Average current control,
3. Independent current control.

In this section, these three control strategies will be applied to the Double Stator Synchronous Machine (DSSM) currents, therefore, indirectly to the machine torque.

3.1 Master-Slave current control

It consists in choosing one three phase windings as master; the other one will be the slave. In this study, the first star windings (a_1, b_1, c_1) is the master and the second windings (a_2, b_2, c_2) is the slave (Fig. 7). This strategy aims to control the three phase currents of the master windings. The slave currents are not controlled. Therefore, the slave doesn't contribute to the regulation. But, as these two star windings are magnetically coupled, therefore, the ripples which appear in the slave currents should have important influence on the master currents. Then, these currents are hardly regulated. For that, it is not preferable to use this master-slave strategy in current control.

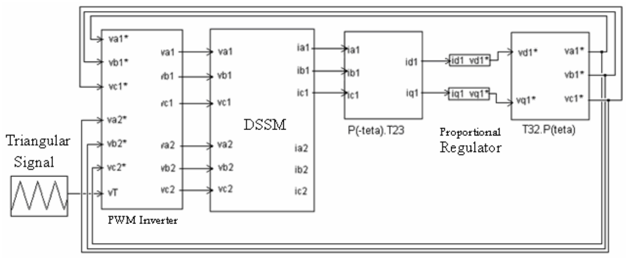

Fig. 7: Master-slave current control.

3.2 Average current control

It consists in calculating the average currents of the Park currents of the two star windings and regulates these average currents. In effect, the three phase currents of each star are transformed to Park currents, i_{d1} and i_{q1} for the first star, i_{d2} and i_{q2} for the second one. Then, the average currents of i_{d1} and i_{d2}, and that of i_{q1} and i_{q2} are regulated separately (Fig. 8). These average values are used as inputs to the proportional regulators. This original strategy requires only two current regulators.

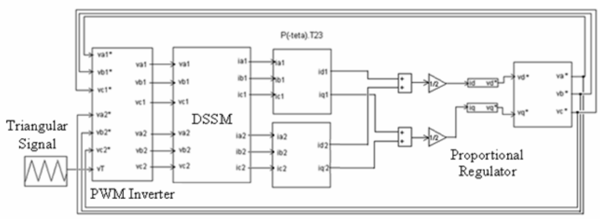

Fig. 8: Average current control.

3.3 Independent current control

In this strategy, the two star windings are considered as masters (Fig. 9). The Park currents of each star are regulated separately. The outputs of the used regulators of these two masters are connected to the corresponding references.

This strategy is very simple and reaches the objective in limiting the current ripples. Its disadvantage is the redundancy in the control loop. It requires four current regulators.

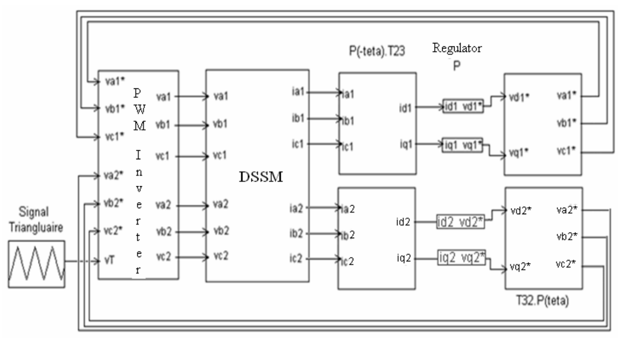

Fig. 9: Independent control.

4 Current control simulation results

The defined three strategies are applied to the Double Stator Synchronous Machine (DSSM). If the stators are none shifted, these strategies give the same results; therefore, they can not be compared.
To evaluate the difference between these strategies, a 30° shifted angle between the two stators of the studied machine is used. This machine is supplied by two independent three phase VSI.
Figure 10 shows the phase currents obtained by applying an open loop control.
When the system functions in the master-slave strategy, the VSI references of the slave are not shifted by 30°, therefore, the phase currents contain ripples with high magnitude (Fig.11).
The simulation of the system using the average current strategy contributes to the presence of small ripples in the currents waveforms (Fig. 12), and that due to the same VSI references used in this control strategy.
Applying the independent control method on each stator, the ripples nearly disappear from the current waveforms (Fig. 13).
As conclusion, if the two stators of the studied machine are not shifted, any of these three control strategies can be used, but if the two stators are shifted, therefore, it is necessary to use the independent control strategy in order to protect the high power system (inverters and machine) from any damage.
Figure 14 represents the torque waveform of the studied machine obtained by applying an open loop control. By using the independent current control, the ripples that appear on the torque waveform decrease (Fig. 15) as result of the current control presented in figure 13.

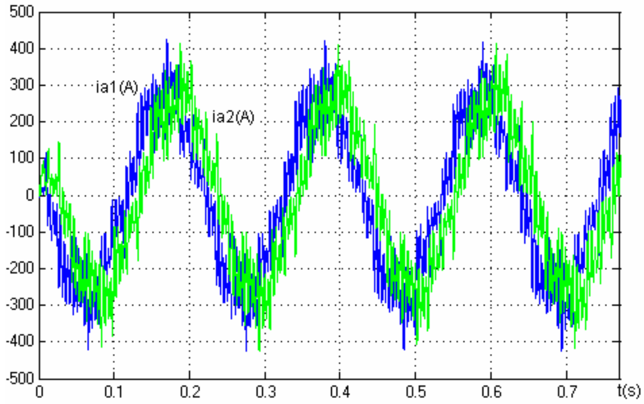

Fig. 10: Currents for an open loop control.

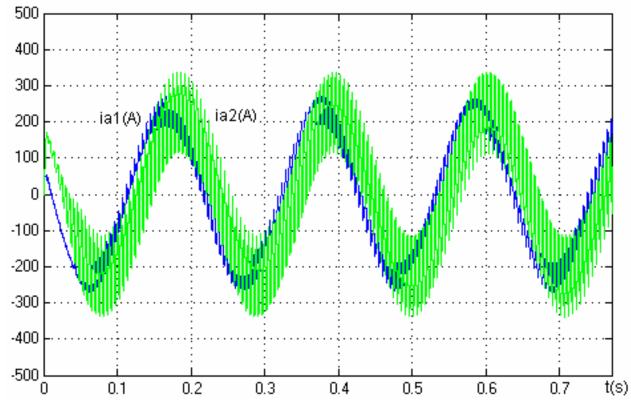

Fig. 11: Currents for the master-slave control.

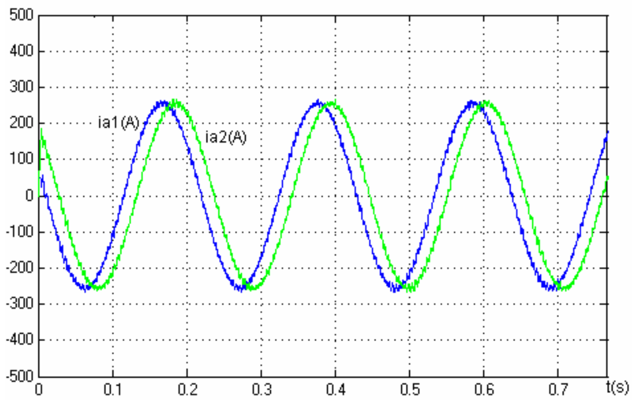

Fig. 12: Currents for the average current control.

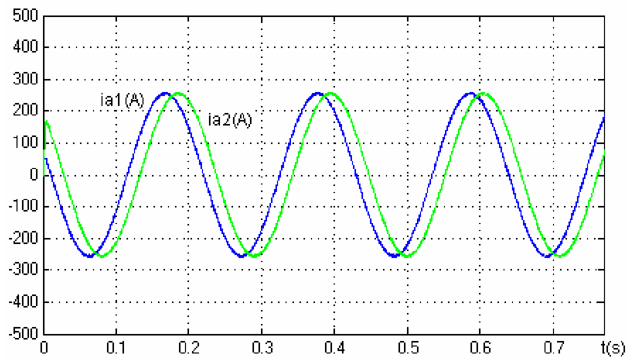

Fig. 13: Currents for the independent control.

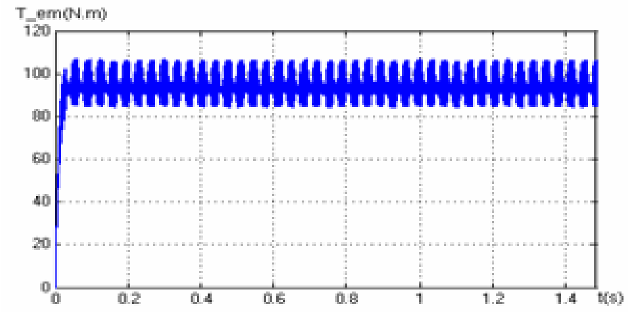

Fig. 14: Torque for an open loop control.

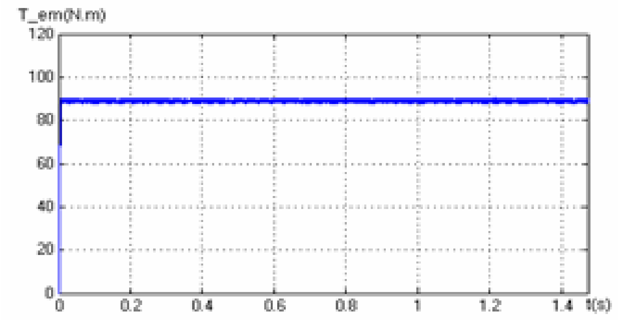

Fig. 15: Torque for the independent control.

5 Speed control

In general, electrical motor speed control has been widely treated in the literature [8], [9], [10]. In this paper, the vector control is used in order to control the speed of the studied machine. The mechanical equations corresponding to this machine are:

$$\begin{cases} T_m - T_L = J.\dfrac{d\Omega}{dt} \\ \omega = p.\Omega \\ \theta = \omega.t + \theta_0 \end{cases} \quad (5)$$

where:

- T_m and T_L are the machine and load torques,
- J is the moment of inertia,
- Ω is the mechanical speed,
- p is the number of pair of poles,
- θ is the electrical position angle. It is reported to the first phase of the first stator.

In the speed closed loop, a PI regulator is placed:

$$PI = K_1.(1 + \frac{K_2}{\tau.s}) \quad (6)$$

where:

- τ is the mechanical time constant,
- K_1 and K_2 are the regulator constants.

By using the strategy of independent current control, discussed in sections 3 & 4, the speed will take the waveform illustrated in figure 16.

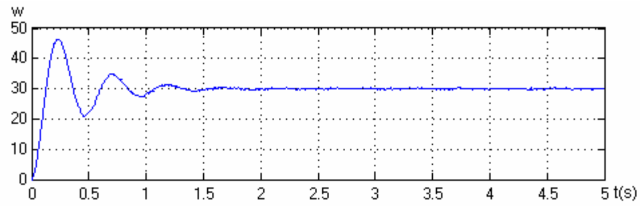

Fig. 16: Speed of the studied machine.

6 Conclusion

In this paper, power division in high power application is discussed. The treated example was the case of a double stator synchronous machine supplied by two independent voltage source inverters. Ripples appear on the current waveforms if the two stars are shifted. These ripples depend on the magnetic coupling existing between the two stators. To eliminate these ripples, these two star windings should not be shifted or the magnetic coupling existing between them should be of weak value.

If the two star windings of DSSM are shifted, three control strategies are used to regulate its currents and torque. The master-slave current control is not able to protect the system from ripples which appear on the currents and on the machine torque. For the average current control, only two current regulators are required, and the ripples are attenuated. Simulation results underline the importance of the independent current control strategy in eliminating these ripples. The disadvantage of this strategy, compared to the second one, is that it requires four current regulators. In the last section, the speed regulation of the studied machine was treated by using the independent current control strategy.

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