Enhanced Torque Control of a PMSM Supplied by a Four-Leg Voltage Source Inverter Using the Third Harmonic

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***Abstract*—In this paper, a four-leg Voltage Source Inverter is used to supply a three-phase star-connected permanent magnet synchronous machine, the fourth leg being clamped to the neutral point. We find the current references that allow smooth torque operation and minimal Joule losses in the presence of an electromotive force third harmonic component. Then we analyze the advantages of the proposed topology in terms of torque increasing and DC link optimization.**

I. Introduction

The aeronautic industry requires electrical actuators with a high torque-to-mass ratio to reduce the total weight of the embedded equipment, leading permanent magnet synchronous machines (PMSM) really attractive in this domain.

Another requirement of the aeronautic applications concerns the reliability of the system. To avoid a "full-redundant" topology, fault-tolerant drives have been investigated for several years [1]-[2]. It has been shown that a four-leg voltage source inverter (VSI) supplying a three-phase machine provides fault-tolerance against most of the inverter faults. In [3] and [4], this fourth leg is connected to the neutral point of the machine and homopolar current is used to allow carrying on the drive in the post-fault operation.

As we dispose of a fourth leg inverter that is connected to the neutral point of the machine, it becomes possible to enhance the drive performance in the healthy mode of operation. Indeed, if we consider a three-phase star connected machine supplied through a three-leg VSI, we need only two degrees of freedom (DOF) for the control of the currents since the homopolar current cannot flow. It remains one DOF for the optimal use of the DC-bus voltage. Adding a fourth leg clamped to this neutral point, the new fourth DOF will be used to control this homopolar current.

This paper presents a method of control taking advantage of this additional DOF in the healthy mode of operation. For this purpose we assume that the electromotive force induced in the stator coils contains a third harmonic component that, combined with third harmonic current, produces an additional homopolar torque. As the homopolar torque is known to be pulsating, the proposed control algorithm is dedicated to minimize this pulsating torque. We also show that the algorithm is optimal for the torque per ampere ratio. Then we analyze the obtained torque per ampere capacity and the DC link optimization in function of the third-to-first harmonic component ratio of the electromotive force.

II. PMSM Drive Model

We consider a drive composed of a permanent-magnet synchronous machine and a four-leg inverter. The fourth leg is connected to the neutral point of the machine and allows imposing continuously the neutral point voltage V_n. We assume that the electromotive force induced by the magnets in the stator coils only has a fundamental and a third-harmonic component with synchronized zero crossings. The model equations for a non-salient machine in the *abc* reference frame are thus given by:

$$\begin{bmatrix} V_a - V_n \\ V_b - V_n \\ V_c - V_n \end{bmatrix} = R_s \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + [L_s] \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} , \quad (1)$$

$$I_n = -(I_a + I_b + I_c) \quad (2)$$

where R_s is the stator resistance and $[L_s]$ is the stator inductance matrix.

Expressed in the *dqh* rotor reference frame, the model becomes:

$$\begin{bmatrix} V_{dn} \\ V_{qn} \\ V_{hn} \end{bmatrix} = R_s \begin{bmatrix} I_d \\ I_q \\ I_h \end{bmatrix} + \begin{bmatrix} L_{dq} & 0 & 0 \\ 0 & L_{dq} & 0 \\ 0 & 0 & L_h \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_d \\ I_q \\ I_h \end{bmatrix} + \begin{bmatrix} E_d \\ E_q \\ E_h \end{bmatrix} \quad (3)$$

where

$$\begin{bmatrix} E_d \\ E_q \\ E_h \end{bmatrix} = \omega_e \begin{bmatrix} -L_{dq} I_q \\ L_{dq} I_d + \psi_1 \\ \psi_3 \sqrt{2} \sin(3\theta_e) \end{bmatrix} \quad (4)$$

and ω_e is the electrical speed, ψ_1 and ψ_3 are the flux linkages related respectively to the first and the third harmonics.

The expression of the electromagnetic torque is:

$$T_{em} = \frac{3}{2} npp \big(\psi_1 I_q + \psi_3 \sqrt{2} \sin(3\theta_e) I_h \big) \quad (5)$$

where npp is the number of pole pairs.

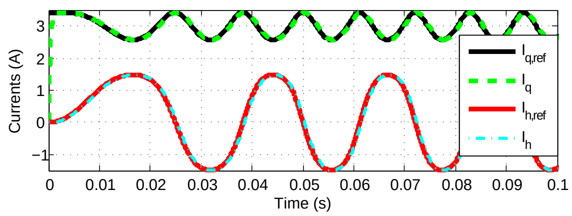

Fig. 1. Current references and real currents for a constant reference torque $T^*_{em} = 5\,Nm$; $w_e = 100\,rad/s$.

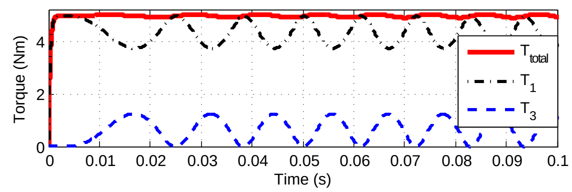

Fig. 2. Electromechanical torques produced by the fundamental currents (T_1), the homopolar currents (T_3) and the sum of both (T_{total}); $T^*_{em} = 5\,Nm$; $w_e = 100\,rad/s$.

III. Proposed Method of Control

It will be shown in the paper that for a given reference torque T^*_{em}, the optimal current references are:

$$\begin{cases} I_d^* = 0 \\ I_q^* = k(\theta_e)\psi_1 T^*_{em} \\ I_h^* = k(\theta_e)\psi_3\sqrt{2}\sin(3\theta_e)T^*_{em} \end{cases}, \tag{6}$$

with

$$k(\theta_e) = \frac{2}{3\,npp\left(\left(\psi_1\right)^2 + \left(\psi_3\sqrt{2}\sin(3\theta_e)\right)^2\right)} \tag{7}$$

where θ_e is the electrical position and $k(\theta_e)$ is a coefficient that is function of the electrical position (7).

As we can see from (6) and (7), the current references are not constant. Then we lose the principal advantage of the Park transformation that provides constant current references that are easy to achieve with simple PI controllers. Hence, the performance of the current loops depends on the electrical frequency of the currents and on their bandwidth.

Figs. 1 and 2 show some simulation results. They respectively show the currents with their references and the torques produced by the fundamental currents (T_1), the homopolar currents (T_3) and the sum of both (T_{total}). If the frequency of the currents increases, ripple in the electromechanical torque will appear.

IV. Analysis of the Enhanced Torque per Ampere Capacity

With the proposed method of control, we can increase the electromechanical torque for a given amount of Joule losses in the stator winding. Fig. 3 shows the normalized optimal torque per ampere in function of the ψ_3/ψ_1 ratio, keeping ψ_1 constant. Also plotted on this figure is the normalized peak value of the electromotive force as a function of ψ_3/ψ_1. Two

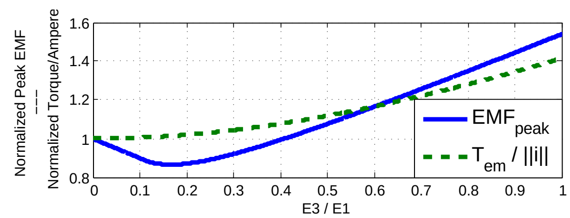

Fig. 3. Normalized peak value of the emf and torque per ampere as a function of the third-to-first harmonic ratio in the emf.

ratios are particularly interesting. The first is the minimum of the emf curve that shows that a ratio 16.6% of third harmonic leads to a decrease of 13.4% of the peak value of the emf. The second ratio is $\psi_3/\psi_1 = 40.8\%$: it shows that for the same peak emf value, the torque per ampere can be 8% higher.

V. Optimization of the DC Link

As mentioned above, the system has four degrees of freedom. Three are used for the regulation of the *dqh* currents. The last one concerns the neutral point voltage. Applying (8) as neutral voltage command allows to make symmetric the reference phase voltages and thus allows to optimize the DC link voltage as is done in [5].

$$V_n = \frac{-\left(max(V_{abc}) - min(V_{abc})\right)}{2} \tag{8}$$

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VI. Conclusion

We presented a method to enhance the torque per ampere capability of a permanent magnet synchronous machine supplied by a four-leg inverter. This is achieved by using the fourth degree of freedom of the system to control the homopolar currents. Then we analyzed the advantages in terms of torque per ampere and DC link optimization. Then we pointed out two ratios of the third-to-first electromotive force harmonic component that are particularly interesting.

Acknowledgment

The authors would like to thank the F.R.I.A. for the financing of this research project.

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