Optimum use of DC bus by fitting the back-electromotive force of a 7-phase Permanent Magnet Synchronous machine

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Keywords

Multiphase drive, Multi-machine system, Converter machine interactions, Harmonics.

Abstract

This paper deals with design constraints of a 7-phase Permanent Magnet Synchronous Machine (PMSM) supplied by a 7-leg Voltage Source Inverter. The optimum back electromotive force waveform is determined in order to get maximum torque for a given DC bus voltage.

Introduction

Multi-phase DC brushless machines suffer from an apparent higher number of switching devices than 3-phase ones. Nevertheless, in high power applications such as electrical ship [1]-[2] or low voltage/high current applications such as on-board systems (traction) [3]-[5], this factor is not so obvious: use of high current devices implies high heat dissipation capabilities especially with high frequencies. Then it is common to use either parallel converters or parallel/serie device associations.

Moreover, when reliability is required such as in aircraft [6], in marine applications [7]-[8] and in offshore variable speed wind generators, multiphase drives [10]-[11] must be considered as an alternative to 3-phase multi-level converter drives whose reconfiguration in safety mode is not obvious.

In this paper, an axial double-rotor 7-phase virtual prototype is considered and has been modelled with 3D-finite element method. The global aim is to fit the machine to its 7-leg Voltage Source Inverter (VSI) in order to optimize the global drive.

For 3-phase machines supplied by 3-leg VSI, the optimum use of the DC bus voltage has been widely studied [12]. It consists in injecting a third harmonic component in the voltage references of the VSI when triangle intersection method is employed or to use a space-vector modulation [13]. When the 3-phase machine is wye-coupled the injection of a third harmonic component has impact neither on the torque nor on the currents of the machine. For wye-coupled 7-phase machines supplied by 7-leg VSI (Fig. 1), the problem is quite all different. The injection of a third component implies currents and eventually torque components in the machine. A Multi-Machine modelling is used in the paper to prove and explain this difference. Nevertheless the injection of a third harmonic component remains interesting for an optimal use of the 7-leg VSI DC bus Voltage [14].

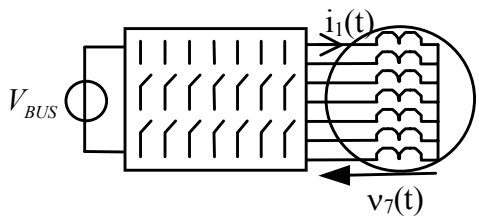

Fig. 1: symbolic representation of 7-leg PWM-VSI and wye-coupled 7-phase machine

The aim of this paper is to find necessary fitting of the machine in order to be able to inject a maximum third harmonic component in the reference voltages.

At first, a Multi-Machine modelling of a 7-phase axial permanent magnet machine is presented: it allows to transform a complex problem into simpler ones. Then, for a given machine and a maximum value of the first harmonic voltage components, effects of injection of a third harmonic voltage component are studied: it appears that results depend on the harmonic spectrum of the back-electromotive force. Finally, thanks to the Multi-Machine modelling, machine design constraints are deduced in order to take maximum advantage of a third harmonic voltage component: extra torque is produced for a given DC bus voltage.

Multi-Machine vectorial characterization

Under assumptions of no saturation, no reluctance effects and regularity of design, a vectorial formalism allows to prove that a 7-phase machine is equivalent to a set of three magnetically independent fictitious 2-phase machines [15] named *M1*, *M2* and *M3*. Each equivalent machine is characterized by its inductance (resp. L_{M1}, L_{M2} and L_{M3}), resistance (resp. R_{M1}, R_{M2} and R_{M3}), and back-EMF (resp. $\overrightarrow{e_{M1}}$, $\overrightarrow{e_{M2}}$ and $\overrightarrow{e_{M3}}$). The torque of the real machine T, is the sum of the torque of these three machines T_{M1}, T_{M2} and T_{M3}. The 7-leg VSI can also be decomposed into three fictitious VSI electrically coupled by a mathematical transformation Concordia's type [15]. A fictitious VSI is characterized by a set of space phasors as it is the case for 3-leg VSI (with the usual hexagonal representation).
The equivalence is based on a generalized Concordia transformation characterized by the $[C_7]$ matrix:

$$[C_7]=\sqrt{\frac{2}{7}}\begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 & 1 & 0 & 1 & 0 \\ \frac{1}{\sqrt{2}} & \cos\frac{2\pi}{7} & \sin\frac{2\pi}{7} & \cos\frac{4\pi}{7} & \sin\frac{4\pi}{7} & \cos\frac{6\pi}{7} & \sin\frac{6\pi}{7} \\ \frac{1}{\sqrt{2}} & \cos\frac{4\pi}{7} & \sin\frac{4\pi}{7} & \cos\frac{8\pi}{7} & \sin\frac{8\pi}{7} & \cos\frac{12\pi}{7} & \sin\frac{12\pi}{7} \\ \frac{1}{\sqrt{2}} & \cos\frac{6\pi}{7} & \sin\frac{6\pi}{7} & \cos\frac{12\pi}{7} & \sin\frac{12\pi}{7} & \cos\frac{18\pi}{7} & \sin\frac{18\pi}{7} \\ \frac{1}{\sqrt{2}} & \cos\frac{8\pi}{7} & \sin\frac{8\pi}{7} & \cos\frac{16\pi}{7} & \sin\frac{16\pi}{7} & \cos\frac{24\pi}{7} & \sin\frac{24\pi}{7} \\ \frac{1}{\sqrt{2}} & \cos\frac{10\pi}{7} & \sin\frac{10\pi}{7} & \cos\frac{20\pi}{7} & \sin\frac{20\pi}{7} & \cos\frac{30\pi}{7} & \sin\frac{30\pi}{7} \\ \frac{1}{\sqrt{2}} & \cos\frac{12\pi}{7} & \sin\frac{12\pi}{7} & \cos\frac{24\pi}{7} & \sin\frac{24\pi}{7} & \cos\frac{36\pi}{7} & \sin\frac{36\pi}{7} \end{bmatrix} \quad (1)$$

Relationships between values of fictitious machines and real values (noted with subscripts 1, 2, …, 7) are then defined by:

$$\overrightarrow{i_{mach}}=\begin{bmatrix}0 & i_{M1\alpha} & i_{M1\beta} & i_{M2\alpha} & i_{M2\beta} & i_{M3\alpha} & i_{M3\beta}\end{bmatrix}^t=[C_7]^t\begin{bmatrix}i_1 & i_2 & i_3 & i_4 & i_5 & i_6 & i_7\end{bmatrix}^t \quad (2)$$

$$\overrightarrow{v_{mach}}=\begin{bmatrix}0 & v_{M1\alpha} & v_{M1\beta} & v_{M2\alpha} & v_{M2\beta} & v_{M3\alpha} & v_{M3\beta}\end{bmatrix}^t=[C_7]^t\begin{bmatrix}v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7\end{bmatrix}^t \quad (3)$$

Currents and voltages obtained using this transformation can be decomposed into three subsystems associated with the *M1*, *M2* and *M3* machines:

$$\begin{cases} \overrightarrow{v_{M1}} = \left[v_{M1\alpha} \quad v_{M1\beta} \right]^t \\ \overrightarrow{i_{M1}} = \left[i_{M1\alpha} \quad i_{M1\beta} \right]^t \end{cases} \quad \begin{cases} \overrightarrow{v_{M2}} = \left[v_{M2\alpha} \quad v_{M2\beta} \right]^t \\ \overrightarrow{i_{M2}} = \left[i_{M2\alpha} \quad i_{M2\beta} \right]^t \end{cases} \quad \begin{cases} \overrightarrow{v_{M3}} = \left[v_{M3\alpha} \quad v_{M3\beta} \right]^t \\ \overrightarrow{i_{M3}} = \left[i_{M3\alpha} \quad i_{M3\beta} \right]^t \end{cases} \tag{4}$$

A key of the problem is that each one of the 2-phase fictitious machine is characterized by an harmonic family (Table I) and a vectorial subspace S_k. The three subspaces are orthogonal each to other. It is this orthogonality which allows to introduce the concept of fictitious machine.

Table I: Harmonic characterization of fictitious machines for wye-coupled 7-phase machine

Fictitious 2-phase machines	Families of odd harmonics
M1	***1***, *13, 15, ..., 7h ± 1*
M2	***5***, *9, 19, ..., 7h ± 2*
M3	***3***, *11, 17, ..., 7h ± 3*

To get a synthetic representation, a graphical formalism (Energetic Macroscopic Representation: EMR) is used (see Appendix and Fig. 2). Interleaved triangles traduce a mechanical coupling between the three fictitious machines ($T=T_{M1}+T_{M2}+T_{M3}$). Interleaved squares traduce an electrical coupling: the three fictitious VSI are supplied by only one DC bus.

The voltage equations of these *M1* and *M3* machines are:

$$\begin{cases} \overrightarrow{v_{M1}} = R_{M1}\overrightarrow{i_{M1}} + L_{M1}\dfrac{d\overrightarrow{i_{M1}}}{dt} + \overrightarrow{e_{M1}} \\ \overrightarrow{v_{M3}} = R_{M3}\overrightarrow{i_{M3}} + L_{M3}\dfrac{d\overrightarrow{i_{M3}}}{dt} + \overrightarrow{e_{M3}} \end{cases} \tag{5}$$

The electromechanical conversion is traduced by equation (6):

$$\overrightarrow{e_{M1}}.\overrightarrow{i_{M1}} = T_{M1}\Omega \quad \overrightarrow{e_{M2}}.\overrightarrow{i_{M2}} = T_{M2}\Omega \quad \overrightarrow{e_{M3}}.\overrightarrow{i_{M3}} = T_{M3}\Omega \tag{6}$$

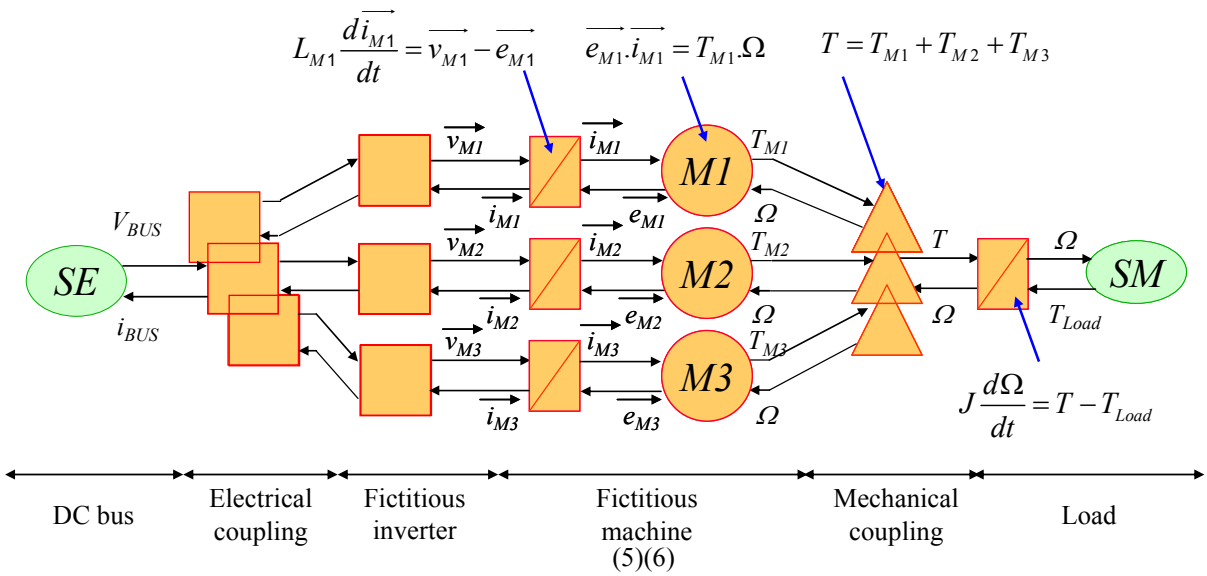

Fig. 2: Multi-Machine Energetic Macroscopic Representation of the 7-phase machine

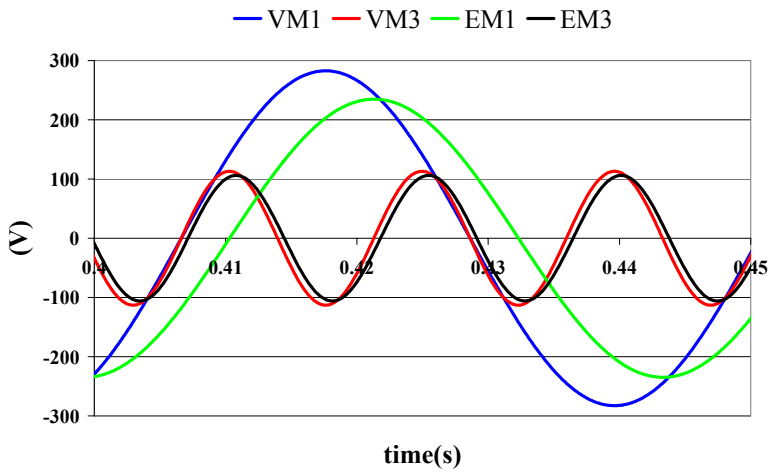

Fig. 8: For one phase, voltages v_{Mh} and back-EMF e_{Mh} of the *M1* and *M3* machines

We get finally from (22) and (23), $\overrightarrow{e_M} = \overrightarrow{e_{M1}} + \overrightarrow{e_{M3}}$, the total back-EMF of the real machine. Its projection relatively to the phase n°1 gives the back-EMF represented in Fig. 9

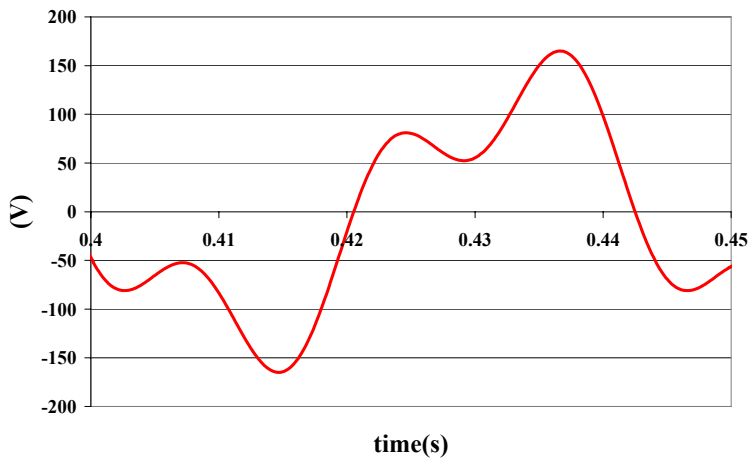

Fig. 9: required optimum back-EMF of phase n°1

Determination of extra torque

The extra torque T_{M3} developed by the *M3* machine is 25N.m, value which represents 20% of the nominal torque (125N.m) developed by the *M1* machine. Of course, extra Joule losses appears. Nevertheless, the imposed constraint of minimum losses ($\overrightarrow{i_M} = k\,\overrightarrow{e_M}$) allows to reduce their increase to 20%. If we impose to work with the same Joule losses, by reducing $\left\|\overrightarrow{i_{M1}}\right\|$ and $\left\|\overrightarrow{i_{M3}}\right\|$ in the same ratio, the torque increase is 9%.

Conclusions

It has been shown that, as for 3-phase machines, it was possible to take advantage of injection of a third harmonic component of voltage. The DC bus voltage is then better used, as it was with the 3-phase machines. Nevertheless, for optimum use of the DC bus voltage, the 7-phase machine must be fitted to the 7-leg VSI. With improvements of design of PM rotor, such as Halbach arrays, such optimal design can be considered. Of course, the obtained extra torque is a “booster” torque for transient states, unless improved heat dissipation is achieved.

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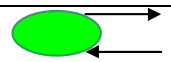
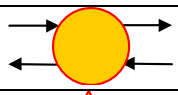
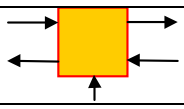
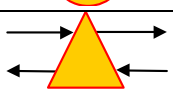
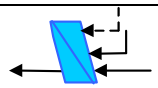
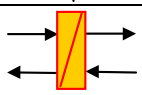
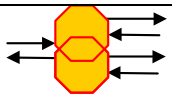
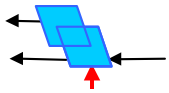
Appendix: Synoptic of Energetic Macroscopic Representation

	Source of energy		Electromechanical converter (without energy accumulation)		Control block without controller
	Electrical converter (without energy accumulation)		Mechanical Converter (without energy accumulation)		Control block with controller
	Element with energy accumulation		Coupling device (distribution of energy)		Control block with coupling criterion