Sensitivity of a 5-phase Brushless DC machine to the 7th harmonic of the back-electromotive force

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Abstract—This paper presents a vector control of a 5-phase drive composed of a 5-leg Pulse Width Modulation (PWM) Voltage Source Inverter (VSI) supplying a permanent-magnet Brushless DC (BLDC) machine with trapezoidal waveform of the back-electromotive force (EMF). To achieve this control a Multi-machine Multi-converter model is used: the 5-phase machine is transformed into a set of two 2-phase fictitious machines which are each one controlled in a (d,q) frame as 3-phase machines with sine waveform back-EMF. In comparison with the 3-phase BLDC drives, the 5-phase ones present one particularity: a high sensitivity to the 7th harmonic of back-EMF. Experimental results show that the 7th harmonic of back-EMF, which represents only 5% of RMS back-EMF, induces high amplitude parasitic currents (29% percent of RMS current). The model allows to explain the origin of this sensitivity and how to modify simply the control algorithm. Experimental improvements of the drive are presented.

Index Terms—brushless, multiphase, 5-phase, drive control.

I. INTRODUCTION

Multi-phase drive systems have several advantages over conventional 3-phase ones [1]-[2] such as higher reliability and reduction of torque ripples. Multi-phase machines have been initially supplied from Pulse Amplitude Modulation Current Stiff Inverter (PAM CSI) [3]-[5]. In this case, a machine with 3-phase stars can be considered as the association of q 3-phase machines mechanically coupled on the same shaft. Each 3-phase fictitious machine is associated with one of the q stars. This decomposition is possible in spite of the magnetic couplings between the stars, because of one property of the PAM CSI drive: when there is commutation of a current in a star, the currents in the other stars have constant values. The mutual inductances between stars have no impact and the stars can be then considered as magnetically independent.

With Digital Signal Processor, it is now possible to use PWM VSI in multi-phase drives [6]-[8].

If vector controls of 3-phase BLDC machines are well known [9], it is not the case for multi-phase ones, particularly if the waveform of back-EMF is trapezoidal. PWM-VSI requires a much more precise modeling than PAM CSI: it is no more obvious to decompose the multi-phase machine into a set of 3-phase machines.

For six-phase induction machines, [10] has proposed a multiple reference frame analysis based on an orthogonal transformation. The natural frame (a,b,c,d,e,f) of the 6-phase machine is transformed into a set of three independent frames (o₁,o₂), (d,q) and (z₁,z₂) where dynamic equations of the machine are totally decoupled. When currents are sinusoidal, the planes (o₁,o₂) and (z₁,z₂) do not participate to electromechanical conversion. Recently, using the same transformation, [11] shows the possibility to improve torque density with the injection of a third harmonic current, harmonic which is relative to the plane (o₁,o₂). For 5-phase induction machines, similar transformations have been used to achieve a DTC control [7] or to drive with only a 5-leg VSI supply two series connected motors [12]. Multi-phase BLDC machines have been less studied [13]-[15] than multi-phase induction machines. In [13], torque density has been increased with 3rd harmonic current injection in a 5-phase synchronous reluctance motor drive.

In this paper, a 5-phase BLDC supplied by a 5-leg PWM-VSI is studied. Using a Multi-machine Multi-converter description, this drive is broken down into two fictitious machines which can be controlled independently. This specific modeling shows that the 7th harmonic of the EMF leads to important parasitic currents. Controls strategies are deduced from this analysis and experimental results are provided.

II. MODELING OF THE DRIVE

A. Equivalent set of two 2-phase fictitious drives

Under assumptions of no saturation and no reluctance effects, the vectorial approach developed in [16]-[19] allows to define the equivalence of a 5-phase wye-connected machine Fig. 1 to a set of two fictitious independent drives, each one being composed of one fictitious machine and one fictitious inverter.

Fig. 1. Symbolic representation of the 5-leg PWM-VSI and 2p pole 5-phase machine

The symmetry and the circularity of the stator inductance matrix are used to achieve the equivalence between the actual and the fictitious drives:

\[
[L_s] = \begin{bmatrix}
L & M_1 & M_2 & M_2 & M_1 \\
M_1 & L & M_1 & M_2 \\
M_2 & M_1 & L & M_1 \\
M_2 & M_2 & M_1 & L \\
\end{bmatrix}
\] (1)
more power devices. Thus, it yields energy distribution between electric and mechanical sources through coupled conversion chains, which can yield interactions (disturbances) between power structures. The MMS have to enable best power reparation with lower cost equipment.

The energy distribution is obtained by specific conversion structures [19]. These power components are common to several conversion chains. They are called coupling structures. A coupling conversion structure links an upstream device with many downstream one’s, or vice versa. Such structures are drawn by forms with intersections (Fig. 21).

The electric coupling is associated with electric converters. It corresponds to a common electric device of several converters (power switch, capacitor...). It leads to a common electric variable (voltage, current...).

The magnetic coupling is associated with electric machines.

The mechanical coupling is associated with mechanical converters.

![Fig. 21: Examples of coupling devices](image)

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**REFERENCES**


