Direct Torque Control of a Multi-phase Surface-Mounted Permanent Magnet Motor Drive: Application to a Five-phase One

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***Abstract*— This paper describes an investigation of direct torque control for multi-phase permanent magnet synchronous motor drives. First, using the Multi-machine Multi-converter System concept, a multi-phase drive is divided into a set of fictitious one or two-phase drives. Each reference voltage vector of a fictitious drive is then computed with a simple direct torque control (DTC) algorithm. Finally, the voltage vector of the real machine is computed according to reference voltage vector of each fictitious drive. Experimental results are presented for a 750W five-phase permanent magnet drive prototype.**

I. INTRODUCTION

Multi-phase machines possess several advantages over conventional three-phase ones as electrical power shared on more switches, higher frequencies and lower amplitude of torque time-harmonics, fault-conditions capabilities ... [1], [2].

If multi-phase machines are known since a long time, very few papers discuss DTC for multi-phase motors [7], [8].

Classical DTC schemes contain generally three parts [3], [4]:

- a torque hysteresis controller
- a stator flux amplitude hysteresis controller
- a look-up table which provides switches combinations according to torque and flux amplitude references.

Classical DTC implies a large voltage time-harmonic spectrum when using hysteresis controllers. Moreover, applied to multi-phase machine, it leads to a large look-up table difficult to achieve [7]. We propose then a DTC with no look-up table and a constant switching frequency.

First, using the Multi-machine Multi-converter System concept [5], the real drive is transformed into a set of simpler fictitious drives. Based on the extended Concordia transformation, it leads to the equivalence between the n-phase machine and a set of one or two-phase fictitious machines. Fictitious machines are totally magnetically independent and posses quantities directly composed of harmonic sets of the real machine.

Each reference voltage of a fictitious two-phase drive is calculated with a simple direct torque control (DTC). On each constant sample-time, the desired voltage vector is computed according to torque and amplitude references.

Finally, the reference voltage vector of the real machine is computed according to each fictitious voltage vector. The closest voltage vector according to the reference one is computed by a vectorial algorithm and applied to the machine. The overall control of the drive is then based on instantaneous quantities and offers a quick-response control. However, and particulary due to the leakage inductance, high harmonics currents are generated.

Algorithms for estimation of the stator flux of each fictitious machine is discussed according to [11] and [12].

Finally, simulation and experimental results are presented for a 750W surface-mounted permanent-magnet prototype machine supplied by a five-legs insulated gate bipolar transistor (IGBT) inverter.

II. MULTI-MACHINE MULTI-CONVERTER SYSTEM CONCEPT

In an orthonormal base B_n composed of the vectors $\{\overrightarrow{x_1^n}, \overrightarrow{x_2^n}, ..., \overrightarrow{x_n^n}\}$ it can be defined the voltage, current and stator flux linkage vectors:

$$\overrightarrow{v} = v_1\overrightarrow{x_1^n} + v_2\overrightarrow{x_2^n} + ... + v_n\overrightarrow{x_n^n} \quad (1)$$

$$\overrightarrow{i} = i_1\overrightarrow{x_1^n} + i_2\overrightarrow{x_2^n} + ... + i_n\overrightarrow{x_n^n} \quad (2)$$

$$\overrightarrow{\phi_s} = \phi_{s1}\overrightarrow{x_1^n} + \phi_{s2}\overrightarrow{x_2^n} + ... + \phi_{s3}\overrightarrow{x_n^n} \quad (3)$$

where q_k ($q = v, i, \phi_s$) is the quantity associated to the phase number k ($k = 1, 2, ...$).

These vectors are linked by:

$$\overrightarrow{v} = R\overrightarrow{i} + \frac{d\overrightarrow{\phi_s}}{dt} = R\overrightarrow{i} + \frac{d\overrightarrow{\phi_{ss}}}{dt} + \frac{d\overrightarrow{\phi_{sf}}}{dt} \quad (4)$$

where $\overrightarrow{\phi_{ss}}$ depends on $\overrightarrow{i}$ and $\overrightarrow{\phi_{sf}}$ depends on the rotor magnets.

In a great majority of cases, there are magnetic couplings between the phases of a multi-phase system and the relation

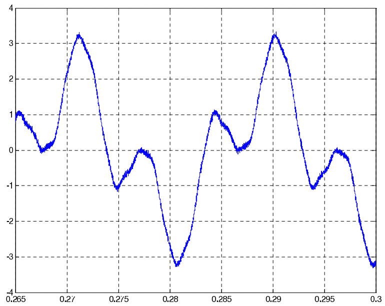

Fig. 12. Current in the real machine (simulation with inductances 10 times greater)

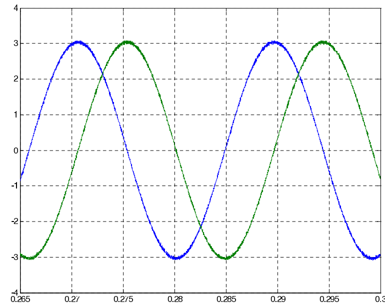

Fig. 13. Currents in the main machine (simulation with inductances 10 times greater)

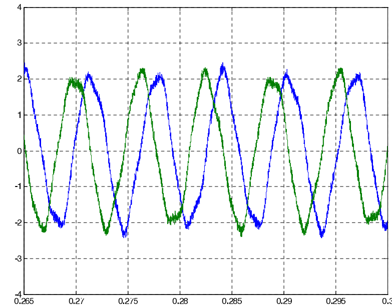

Fig. 14. Currents in the secondary machine (simulation with inductances 10 times greater)

Phase currents are then mainly composed of harmonics one and three. Independent controls of the two fictitious machine lead to a shift between harmonic one and three and then to possible high peak value of phase currents (see equation (9)). The reduction of this peak value can be achieved by a good choice of torque and flux references of the fictitious machines.

VII. Conclusion

In this paper DTC for multi-phase permanent magnet machine is investigated. Multi-machine Multi-converters System concept has shown that a complex drive can be transformed to more simpler ones.

Using an extended Concordia transformation, a five-phase machine is transformed into two fictitious two-phase machines. Each quantity of a fictitious machine is composed with an harmonic set of the real machine. Therefore a complex DTC is replaced with more simpler ones. With the five-phase machine, using a fixed sample-time and two PI controllers, it is possible to generate more torque using the third harmonic of magnet flux.

The large airgap of surface-mounted permanent magnet machine implies low inductances and therefore high switching frequency is necessary to avoid large ripples in phase currents. Moreover instantaneous control of voltage increase this trend. A solution can be to use Pulse Width Modulation for generating the required voltage. Nevertheless, dynamic response is reduced and the overall scheme control moves away from historic DTC one.

Experiments and simulation have shown, on condition that a good compromise has been maid between machine's time-constant and switching frequency, that DTC can be applied to multi-phase machines. With an accurate algorithm of stator flux estimation based on a voltage method, DTC of multi-phase permanent magnet machines can become sensorless ones. Further experimentation are in progress.

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