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Susceptibility of the winding switching technique for flux weakening to harmonics and the choice of a suitable drive topology

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ABSTRACT

The concept of winding switching for flux weakening of permanent magnet machines has recently evolved. Ideal sinusoidal flux and back-EMF of the machine are assumed for such a technique to demonstrate the flux weakening capability of the machine. In this paper, we present a real-world problem of a non-ideal sinusoidal back-EMF and investigate the susceptibility of this technique to the machine harmonics. Impacts of the harmonic contents on the field weakening capability of the machine under such conditions are explored. We show that the winding switching technique is particularly susceptible to 3rd order harmonics. Therefore, we investigate the impact of 3rd order harmonic components on the winding switching technique in details. Moreover, a suitable drive topology for the technique under harmonic conditions is investigated. Current control schemes for an ideal sine wave, a sine wave with fundamental and 3rd order harmonics, and square wave currents are discussed. All these drives are implemented, and the performance of the machine under these drives is compared. Simulation and experimental results are presented side by side to allow for analysis of issues mentioned above.

1. Introduction

Permanent Magnet (PM) machines are widely used in various applications due to their favorable characteristics such as high power density, high torque to inertia ratio, compact size and lack of external excitation requirement. However, high-speed operation of such machines presents challenges due to the constant PM excitation and ever increasing back EMF with increasing speed. Conventionally, negative d-axis current has been employed to counteract the PM flux and to reduce the back EMF in order to satisfy the inverter voltage limits. On the other hand, flux weakening using a negative d-axis current is a function of the d-axis inductance of the machine. A relationship between d-axis reactance and the flux weakening capability of the PM machines was derived in [1]. The flux weakening capability of the PM machines with respect to E/X_s was presented in [2], where E and X_s are per unit values of the back EMF and the synchronous reactance of the machine, respectively. In general, a large d-axis inductance is required for the flux weakening of the machine using a negative d-axis current [1,2]. However, non-salient PM machines exhibit low inductance characteristics due to their surface mounted low permeability PMs. Therefore, these machines are not considered good candidates for flux weakening operation [3]. Concentrated winding with increased number of slots and slot depth was adopted in [3,4] to increase the flux weakening capability of surface mounted permanent magnet (SMPM).

The synchronous speed of the electric machines is inversely related to the number of poles in the PM machines. Hence, pole changing techniques are also employed in order to increase the speed of the electrical machine. Initially, machines are operated with a high number of poles at low speed. Then, the machine operation is converted to a low number of poles with high speed operation. An electronic pole changing induction machine capable of changing pole numbers from four poles to two poles was presented in [5]. Whereas, an 8-pole to 4-pole changing PM machine was presented in [6]. A pole changing machine that changes the pole number in a 3:1 ratio (6-pole to 2-pole) was investigated in [7]. A technique for double layer 3-phase winding used in pole changing (4/6) was proposed in [8]. This technique also changed the star delta connection of the machine during pole changing. Machines with double rotors or double stators have also been investigated to associate low speed and high speed operation with alternate rotors or stators. A dual rotor flux switching machine was researched in [9], whereas dual rotor brushless radial flux and axial flux machines were investigated in [10,11]. Wang et al. presented a flux modulation machine with dual stator topology to obtain a

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wide constant power speed range of the machine [12]. Concept of radially sliding magnets where magnets are physically slid in order to achieve flux weakening of the machine was presented in [13]. However, these topologies complicate the machine structure and increase the size of the machine in order to accommodate the dual rotors or stators and the sliding magnets.

Winding switching technique provides an alternate way to achieve high speed operation in the machine. Conventionally, star, delta, series and parallel connections have been utilized in order to operate the machines at different speeds [14–16]. Recently, a novel promising winding switching technique was proposed in [17] and was experimentally validated in [18]. This technique provided flux weakening independent of the machine d-axis inductance unlike conventional techniques. However, this flux weakening technique assumed ideal flux and back EMF waveforms that are ideally sinusoidal without any harmonics. Practical machines, on the other hand, are not ideal and contain some harmonics. Moreover, this flux weakening technique divided the machine into two equal half windings and then reversed the polarity of half of the winding. This further exacerbated the harmonic conditions of the machine. It is, therefore, assumed that the flux weakening range of the machine under harmonics conditions will deviate from the ideal conditions.

Contributions of this paper are twofold. Firstly, we investigated harmonic contamination in the process of winding switching technique and its impact upon the field weakening range using winding switching technique. We showed that the flux weakening technique using winding switching is most likely to be affected by 3rd order harmonics. Therefore, the contributions of 3rd order harmonics were also investigated in details. Secondly, we examined the choice of a suitable drive topology while working under harmonic conditions. Current control schemes for the ideal sine wave ($sine_{(f)}$, *a sine wave with only a fundamental component*), a sine wave with a third order harmonic ($sine_{(f+3rd)}$, *a sine wave with a fundamental and third order component*) and square wave drives are presented. A prototype machine was tested using all these drives to compare the machine performance. The remainder of this paper is arranged as follows. Section 2 presents an overview of the winding switching technique followed by harmonic analysis of the machine during the process of winding switching in Section 3. Section 4 presents the current control strategy to operate the machine with different kinds of current waveforms. The choice of a suitable drive topology under harmonic conditions is presented in Section 5. A summary of the overall research work is presented at the end.

2. Overview of the winding switching technique for flux weakening

A winding switching technique for flux weakening of non-salient PM machines was proposed in [17]. A suitable drive topology with a sine wave current for this flux weakening technique was proposed and experimentally verified in [18], and is presented here for reference. The machine used for flux weakening using winding switching passes through three stages during flux weakening operation. In Stage 1, there is a three phase machine with a sinusoidal back EMF whose flux must be weakened for high speed operation. This is referred to as a basic three phase machine in [18]. In Stage 2, the winding of the basic three phase machine is divided into two equal sub-windings ABC and XYZ. Here, the winding XYZ is displaced from winding ABC by some angle δ. The machine is converted into a six phase configuration in this stage. The phase back EMFs of the two sub windings of the machine are given by (1) and (2).

$$E_a = E\sin(\omega_e t) \tag{1}$$

$$E_x = E\sin(\omega_e t - \delta) \tag{2}$$

Here, E_a and E_x are the phase back EMFs of phase A from winding ABC and phase X from winding XYZ, respectively. E is the magnitude of the EMF, whereas ω_e is the electrical angular velocity of the machine.

The machine is operated in a cumulative mode in this stage such that the flux of the XYZ winding adds to the flux of the ABC winding. The net air gap flux of the machine in this stage is equal to the net air gap flux of the machine in Stage 1. Therefore, the expression for the net back EMF of the machine during the cumulative mode of operation can be written as in (3).

$$E_{cum} = E\sin(\omega_e t) + E\sin(\omega_e t - \delta) \tag{3}$$

Here, E_{cum} is the net phase back EMF of the machine during a cumulative mode of operation that is actually equal to the back EMF of the basic three phase machine.

In Stage 3, windings of the machine are switched such that the polarity of winding XYZ is reversed. The machine operates in a differential mode, and the flux of winding XYZ is subtracted from the flux of winding ABC. The net phase back EMF of the machine in differential mode (E_{dif}) is given by (4)

$$E_{dif} = E\sin(\omega_e t) - E\sin(\omega_e t - \delta) \tag{4}$$

Flux weakening upon winding switching (fw) is defined as the ratio of the back EMF of the machine in cumulative mode to the ratio of the back EMF of the machine in differential mode and is given by (5)

$$fw = |E_{cum}|/|E_{dif}| \tag{5}$$

3. Harmonic analysis of the machine

The winding switching technique for flux weakening assumes an ideal sinusoidal back EMF without any harmonics except the fundamental component. However, in general, the real world machines are not ideal and contain some harmonic components in the back EMF. The effect of these negligible harmonics becomes pronounced when a three phase machine is converted into a six phase machine in Stage 2. The harmonic condition of the machine is further exacerbated when the polarity of half of the machine winding is reversed in Stage 3.

In this section, we analyzed the harmonic conditions of the machine step by step from Stage 1 to Stage 2 and then Stage 3. A 4-pole, 24-slot machine was used for this analysis where ABC and XYZ windings were displaced by an angle of $\pi/3$ radians (electrical). The flux weakening range for this case was calculated to be 1.73 using (5) [18]. A simulation model of the machine was developed in the Maxwell 2-D software for finite element analysis (FEM). Fig. 1(a) shows the simulation model of the machine wherein the six phase winding of the machine can be arranged to operate the machine in Stage 1, Stage 2 and Stage 3 configurations. A prototype machine was built and analyzed for harmonic contamination during the process of field weakening using winding switching. Fig. 1(b) shows the stator and the rotor of the prototype machine. As shown, twelve leads (two terminals for each phase) are coming out of the stator winding. These leads can be connected to operate the machine in Stage 1, Stage 2, and Stage 3. Both simulation and experimental models were evaluated at a base speed of 900 rpm. Rated torque of the machine was 7.01 Nm that decreased by an amount equal to the flux weakening of the machine during flux wakening operation. Analysis and discussion of the results are presented in the following subsections.