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UNBALANCED MAGNETIC PULL IN DUAL THREE-PHASE MACHINE

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This paper examines the emergence of unbalanced magnetic pull (UMP) in dual three-phase permanent magnet synchronous machines (DTM) during post-fault (PFO) and synthetic loading operation (SLO). Through FEM (finite element method) simulations, the paper reveals that UMP arises due to interactions between field harmonics with differing spatial orders, specifically the 4th and 5th harmonics during PFO and SLO. The presence of both odd and even harmonics in the machine's field spectrum is identified as a critical factor in UMP generation. The simulation results confirm that while UMP in DTM increases bearing stress and reduces lifespan, it does not compromise mechanical integrity, providing insights for machine design and control strategies under PFO and SLO.

Keywords:
unbalanced magnetic pull,
dual three-phase machine,
multiphase machine,
synthetic loading,
post-fault operation

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I Introduction

Principal benefits of multiphase machines are power sharing among phases and a fault-tolerant operation that ensures continuous control over flux and torque even in the event of fault. This capability not only ensures continuous operation but also offers additional control flexibility to improve torque, minimize torque ripple, and increase redundancy and safety. Multiphase machines provide higher rated power and reduced power losses, making them suitable for diverse applications.

Among the variety of multiphase configurations, the dual three-phase machine (DTM) with two neutral points is the most popular. This design capitalizes on conventional three-phase inverter technology, enabling the use of existing, well-understood, and cost-effective power conversion strategies. The dual three-phase topology also enhances drive versatility through power sharing between winding sets. The sets can be connected to two three-phase power sources or consumers simultaneously, thereby allowing for an efficient transfer of active and reactive power across the windings. This capability can be used for synthetic loading, offering a simplified approach to determine the machine's power losses.

However, the operation of DTM introduces specific challenges, notably the issue of unbalanced magnetic pull (UMP). This phenomenon becomes particularly critical during certain modes of operation, such as post-fault operation (PFO) with only one winding set active, and during synthetic loading operation (SLO). UMP negatively influences machine's performance (noise, vibrations) and shortens bearings lifetime.

In this paper we focus on the performance of interior permanent magnet synchronous DTM during PFO and SLO. We shed light on the mechanism leading to UMP and quantitatively assess it through a series of FEM simulations.

II dual three-phase machine

DTM has 18 slots and 8 poles resulting in 20° mechanical angle between slots. Each phase winding consists of three series connected coils each spanning over two slots. Six phase windings are arranged in two three-phase winding sets *abc* and *xyz*, respectively, each having their own neutral point. The coils associated with respective winding set are placed in alternate stator slots along the circumference (Fig. 1).

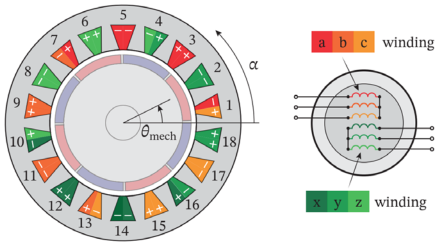

Figure 1: DTM with 18 slots and 8 rotor poles. Offset between three-phase winding sets *abc* and *xyz* is 9 slots.

Offset between winding sets *abc* and *xyz* is 9 slots or 180° mechanical. This is a standard choice among 18 offset possibilities, all of which are viable and lead to favourable properties in normal operation (NO): a) enhancement of 4th order space harmonic that interacts with rotor magnetic field and generate electromagnetic torque and b) cancelation of odd space harmonics (Fig. 2, top). During NO radial magnetic force generated by the *abc* set is counteracted by the *xyz* set resulting in cancellation of UMP [1].

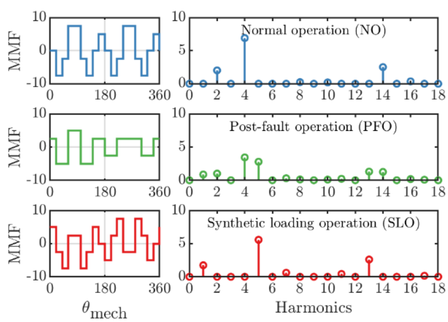

Figure 2: MMF profile (left) and harmonic spectra (right) for NO (top), PFO (middle) and SLO (bottom)

This winding layout offers enhanced fault tolerance benefits as it enable balanced PFO with derated torque output. In contrast to NO, the MMF harmonic spectrum of PFO (Fig. 2, middle) also contains odd harmonics, especially prominent is the 5th.

Similar observation can be made for SLO, a method for determining losses of electrical machines, where only odd harmonics are found in its MMF spectrum (Fig. 2, bottom). As the main rotor field harmonic is the 4th, its interaction with the armature's odd-harmonic spectrum results in undesirable effects, such as UMP.

III FE simulation

UMP refers to an asymmetrical force that acts on the rotor and occurs due to non-symmetric distribution of the magnetic field in the airgap. To estimate UMP a series of time-stepped 2D transient FEM analyses were performed using the Motor-CAD EMag module. Radial B_r and tangential B_a flux density within the airgap were calculated for a) no-load and four current levels, b) three modes of operation (NO, PFO and SLO) and c) 160 rotor positions θ_{mech} from 0° to 180° mechanical. Current displacement angle was set to 90°.

The force components F_x and F_y, exerted on a rotor with an axial length of l_{rot}, are determined by evaluating the integral along a surface with an airgap radius r_{AG} [2]

$$F_x = \frac{r_{\text{AG}} l_{\text{rot}}}{2\mu_0} \int_0^{2\pi} \left[B_\alpha^2 - B_r^2) \cos\alpha + 2B_r B_\alpha \sin\alpha \right] d\alpha$$
$$F_y = \frac{r_{\text{AG}} l_{\text{rot}}}{2\mu_0} \int_0^{2\pi} \left[B_\alpha^2 - B_r^2) \sin\alpha + 2B_r B_\alpha \cos\alpha \right] d\alpha \qquad (1)$$

UMP is then calculated as $F_{\text{UMP}} = \sqrt{F_x^2 + F_y^2}$.

A. Radial flux density and magnetic force

Fig. 3 shows radial flux density for all three operation modes. Harmonic analysis of the waveforms reveals that in NO only even harmonics exists, whereas in PFO and SLO odd harmonics appear as well as predicted by MMF profile (Fig. 2). Radial magnetic force is a consequence of interaction between these field harmonics. For NO (Fig. 4a), the force profile along the airgap exhibits half-wave symmetry, ensuring balance. Consequently, this symmetry prevents the emergence of UMP. In contrast, PFO and SLO (Fig. 4b and 4c) are not balanced which leads to UMP.

The UMP originates from the first spatial order harmonic of the force wave, which is generated by the interaction of field harmonics with spatial orders differing by one [2]. That means that UMP cannot be produced if the machine's field in the airgap comprises exclusively even or odd harmonics. In case of PFO and SLO the UMF is primarily due to interaction of 4th and 5th field harmonics (Fig. 3 bottom).

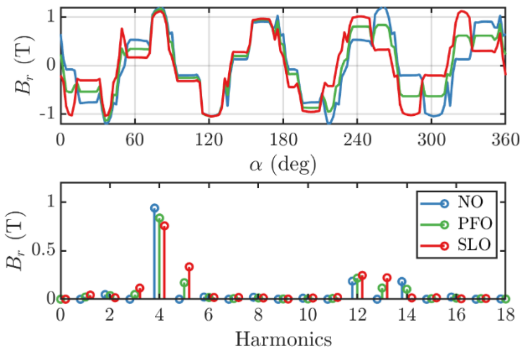

Figure 3: Radial flux density B_r at $t = 0$ s and $I_s = 100$ A for all modes

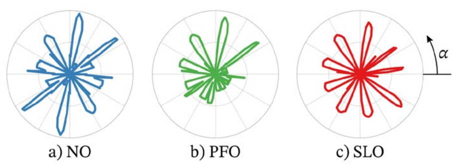

Figure 4: Radial magnetic force F_r at $t = 0$ s and $I_s = 100$ A for all modes

B. Rotor position dependence

Fig. 5 and 6 depicts UMP for 4 current levels and rotor positions in the range from 0° to 180° mechanical. The amplitude of UMP is similar for both PFO and SLO. By increasing the current the UMP ripple starts to amplify, especially for PFO. This can be attributed to the rise of higher order harmonics due to saturation.

IV Conclusion

For this DTM, PFO and SLO inevitably lead to the emergence of UMP as its field spectrum contains odd and even harmonics. The UMP adds additional strain on the bearings; however, its amplitude is still order of magnitude below bearings' load rating. It appears that at this level UMP reduces the lifespan of bearings, rather than presenting an immediate danger to mechanical integrity. Moreover, PFO and SLO are intended to be temporary, active only for a constrained period.

Table 1: Data and Parameters of Dual Three-Phase machine

Rated values	
Maximum current $I_{\max}$	200 A
DC-link voltage U_{DC}	48 V
Motor parameters	
Number of pole pairs p_{p}	4
Number of stator slots	18

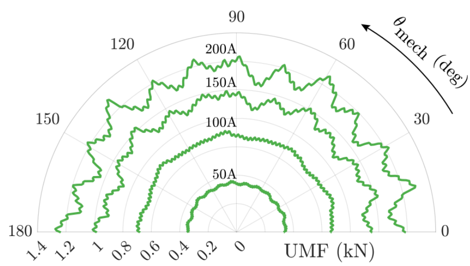

Figure 5: UMP during PFO for four currents and rotor positions from 0° to 180°

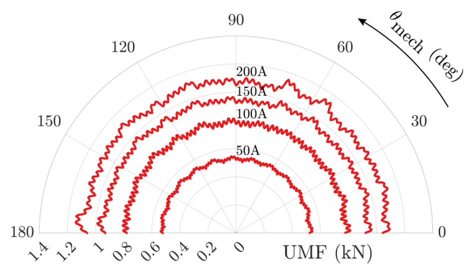

Figure 6: UMP during SLO for four currents and rotor positions from 0° to 180°

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