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Remedial Strategy for a Permanent Magnet Synchronous Motor Drive

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Abstract

This paper discusses the use of a permanent magnet synchronous motor drive (PMSM) in safety-critical applications. A remedial strategy to drive the motor under open circuit and short circuit fault conditions is described. Special emphasis is laid on the torque ripple produced by the faulty drive as the application demands smooth torque.

Summary

Aerospace as well as automotive applications demand drives with a high power density and a high reliability. Permanent magnet motor drives offer a high power density. Reliability can be improved by special motor designs [JAH-80], [MEC-96] or by means of remedial operation strategies [SPE-91], [ELC-94]. This paper describes a remedial approach with a standard three phase machine. If one phase is faulted, the remaining phases won’t be affected and will achieve in most cases the same performance as the unfaulted drive. This will be reached by separating the three phases electrically.

Some applications demand high torque at low speed with little or no torque ripple. Special attention will be paid to the torque ripple, if a part of the drive is faulted.

Fault conditions

Many different faults are possible, but not every fault condition will be treated within this paper. Mechanical faults concerning bearings, shaft etc. are not considered, neither faults of the position transducer. Power supply is assumed to be unaffected. Only electromagnetical and electrical faults of the motor and the converter are investigated. They can be summarized:

- winding open circuit
- winding short circuit (at the terminals or terminals to ground)
- power device open circuit
- power device short circuit

The final paper will discuss the behaviour of the drive harmed by these faults.

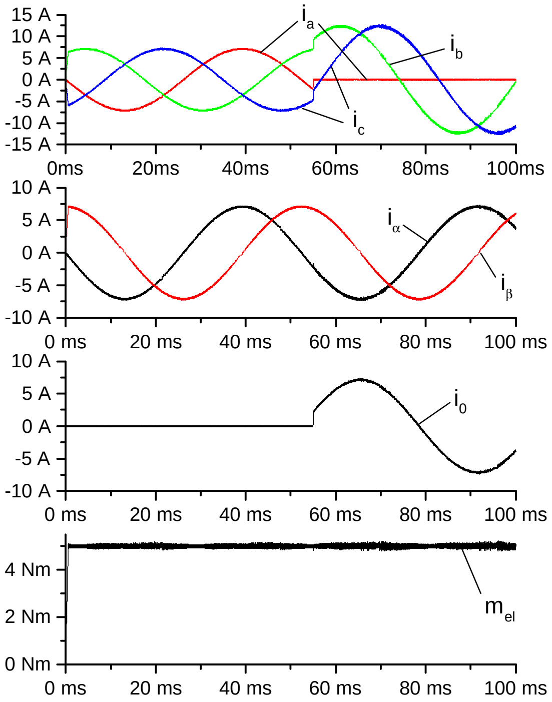

Figure 1. Remedial strategy (simulated results)

Two-phase remedial operation

Two-phase remedial operation with a three-phase PMSM is described e.g. in [ELC-94]. If one phase is turned off due to an open circuit of a power device or a winding, the same fundamental m.m.f wave form can be obtained by the remaining two phases. Appropriate reference values for the other two phase currents will be necessary to get the same wave form. This is illustrated in fig. 1: After turning off one phase (phase *a*) the other phase-currents are shifted $\pi/3$ (instead of $2\pi/3$) and amplitudes are multiplied by $\sqrt{3}$. Phase currents transformed to the $\alpha\beta$-reference frame are not affected, but the homopolar component i_0 is no longer equal to zero. Designing the motor these higher currents have to be considered.

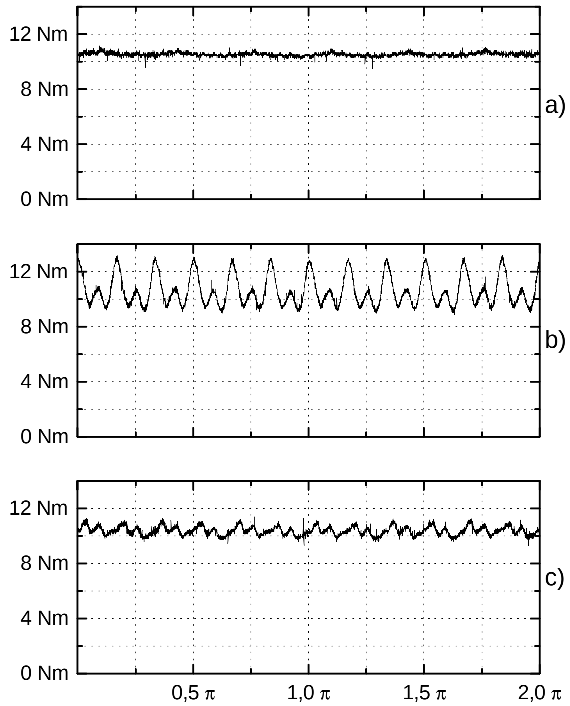

Figure 2. Measured torque (12-pole PMSM)
a) three phase operation
b) two phase operation
c) two phase operation, current shapes adjusted

The simulated results show no torque ripple in the two-phase operation mode. Nevertheless measurements show a significant torque ripple (see fig. 2b): The force acting on a single conductor is given by

$$F = l \cdot (I \times B)$$

Instead of summing the forces acting on single conductors the current distribution a_s is introduced. It can be described as the sum of the Fourier series of the three phase current distributions:

$$a_s(\Gamma, g) = \sum_{q=1}^{3} i_q(g) \sum_{n=1}^{\infty} ca_n \cdot \cos\left(n\left(\Gamma - j_q\right)\right)$$

Γ – stator angle
γ – rotor angle
φ_q – phase shift angles

With the air-gap flux density

$$b(\Gamma, g) = \sum_{n=1}^{\infty} cb_n \cdot \cos\left(n\left(\Gamma - g\right)\right)$$

the electromagnetical torque can be written as

$$m_{el}(g) = r \int_{0}^{2p} a_s(\Gamma, g) \cdot b(\Gamma, g) \cdot l \cdot r \, d\Gamma \, .$$

This equation can be simplified because the integration will yield to zero, if the harmonic number of the current distribution is not equal to the harmonic number of the air-gap flux density:

$$m_{el}(g) = p \cdot l \cdot r^2 \sum_{q=1}^{3} i_q(g) \sum_{n=1}^{\infty} ca_n \cdot cb_n \cdot \cos\left(n\left(g - j_q\right)\right)$$

Since the m.m.f. wave form is determined by the winding distribution and the air-gap flux density by the magnets torque ripple can only be influenced by the shapes of the phase currents.

In two-phase operation the dominant third harmonic is not eliminated as it is in three-phase operation. Together with the sinusoidal phase current the third harmonic will result in a torque ripple of the second and the fourth harmonic as depicted in fig. 2b. If the phase current shapes are adjusted, torque ripple can be reduced (fig 2c).

In the final paper means are discussed to compensate torque ripple.

Implementation

Fig. 3 depicts the block diagram of the experimental setup. The converter consist of three bridges to supply each phase separately. The machine has a special winding configurationin which every terminal is connected to the corresponding converter bridge.

Currents are controlled by a space vector controller in stationary αβ-coordinates as described in [KAZ-91]. The outputs of the three-level hysteresis comparators address a switching table to select the appropriate voltage vector (see fig. 4). In contrast to [KAZ-91] an i_0-comparator is introduced because the sum of the three phase currents is not necessarily equal to zero as with wye- or delta-connected phases.

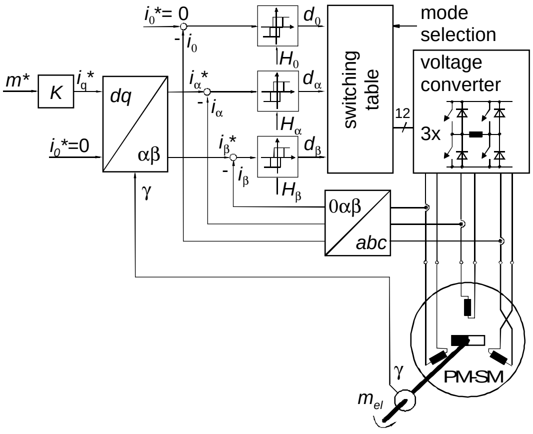

Figure 3. Block diagram of the experimental setup

Reference values i_α* and i_β* are calculated according to the actual rotor position and the torque demand, i_0* is zero for normal operation.

In normal operation mode every converter bridge can apply positive or negative supply voltage or zero voltage to the phase winding to produce three voltage vectors (e.g. phase a: $\underline{v}_1$, $\underline{v}_4$ and $\underline{v}_0$) (fig. 4). If one phase is faulted, the other two phases won't be affected due to the converter and winding topology. They can replace the missing voltage vectors with the adjacent vectors. If e.g. phase *a* is turned, off $\underline{v}_1$ and $\underline{v}_4$ will be missing. $\underline{v}_1$ can be replaced with the vector sum $\underline{v}_2$ plus $\underline{v}_6$, $\underline{v}_4$ can be replaced with $\underline{v}_3$ plus $\underline{v}_5$. To select such a remedial operation mode, the switching table has to be changed according to the fault condition. This can easily be done with additional address lines (mode selection) at the switching table.

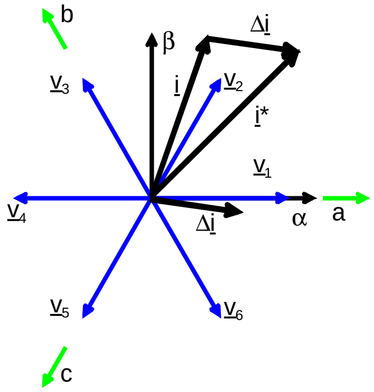

Figure 4. Voltage vectors

Not only open circuit faults as described above but also short circuit faults can be handled with this structure as will be shown in the final paper.

References

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