# Literature Overview of Fault Tolerant Electrical Machines

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**Abstract**—In this paper, a literature overview of fault tolerant electrical machines (FTEM) is presented. Various electrical machine designs are shown, their advantages as well as design and technology challenges are briefly discussed**.** It was found that one of the most popular types of FTEM is permanent magnet synchronous machine (PMSM) with fractional slot concentrated winding. In order to define boundaries of starting parameters for the design of FTEM, several important aspects of design of electrical machines are also provided.

**Keywords**—motor, generator, fault tolerant electrical machine (FTEM), permanent magnet synchronous machine (PMSM), fractional slot concentrated winding, tooth-coil winding.

## 1. INTRODUCTION

Modern requirements for reliability of safety critical electrical drive systems, e.g. electrical vehicles, aerospace applications, wind power generation applications, and technological limitations during manufacturing of electrical machines provide solid foundation for the development of fault tolerant electrical machines. The inter turn faults in the stator coils of an electrical machine can sometimes occur despite precise quality control of its manufacturing process. Surge voltage tests of the coils before their connection have own limitations and are not capable to detect all potential defects of inter turn insulation. Amplitude increase of the test voltage pulse for detection of small defects in the insulation can damage it and cause a flashover between the first and the last turn of the coil. There are more potential aspects which can lead to a failure of a winding, e.g. weak joints between rotor bars and short-circuit rings of induction motors, partial discharges even in low-voltage machines caused by frequency converters, different issues with temperature detectors, harsh environment conditions. On the other hand, significant advances in technology of power electronics and frequency converters allow to overcome these challenges by applying of wider set of winding arrangements, magnetic circuit designs and control methods of electrical machines. An excellent example of such a development is switched reluctance machine (SRM), which has cheap and rugged construction, but demanding requirements for both its intelligent control and electromagnetic calculations, taking into account saturation effects of the magnetic circuit as a function of rotation angle. Still, such a machine has its limitations in some applications as well. For example, the usage of SRM in fuel-filled pumps would lead to a significant increase of hydraulic losses, and consequently to the reduction of the efficiency of the fuel pump [1]. Further, if such an important demand as high torque density applies, SRM will concede to permanent magnet machine (PMSM), which is shown in [2]. This requirement is especially relevant e.g. for electric aircraft propulsion applications, which have been gaining popularity in recent years. Consequently, due to the high performance characteristics of PMSM, this type of electrical machines has received high attention among other fault tolerant electrical machines (FTEM), which is illustrated e.g. in the literature reviews [3] and [4]. Inherently, PMSMs have own design and technological challenges, such as impossibility of deexcitation of the machine, poor default fault tolerant capabilities, risk of demagnetization of permanent magnets (PM) due to their overheating or short circuit in the winding, gluing and bondage of PMs to the rotor, limited speed range, high cost. Accordingly, cooling capabilities of a PM FTEM must be able to manage with excessive heating of permanent magnets during turn-to-turn short circuit as well. Thereby, all above mentioned factors demand careful attention during design of FTEM for the particular application. This paper will provide some achieved results in the development of FTEMs and several important aspects of their design.

## 2. EXISTING SOLUTIONS

Different measures listed in literature to meet fault tolerant requirements, reduction of losses and torque ripple are represented in this chapter. Solutions below are intended to introduce designer to the existing achievements and help to select, adopt and develop appropriate methods for design of relevant FTEM.

A four-phase fault tolerant permanent magnet machine for an engine fuel pump was presented in [5]. High specific output for this machine has been achieved with help of fuel cooling and PMs arranged into Halbach array. The four-phase motor has six poles rotor and four stator coils, wound around four of the eight stator teeth. It was demonstrated, that the drive continued to produce rated output even in the presence of faults in the machine.

Torque ripple and converter power rating of a duplex 3-phase machine are significantly lower compared to a duplex 2-phase machine, which has been shown in [6]. However, a duplex 2-phase machine has a higher average torque capability. Also, an effective technique based on search coils has been presented for detection of winding short-circuits.

Surface PM machines with different multi-layer FSCWs and different slot/pole combinations were analyzed for turn-to-turn faults in [7]. Among other conclusions it has been shown that turn-to-turn fault between two different phases generates lower fault current than turn-to-turn fault within the same phase.

Comparison of fault tolerant permanent magnet motors with five different topologies was presented in [8]. These are one surface-mounted topology, one surface-insert topology and three interior topologies (spoke-type, conventional and V shape). It has been shown that each topology has a potential for use in suitable applications.

Detailed design, tests and analysis of a 175 kW main power fault-tolerant embedded PM generator for aerospace applications was presented in [9]. Before the design of the generator, a literature review was provided, including the guides and references for the choice of the feasible number of phases, stator slots and rotor poles. After test results it was shown, that the generator can deliver the full power of 175 kW over the wide 4:1 speed range with regulated DC bus voltage.

An example of a water-cooled five-phase fault tolerant 20-slot/18-pole permanent magnet synchronous machine with single layer fractional slot concentrated winding for electric vehicles was investigated in [10]. Among other results it was shown, that after segmentation of PMs, eddy current losses in them are decreased by more than 50%.

For the given rotor diameter and armature current density, fault tolerant PMSM is shorter, has larger slot areas and higher number of turns per slot in comparison to a non-fault tolerant PMSM, which was shown in [11]. Further, the advantages of short-circuit ratio value = 1 and a shorter stack length were discussed.

An asymmetrical six-phase salient-pole synchronous generator for the aircraft power system was proposed in [12]. The pulsating torque of such a machine is reduced due to the fact that the 5th and 7th harmonic components of the MMF wave have no influence on the air-gap flux thanks to the asymmetric phase displacement in the winding of the machine.

A 5-phase fault tolerant outer-rotor PM machine with flux barriers in rotor yoke was designed in [13]. The armature reaction magnetic field in such a machine is greatly reduced without affecting the main pole magnetic field. As a result, eddy current losses in the PMs are reduced as well.

Different rotor structures of fault tolerant PMSM are discussed from the perspective of fault tolerance capability in [14]. Irreversible demagnetization of the PMs during short-circuit fault is avoided by the decrease of short-circuit current due to the increased self-inductance, using appropriate air-gap length and stator slot size. The effective limitation of the short-circuit current by the proposed rotor structure was demonstrated with help of simulation.

An integrated modular motor drive system with three, four, symmetric and asymmetric six phase winding configurations was examined for fault tolerance capability in [15]. It was shown, that symmetric six-phase machine is the most promising configuration by means of fault tolerance and redundancy among all configurations.

A comparison of optimized tooth-coil-winding modular permanent magnet synchronous machines with U-shape and H-shape stator segments for fault-tolerance applications was presented in [16]. It was shown that U-shape machines provide minimum mutual inductance and develop the highest mean torque and efficiency, which makes them suitable for high-torque and fault-tolerant applications. Instead, H-shape machines showed lower torque ripple and are less appropriate for fault-tolerance applications.

## 3. DESIGN CONSIDERATIONS

The following requirements for the fault tolerant electrical machines have been noted in literature as one of the most important: higher number of phases, implicit limiting of fault currents, complete electric isolation between phases, magnetic isolation between phases, effective thermal isolation between phases, physical isolation between phases [3]. It has also been shown that the fractional slot concentrated windings are one of the most popular solutions in applications requiring high fault tolerant capability [17], with the advantages of high power density, high efficiency, short end turns, high slot fill factor particularly when coupled with segmented stator structures, low cogging torque, flux weakening capability [3].

The values of linear current density $A$ and air gap flux density $B_\delta$ are very important in the design process of an electrical machine, drafting the size of its rotor at the very beginning. Further, the value of current density $J$ defines amount of the copper required for the delivery of the requested power. Often, FTEMs have unusual environmental conditions and duty cycles, e.g higher output power during limited period of time, operation under one or several faulty phases, operation under extremely low or high temperatures, etc. That means the electric loadings must be considered individually for each specific application. To illustrate this diversity, electric loadings given in [1], [11], [14], [18], [19] references are summarized in the Table I, where $P$ is the output power, $D_r$ is the rotor diameter and $l$ is an active length. If the value of $A$ is not given explicitly in a reference, it can be estimated using the formula:

$$A = \frac{2 \cdot I \cdot N \cdot m}{\pi \cdot D_\delta}, \tag{1}$$

where $I$ is the current in a turn, $N$ is the total amount of turns in a phase, $m$ is the number of phases, $\pi D_\delta$ is the circumference of the air gap.

**Table I:** Electrical loadings of some fault tolerant PMSMs

| **Ref.** | ***A*, [kA/m]** | ***J*, [A/mm²]** | ***P*, [kW]** | **$D_r \times l$, [mm]** | **Winding** | **Notes** |
|---|---|---|---|---|---|---|
| [1] | 174 | 18.7 | 15 | 68 × 40 | 6-phase | fuel-filled |
| [11] | ≈ 200 | 10, 15, 20 | 30 | 150 × 100 | poly 3-phase | no info on cooling |
| [14] | 36 | 22.5 | 20 | 127 × 100 | 5-phase | $T_{amb}$ = -183 °C |
| [18] | 36.5 | 4.4 | 1 | 71 × 90 | dual 3-phase | |
| [19] | 5.5 | 11 | 14.7 kVA | 120 × 70 | 3-phase | $k_{Cu} = 0.15$ |

One of the core challenges for the design of FTEMs is to combine fault tolerant capabilities of the machine with the required torque density, which constitute a direct contradiction to each other. For example, open slots close to rectangular shape and unequal teeth width can contribute to the higher torque density of the machine, whereas semi-closed slots or closed slots can significantly increase phase inductance of the machine and reduce rotor eddy current losses.

The short circuit current of a synchronous machine is defined by its d-axis inductance, which includes magnetizing and stator leakage inductances $L_d = L_{md} + L_{s\sigma}$, and rotor leakage inductances. Magnetizing inductance can be calculated acc. to the equation (2):

$$L_{md} = \frac{\mu_0}{\pi} \cdot \frac{m N_{ef}^2}{p^2} \cdot \frac{D_\delta l'}{\delta_{ef}}, \tag{2}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum permeability, $m$ is the number of phases, $N_{ef}$ is the number of effective turns, $p$ is the number of pole pares, $D_\delta$ is the diameter in the middle of the air gap, $l'$ is the equivalent stator length, $\delta_{ef}$ is the effective air gap, taking into account PM and iron length along the flux line. If magnetic circuit saturates too much during the short circuit, the increase of the effective air gap and decrease of the magnetizing inductance can lead to the unfavorable high value of the short circuit current. This must be taken into account especially during design of FTEM.

Stator leakage inductance can be divided into several components:

$$L_{s\sigma} = L_{\delta} + L_{u} + L_{tt} + L_{ew} + L_{sq}, \tag{3}$$

where $L_{\delta}$ is the air gap leakage inductance, $L_u$ is slot leakage inductance, $L_{tt}$ is tooth tip leakage inductance, $L_{ew}$ is end winding leakage inductance and $L_{sq}$ is skew leakage inductance. Rotor leakage inductances depend on the design of the rotor of the machine and must be considered individually. While increase in leakage inductance can limit short circuit current, it can also contribute to the decrease of power factor and efficiency of the machine. Low leakage components of the synchronous inductance allow to obtain larger torque from the machine. In this regard tooth-coil windings can offer another advantage in e.g. limiting of the end winding leakage inductance, by decreasing of end winding length and its wrapping closely to the electrical sheet stack. This is especially relevant for the machines with the short stacks, since their end-winding leakage inductance contributes considerably to the total inductance. Finally, some applications imply long-term operation during a fault, which means that the fault state leakage inductance can be considered as a new rated leakage inductance.

## 4. CONCLUSION

This paper summarized some achieved results in the development of FTEMs and provided several important aspects of their design listed in the literature, such as choice of the number of phases, slots and poles, special stator and rotor designs, usage of PMs. It was shown that diversity of applications implies unique approaches to the design of FTEMs, in order to fulfill all the requirements to the fault tolerance, torque density and operational modes of a particular drive system. Among different variables defining design of the machine in the beginning, especially careful attention should be paid to the choice of its air gap diameter. For the purpose of higher torque density and fault tolerant capability one approach can be to choose the longest air gap diameter possible at the first stages of the design process, keeping active length of the machine and its end winding length within reasonable limits. This measure allows to choose between broader number of stator slots, defining their shape in the most optimal way and potentially apply broader number of winding arrangements. Finally, it is a task for the designer to find an optimal balance between fault tolerant capabilities of the machine and its torque density, required for the given application.

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