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Fatigue life calculation procedure for the rotor of an embedded magnet traction motor taking into account thermomechanical loads

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ABSTRACT

Working cycle and load fluctuation have to be considered in the design process of traction motors in order to be able to optimize the size, life cycle, and performance of the electric drive. The total stress and fatigue life of an electric motor rotor are determined to a large extent by centrifugal forces, tangential forces caused by torque, and the temperature gradient along the rotor. Rapid increase in heat as a result of sudden variation in the electric current and the differing thermomechanical characteristics of the components leads to non-uniform stress in the assembly. By applying the principle of superposition to the transient mechanical and thermal stress, a multidisciplinary method is proposed for the calculation the equivalent von Mises stress for a fatigue life analysis. This paper presents a fatigue life calculation procedure considering the mechanical and thermal stresses. The method is presented using the rotor of the Electric RaceAbout (ERA) traction motor as a case example. The presented approach is validated by comparing simulated and measured temperature data from ERA drive tests at the Nürburgring Nordschleife track. The results indicate the great importance of taking into consideration both mechanical and thermal loads in lifetime calculation.

1. Introduction

The electrical machine is one of the key components in electrical traction technology. Typical requirements for electric traction motors are a high power density and high efficiency over wide torque and speed ranges. The trend in traction applications is to use a different variations of permanent magnet synchronous motor (PMSM) which has numerous beneficial features for this purpose. Since the vehicular applications impose many simultaneous requirements for traction drives, many different traction motor drives and drivetrain architectures has been proposed [1–3].

Multidisciplinary analysis considering electromagnetic, thermal and mechanical fields should be adopted when optimizing designs of traction motors. Quite often this is done by evaluating the electromagnetic performance as a function of rotational speed of the machine and utilizing the calculated electromagnetic losses as heat sources in thermal analysis. In addition, electromagnetic forces are utilized in mechanical analysis to find out the noise and vibration characteristics [4,5]. The aforementioned design procedure reveals the bottlenecks of the electrical machine design, but it is by no means

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Nomenclature

b	Basquin exponent or fatigue strength exponent
k	number of the rainflow stress classes
n	rotational speed (rpm)
N	number of stress cycle repetitions in total
N_f	number of equivalent applied stress cycles
P	power loss (W)
T	torque (Nm)
z_i	number of repetitions in ith stress class
β	S-N curve slope
σ	stress (Pa)
σ'_f	fatigue strength coefficient
$\Delta\sigma$	stress variation
$\Delta\sigma_{eq}$	calculated equivalent stress (Pa)

optimized for traction motors. Since the operating conditions in traction motors vary significantly, the multidisciplinary analysis should be conducted over the drive cycle as was done, for example, in Fatemi et al. [6].

The calculation of mechanical stresses and fatigue life of PMSM rotor structure in traction applications is often based on different analytical and finite element (FE) based numerical approaches. According to the results found for instance in Chai et al. [7], Knetsch et al. [8], and Lindh et al. [9], the centrifugal force acting on the rotor structure is considered to be the dominant stress source, but in all the cases the effect of the thermal loads on the mechanical stresses and fatigue life were neglected. The total stress level is directly coupled with the fatigue life that can be analyzed by different methods as introduced in [10]. Mechanical stresses caused by internal and external loads and centrifugal force have an effect on the fatigue life of an electric motor. Furthermore, stresses generated by thermal loads that can be caused by ambient temperature variation or internally generated heat losses affect the fatigue life. While the effect of temperature on the electromechanical properties of components and the electric machine performance has been studied from many different perspectives, the influence of thermal loads on the mechanical durability of rotor assemblies has received limited attention.

According to the published literature, the interest of thermomechanical stress effects in electrical machines are limited to the degradation of stator insulation [11] or rotor bar braking mechanisms in squirrel-cage induction machines [12]. In the traditional mechanical dimensioning of the rotor structure of a permanent magnet traction motor the thermomechanical stresses are usually neglected, leading to a fact that the mechanical dimensioning is based mostly on the centrifugal forces affecting to the rotor.

In this paper, a calculation method of performing a thermomechanical fatigue life analysis for a rotor of an electric traction motor over the known drive cycle is presented. The fatigue life calculation with inclusion of thermal expansion induced stress in the rotor part using real drive cycle gives much more realistic fatigue life estimation compared to the standard approach where only the centrifugal loads are included. The proposed calculation method can be utilized in the structural optimization of the traction motor rotor on the given drive cycle. The presented stress calculation procedure is a combination of analytical and finite element methods (FEM) and developed such that it allows solution over the drive cycle within a reasonable computational effort.

The proposed thermomechanical fatigue life analysis was applied in the analysis of a permanent magnet synchronous motor used as a traction motor in a full electric sports car. Data measured from the rear right wheel of the vehicle running on the Nürburgring Nordschleife track [13] was utilized as the drive cycle. As an end result of this study, an important discovery was made. Based on the analyzed traction motor within the utilized drive cycle, it was found out that the thermal expansion induced stresses are actually greater than the mechanical stresses. Also, the combined thermal–mechanical stresses are significantly greater than, typically studied, centrifugal force induced stresses only. These findings represents the importance of using the real drive cycle and the calculation procedure proposed in this paper as part an electric traction motor design.

2. Thermomechanical analysis

The proposed procedure for thermomechanical analysis of a permanent magnet traction motor rotor under mechanical and thermal loads consists of four main stages. Firstly, utilizing the rotational speed and torque data of the drive cycle, the sources of heat generation, that is rotor losses, and convection coefficients from the rotor surface to surrounding air are identified. Secondly, the transient thermal FEM is applied to evaluate the temperature distribution within the drive cycle. Thirdly, the stress calculation at every calculation time instants is performed utilizing static structural FEM. Finally, the fatigue life is estimated from the stress history during the drive cycle.