Permanent Magnet Synchronous Motor

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The most common special features and demands of the PMSMs are described in the appearance of the motor's failures caused by uncontrolled temperature rise. In addition, heat sources and energy losses, including copper loss, core loss versus motor speed, and output power, are analyzed. Various cooling strategies are listed and discussed. Scope of this review is to develop PMSM for a heavy duty green mobility with the smart light weight materials and with the enhanced cooling approaches.

thermal mapping traction motor PMSM thermal management temperature analysis thermal design thermally conductive materials

1. Introduction

Electric vehicles are replacing conventional internal combustion engine vehicles, which are an important part of meeting global goals on climate change. The propulsive force created in the electric vehicle is due to the friction between the road and tire. Traction control in electric vehicles has gained tremendous attention because, relative to traditional internal combustion engines, traction control can generate very rapid and reliable torques, improving drive performance, protection and stability [1]. The traction motor is the core of electric vehicles, converting electricity into mechanical energy or vice versa, thereby interfacing the battery source with the wheels of the vehicle. Traction motors are to be designed to realize up to five times the base speed, with a great torque-power density and good efficiency map for highway cruising and hill climbing. For multi-quadrant operation and multiple-motor synchronization, traction motors require good controllability, greater steady-state precision, and the best dynamic efficiency [2]. In addition, the traction motor should have low acoustic noise, and greater consistency and strength for the vehicular setting. The high-speed electric motor achieves the mentioned traction requirement. The typical advantages of high-speed traction motors include higher efficiencies, more compactness, and low cost due to reduced mechanical transmission. However, there are various electrical, thermal and mechanical limitations in high-speed traction motors [3]. The maximum speed of a system is constrained by the centrifugal force and critical speed-related elastic instability. On the other side, the stator and rotor temperature is restricted, and thus the peak power, maximum power, and constant power can be maintained [4].

In general, high speeds also imply high voltages and fluxes, which are to be taken into account in electromagnetic as well as electrical design [5]. The mechanical limitations in high-speed electrical motors mainly include bearing friction, ventilation losses due to non-linear friction, and vibrations caused by hysteresis [6]. Similar to the mechanical stress on high-speed motor drives, the thermal stress influences the performance and life span of the system because of the higher loss of densities arising from a smaller surface area and volume [7]. The conventional method of optimization, considering only electromagnetic and mechanical factors for a given particular electrical loading, can no longer be taken into consideration in order to design a stable and optimal system, and the thermal design must be part of the machine design process [8]. Importantly, the thermal augmentation of an electric motor affects the core, insulation and permanent magnets, which deteriorates the machine's performance and life span. Iron losses are the common term for loss occurrences associated with the presence of non-constant magnetic fields in laminated ferromagnetic materials [9]. The iron losses are caused by the magnetic hysteresis loop, termed hysteresis loss, and spatial eddy currents termed eddy current losses. The current redistribution generates internal eddy currents at higher frequencies due to higher speeds, which plays a critical role in iron losses. This happens because of ferromagnetic compounds that conduct electricity as well. It is easy to heat up the core material made of stacked iron, which implies the thin insulating coatings on the plate are destroyed. Due to high temperatures, the insulation across the conductors has its lifespan decreased; a constant over the temperature of 10 °C halves the existing lifetime [10][11]. Similarly, at a higher temperature, permanent magnets can be irreversibly demagnetized, and thus a temperature profile of the motor (thermal mapping) has to be estimated.

Thermal mapping is estimating the temperatures of the components of an electric traction motor in particular. This is essential because the components are made of different materials and their individual thermal expansion may lead to thermo-mechanical stresses. Heating in the motor through copper, magnet, lamination and bearing frictional losses is a cause of concern. Thermal gradients set due to these heat sources could lead to stresses in the radial and axial directions, causing uneven deformations. As such, thermal mapping is a very important parameter to assess the performance of any electric motor [12]. Electric motor temperature variations in rotors, stators and windings are analyzed under constant motor torque and speed (80 Nm and 2500 rpm). This in general represents a situation wherein an EV has to move on an inclined surface. Researchers observed that the double layer interior permanent magnet motor works effectively over a wide range of speed and load. The motor temperature was observed to be under the safe limits, in spite of a temporary overload condition, as it is thermally stable, as given in the illustration in Figure 1 [13].

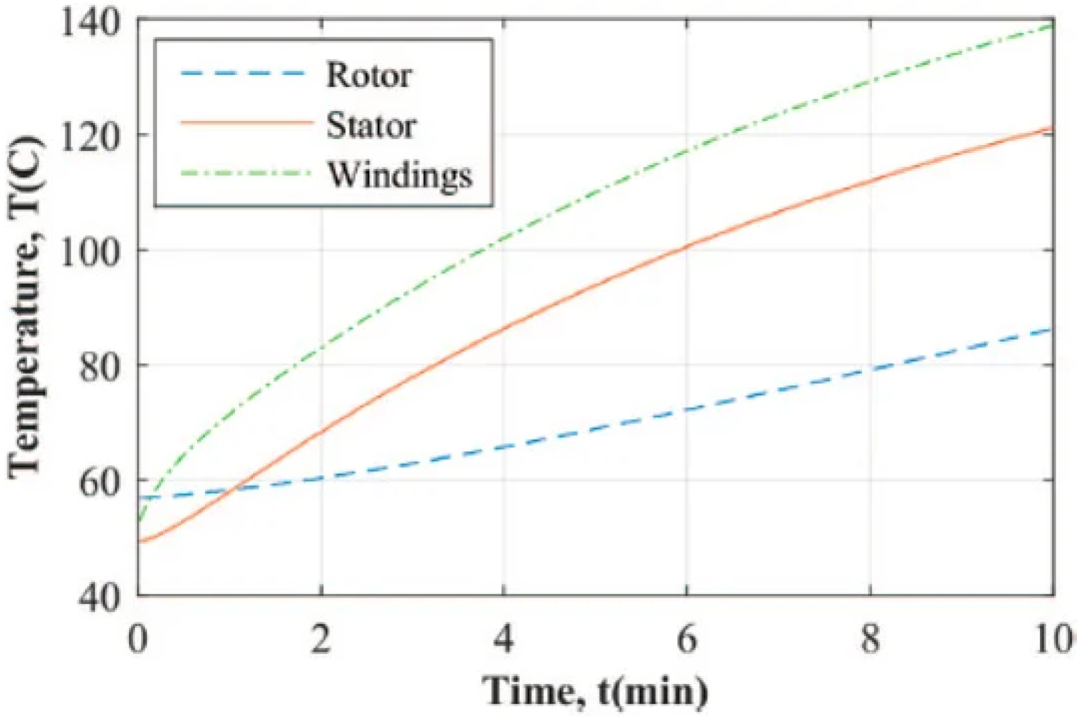

Figure 1. Rise in temperature under instantaneous load scenario [13].

The accurate cooling of the electrical motor is not easy. Most of the standard electrical machines are air-cooled, often with a ventilator mounted on the shaft, with external cooling fins. At higher speeds, the motor can be very noisy and take up a reasonable amount of torque, so it needs independent cooling. It is still very tough and complicated to quantify the cooling of the spinning parts, as this must be done by the airflow in the air gap and in the end-winding area. For this purpose, the cooling fins are often placed at the ends of the rotor [14]. The cooling system's challenge is to effectively eliminate this heat and retain the temperature of the motor within the specified range, while reducing energy consumption. In addition, in military ground vehicles, it is important to consider the design, the requisite reliability, and stringent operating conditions. Therefore, smart thermal management control with compact design and dynamic heat transfer capability is essential for traction motors [15]. Based on the power level, the operating conditions and the system environment, the cooling method should be adapted. Usually, the industrial motors are air-cooled, which cools the machine through natural or forced convection by employing a fan mounted on its shaft. However, this type of cooling will not be suitable for traction motors due to the inadequate space for radial fins, the waterproof design, and the uncertain ambient temperature and humidity. Moreover, for traction, the high-power density motors are preferred, which generate much heat; hence the selection of cooling must be done properly.

Liquid cooling is one of the most efficient cooling approaches for traction motor drives which contain a pump, radiator, and assorted hoses. The heat is transferred by the coolant through heat pipes inside the motor and passed through the radiator. The effectiveness of liquid cooling has been expansively analyzed in [16]. Soparat et al. built a liquid cooling system based on an electric motor to substitute a traditional fan-cooled configuration with enhanced cooling ability. Farsane et al. checked the efficiency of a liquid cooling system experimentally for an enclosed electric motor [17]. In addition to device architecture, control theory has been applied to minimize the energy consumption of the thermal management system. In order to manage the electro-mechanical actuators (e.g., fans and pumps), Tao et al. introduced optimum control theory to preserve the temperature of the e-motor for a hybrid electric vehicle (HEV), as well as to reduce power consumption [18]. Moreno et al., by ultra-capacitors and neural networks, established and confirmed an energy storage system for the HEV [19]. The real-time achievability of thermal control optimization algorithms in wired and autonomous hybrid electric vehicles has been investigated by Zhu et al. [20].

Advanced materials with high thermal conductivity and cutting-edge electric motor cooling structures were explored with the development of revolutionary manufacturing technologies [21]. A motor cooling system by means of heat pipes was realized in [22]. To absorb heat, the heat pipe evaporator was implanted into the motor housing; however, the condenser was mounted in a heat rejection cooling chamber. A heat pipe-based thermal bus for motor cooling was developed by Shoai-Naini et al., with system efficiency studied for different drive cycles [23]. A motor refrigeration system with L-shaped heat pipes was proposed by Putra et al. [24]. Furthermore, new internal mechanisms of the motor that benefit from a device cooling have been studied. A permanent magnet motor concept with a hollow shaft that allows coolant movement to help facilitate cooling was proposed by Lee et al. [21]. Air-cooling is simple and provides a simple foundation, but the cooling efficiency might not be satisfactory. In addition, a cooling fan is normally attached to the motor shaft, which absorbs energy and could be operated indirectly. Liquid cooling is efficient, but operating the coolant pump and radiator fan consumes electricity. On the other hand, owing to the cooling sides, liquid cooling adds additional weight and complexity. Heat pipes can work passively with the temperature gradient; nevertheless, there are heat transmission restrictions because of the operating temperatures, fluid properties, capillary limit, etc. [25].

2. Topologies of Electrical Motors

There are several categories and groupings of electric motors, such as DC and AC motors, linear and rotating motors, synchronous and asynchronous (induction) motors [26]. The most common motor topologies used in electric vehicles (EVs) are induction machines (IM), permanent magnet synchronous machines (PMSM) and switched reluctance machines (SRM). Comparing different topologies, interior PM (IPM) motors for passenger car applications have higher overload capability and efficiency than IM and surface-mounted PM (SPM) machines [27].

Lastly, the traditional surface inset PM synchronous machines (SIPMSM) and the novel SIPMSM have been trial-manufactured and compared [28]. The permanent magnet in the novel SIPMSM is a magnetic pole of unequal thickness with different inner and outer radians, which results in the uneven distribution of the radial air-gap flux density and a remarkable magnetic congregate effect.

In addition, different approaches have been discussed for an AC armature employing conventional copper coils on the stator. Superconducting AC homopolar motors for high-speed applications, which employ a high-temperature superconductor (HTS) DC excitation coil, are analyzed and constructed [29].

In recent years, the consideration of the lack of rare-earth PMs compared to the PMSM has attracted researchers to study synchronous reluctance motors (SynRM) for traction applications [30]. Another motor type is the permanent magnet synchronous reluctance motor (PMSynRM), which benefits from a ferrite-magnet. The performance of PMSynRM is competitive with PMSM, and is attracting the attention of motor manufacturers.

DC motors, such as brush (BDC) motors or brushless (BLDC) motors, are more suitable for low-power and low-speed applications, such as electric carts. A general overview of electrical motor topologies is presented in Figure 2.

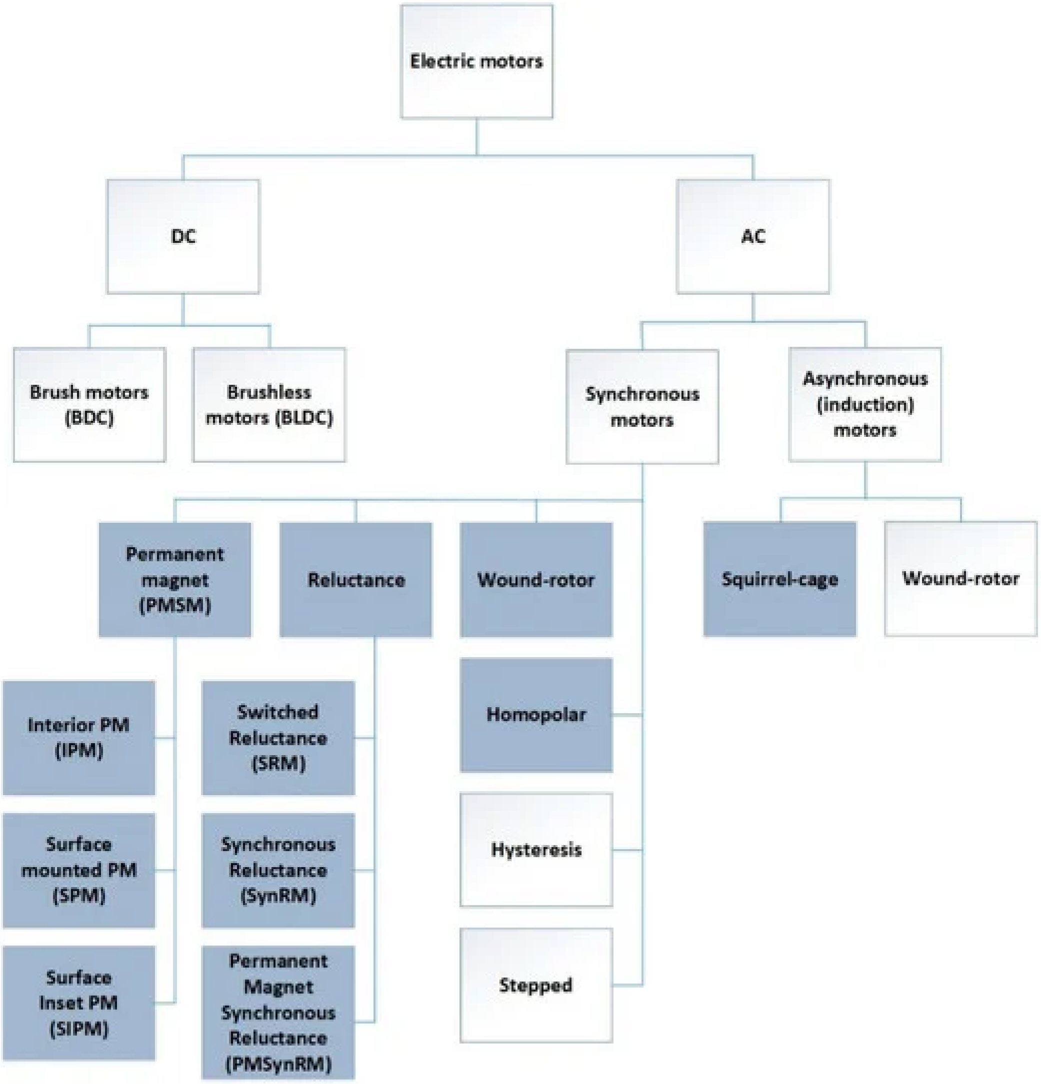

Figure 2. Electrical motors and the selected topologies used in electric vehicles (EVs).

Advanced electric machine topologies, such as stator permanent magnet (stator-PM) motors [31], hybrid-excitation motors [32][33], flux memory motors and redundant motor structures [34], are currently considered in electric motor design and manufacturing.

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