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A review on methods of finding losses and cooling methods to increase efficiency of electric machines

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ABSTRACT

Performance of electric motors and losses in terms of heat and temperature are reviewed in this paper. Airgap eccentricity, electromagnetic performance, effect of temperature and losses are shown as factors affecting the efficiency. Several methods of computer aided analyses are listed. Temperature distribution in an induction motor is shown through the results of a simulation. Different cooling methods are reviewed. Future directions for research include cryogenic cooling, heat pipes and usage of phase change materials.

1. Introduction

Electric motors have been utilized since 1834, and they have played a vital role in our day to day lives. Today, they continue to replace diesel and gas engines, as well as hydraulic cylinders, while evolving into new designs optimized for EVs (electric vehicles) and other technologies. "Electric motors are being used more widely in ships, airplanes, trains, and cars. We're also seeing a lot more electric motors in electric vehicles. "The ongoing transition from gas to electric is primarily driven by the need for more efficient devices that run with cleaner energy sources. Yet, electric motors also tend to be more responsive, and are more adaptable to new applications, especially in Electric truck. There is an increasing need to improve the fuel economy and reduce Green House Gas (GHG) emissions of heavy duty trucks due to high fuel prices, regulatory pressures, and climate change. Three approaches can be used to improve the fuel economy and/or reduce GHG emissioans of heavy-duty trucks: non-electrification efficiency-improving technologies on conventional powertrains and vehicles [1–3], hybrid powertrain technologies [3,4], and the substitution of natural gas, electricity or hydrogen for diesel fuel [5,6]. So far different types of motors have been used in electric truck. The main difference between electric propulsion on ships vs. cars is related to torque requirements, says Kirtley [7,8]. The variable speeds used in a car require that "the gearbox adapt the engine to the road, You can generate an electric motor that can propel an automobile without a gear shift. In the past, Kirtley has consulted with Tesla Motors on its electric cars, and both agree that "the induction motor" is the best for electric automobiles.

2. Performance of electric motors

The types of high-speed machines include induction machines, permanent-magnet machines and switched reluctance machines. Electric motors have a very high efficiency and high-power density, hence they find a perfect application in vehicle traction. They are fit for the downsizing concept also because they can produce maximum torque at low rotational speed. In all the types of electric

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machines, the squirrel-cage induction motor is the most opted one. A motor failure can result in the loss of large revenues, hence a thorough thermal analysis is done [9–11].

Electric motors and drive systems account for 64% of industrial electricity consumption. Energy which is not converted into useful work results in heating of the various motor components, and accounts for the motor losses. Heat generated during operation causes a negative effect on motor efficiency. The torque/rotational speed of the electric motor is being affected by temperature and internal losses viz. winding conduction losses, stator core losses, rotor core losses, and permanent magnet eddy current losses as well. To ensure a satisfactory life span for the motor, temperature rise must be limited to safe values. Obviously, the quantity of heat generated must be effectively removed to prevent damage to the machine using appropriate cooling methods [12–14].

Fig. 1 shows the contributors for developing high torque. Maximum torque can be obtained by the electric motor using power electronics, and high voltage battery, but increases the weight as well. In addition, although they have high efficiency, they produce a significant amount of heat that has to be removed. Much lower temperature can be accepted and higher values can request **power de-rating** in order to preserve their functionality. High voltage battery is even more critic, since it can work correctly only in a specific temperature window and outside this, it has a **rapid thermal degradation**. Maximum torque at different speeds possible for a specified winding and rotor temperature. Peak torque envelope for thermal transient condition can be calculated for a set amount of time that gives a certain maximum winding temperature [15].

2.1. Factors affecting the efficiency of electric motors

The calculation of losses in induction motors is particularly important, as it directly influences the temperature distribution, and also the overall motor efficiency. Predicting the temperature distribution is made difficult because of the uncertainties associated with assigning losses and thermal coefficients. These losses play an important role in determining the efficiency and temperature rise, and hence, the rating of a machine. The importance of **stray load losses** in induction machines was illustrated, indicating that a small improvement of the efficiency would mean about five times reduction in the losses of the input power. Hence, a small improvement of the average effective efficiency of the industrial motor would save energy [16,17]. Fig. 2 shows the factors affecting the motor efficiency.

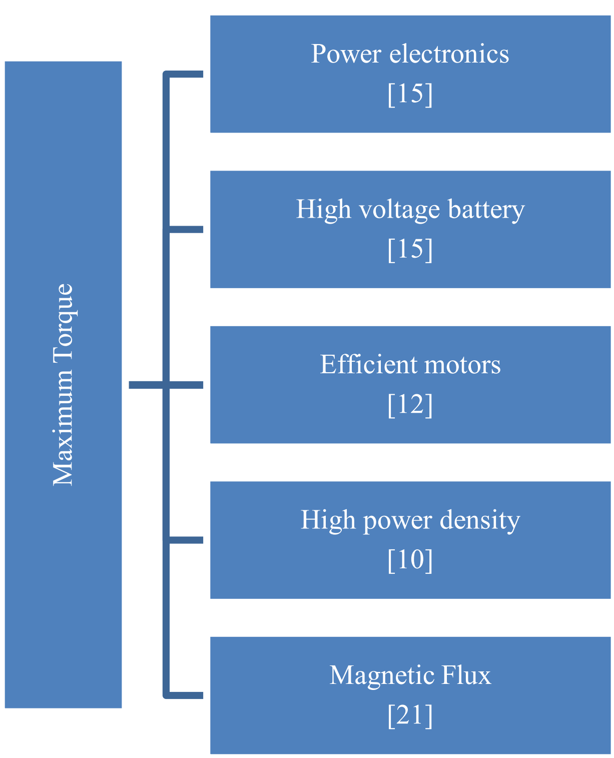

Fig. 1. Contributors for high torque.

2.1.1. Airgap eccentricity

One of the types of faults that can occur in Induction motors is **air gap eccentricity**. Static eccentricity is displacement of the rotation axis of the rotor with regard to the geometric center of the stator, hence the field distribution in the air–gap is unsymmetrical. The reasons for eccentricity include intrinsic shaft tolerance, ball-bearings defects or problems related with the fixing of these motor parts. This would cause the eccentricity to create additional motor vibrations and unbalanced magnetic pull (UMP). The static eccentricity leads to a non-uniform temperature distribution and the small eddy-current losses which occur in the magnets, contributes to the rise of the highest temperature spot in the motor, potentially shortening the lifespan of the **stator insulation system**. In Dynamic eccentricity the rotation axis of the rotor do not coincidence with its geometric center [11,18–22].

2.1.2. Electromagnetic performance

Mass, volume and material properties of electric motor have to be temperature-dependent so that temperatures inside the machine can work with a good **electromagnetic performance**. This analysis makes it easier for designers to maximize the winding current density to achieve the highest possible torque/power ratings within thermal limits set by the winding insulation or **demagnetization** limits [23,24]. The electrical machines in the automotive industry use permanent magnets in their rotors as they possess very good efficiency and high power density. On the other hand, sensitivity of the magnets in high temperatures is the major drawback. The losses caused by the eddy-currents induced in the rotor magnets are relatively small compared to the other losses generated in the electric machine. But due to the relatively poor

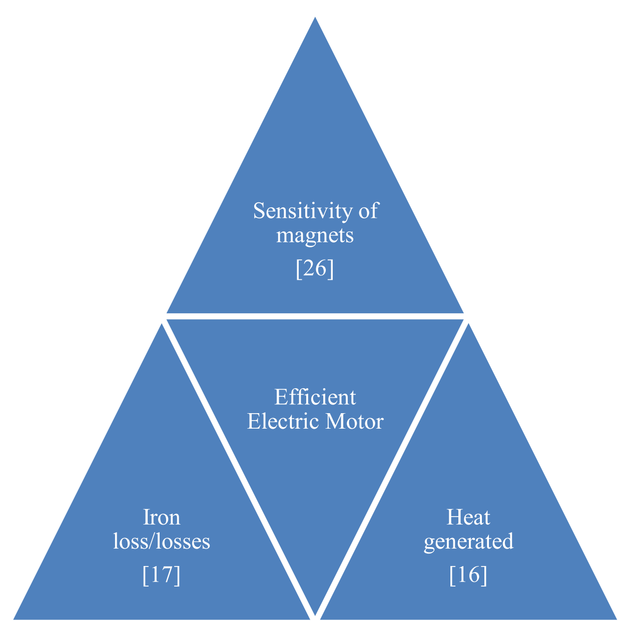

Fig. 2. Factors affecting the motor efficiency.

heat dissipation of the rotor, these losses can cause significant heating of the magnets. Increased temperature in the magnets may result in partial irreversible **demagnetization** of them as shown in Fig. 3. Abnormal high temperature will also affect the **core resistivity, thus affecting the eddy current loss** [25].

2.1.3. Temperature rise and losses

Operating point of the permanent magnet is subjective to the exposed temperature. Hence, the distribution of the **magnetic field** inside the motor, the **magnetic flux density** in the **air gap** and the core will change. Changes in magnetic field will affect **iron losses** and **permanent magnet eddy current losses**. Rise in temperature may alter the thermal conductivity, the resistance of the copper core, the permanent magnet remanence and intrinsic coercivity.

In general the highest temperature appears in the winding copper core, and the lowest temperature appears in the housing as shown in Fig. 4. Because the winding copper core is the main heat source and the small heat dissipation factor of the insulation layer leads to poor heat dissipation, the peak value of the temperature is located at the center of the stator winding. The eddy current losses are regarded as heat sources. With the increase of the load, the temperatures of the housing, stator core, winding copper core increases non-linearly. As the main heat source, the copper core is located in the middle of the stator and surrounded by insulations. The temperature will sharply rise because of the eddy current loss in the permanent magnet and poor thermal conduction ability of the rotor [26].

Increase of the power density would allow the motor temperature rise in the range of allowable limit value. Reducing the temperature rise can happen by improving the cooling capacity of motor and by reducing the losses. With the high speed and large carrier frequency, the **eddy current loss** of the permanent magnet is large [27]. Heat generated by a running induction motor and the temperature raise, eventually leading to thermal stresses. If the thermal stress is more than the limiting stress of the structure of the cage, it may lead to **broken bar fault** and the **cage fracture in the joint of the bars and the rings**. This is a very serious accident as it would lead to asymmetric rotor operation. Temperature rise is a key performance parameter of concern in the industrial arena. The temperature rise can limit the rated power and reduce the motor efficiency, and it also imposes special demands on the material of the motor. Hence, thermal mapping is crucial for satisfying the requirements of functionality and safety [28].

The influence of the end of the stator and rotor on axial temperature distribution also contributes to thermal loss. The temperature of stator and rotor increase rapidly in the beginning and the rotor temperature is higher than the stator temperature all the time. The maximum temperature point is around the axial center of the rotor bar. The axial temperature difference of the rotor core is larger than that of the stator core while the radial temperature difference of the stator core is larger than that of the rotor core [18].

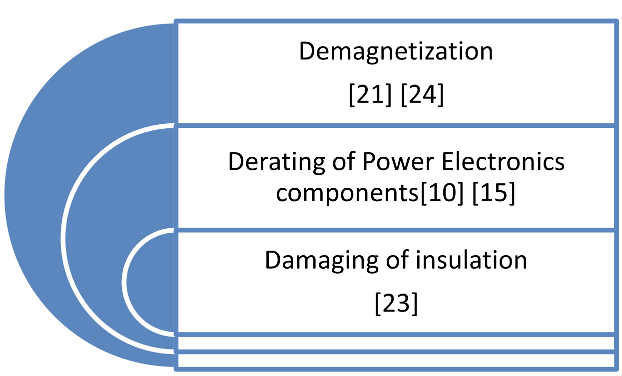

Fig. 3. Damages caused by temperature rise.

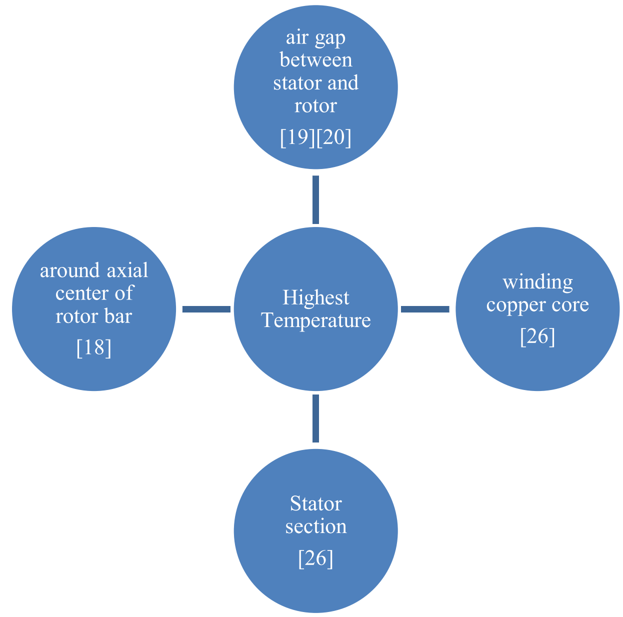

Fig. 4. Hottest spots in the motor.

2.1.4. Power losses

Fixed losses are losses in the active iron, and additional no load losses in other metal parts, Losses due to friction and windage loss in the machine. Load losses are copper losses in primary windings, losses in secondary windings and additional load losses. Stator losses,

a. Stator Copper losses: losses are produced when the current passing through the stator windings, and generates the heat and consequently, the temperature of the motor rises. These losses are dependent on the square of stator current.
b. Rotor bars losses: losses are produced when the current passing through the rotor bars, they are dependent on the square of rotor current.
c. Iron losses or core losses: losses are generated in the conducting core laminations, due to hysteresis, eddy-current. These play an important role in design of the machine and in determination of its thermal rating.
d. Mechanical losses contain air friction losses and bearing friction losses. Air friction losses result following the air circulation around the rotor during its operation. The air friction losses are divided in to two parts: the losses corresponding to the rotor seen as a rotating cylinder and the losses corresponding to the end surfaces of the rotor. Bearing friction losses are the results of the relative motion in bearings.

Copper losses are due to Joule losses, iron losses are due to eddy current and hysteresis effect. Compared to the conventional engine losses, they are quite low because the power is generally lower and the efficiency is much higher. Electric motors have very high efficiency, however their power losses produce a significant amount of heat. All the power losses become heat and increase the temperature of the component. The maximum temperature have an important effect on the **de-rating** of the power electronic components. In order to avoid premature de-rating, it is important to leave the temperature as low as possible [10]. **Core loss** seen in Fig. 5 is much greater than other losses and is the main source of heat due to the high operating frequency. Therefore, it is of crucial importance to calculate the core loss accurately, taking operating temperature into account. The **core eddy current loss and hysteresis loss** are due to temperature-induced changes in core material resistivity [9]. In order to design a high-efficiency motor, the iron loss generated in the motor should be reduced. The **stator loss, armature winding loss, rotor loss, and axial structure loss** are assigned as the heat sources in the electrical machine. The large rotor's **eddy current loss** will cause the temperature of permanent magnet to increase considerably [29–32].

2.1.5. Methods of reducing losses

A speed vector control system of induction motor (IM) with minimization of the copper and iron losses has been introduced. This method reduces heat losses from the rotor windings and stator and core losses from eddy currents [52]. Results of a sensitivity analysis of the heat sources and the properties of the structural changes within a 3D-model are presented. Iron losses and ohmic losses in copper are examined on the basis of electromagnetic design. The criteria for future design of electric motors are shown [53]. High temperature superconductor (HTS) machines have been designed to use an iron core to reduce the HTS tape length. Further study is required to find the arrangement of HTS tape in iron core to reduce losses [54]. A stator magnetic core from segments of amorphous steel is developed. Ducts inside the stator are used as cooling ducts. These arrangements promote the dissipation of heat from the stator and minimize temperature [55]. Three different types of tape-wound laminations were analysed viz. heat treated (HT), glued and heat treated (GHT) and conventional non-treated (NT). HT and GHT type laminations have lower iron losses than NT and conventional stacked laminations [56]. Lumped parameter thermal network (LPTN) was used to find the thermal performance. Optimization of the reduction in iron loss and copper loss, eddy current loss in permanent magnet was carried out considering harmonics to improve thermal performance [57]. Experiments were carried out using lamination sheets fabricated through different manufacturing processes: insulation, laser cutting, electrical discharge machining (EDM) and thermal treatment. The best manufacturing processes were found to be the bonding varnish insulation and EDM cutting. Second stress-relieving thermal treatment on CoFe alloy reduced iron loss by 28% [58]. Hybrid excited axial field flux-switching machine (HEAFFSM) with permanent magnets (PMs) and excitation windings in its stator is a novel hybrid excited flux-switching PM machine. Experimental results show that the minimum-copper-loss (MCL) strategy minimises the copper loss of the HEAFFSM drive system [59]. Another study focused on the core losses in the stator region of high-speed permanent magnet synchronous motors, magnetic field characteristics in the load region, and variations in iron losses caused by changes in these areas. It was demonstrated that the running status of high speed motors is closely related to the stator iron losses [60].

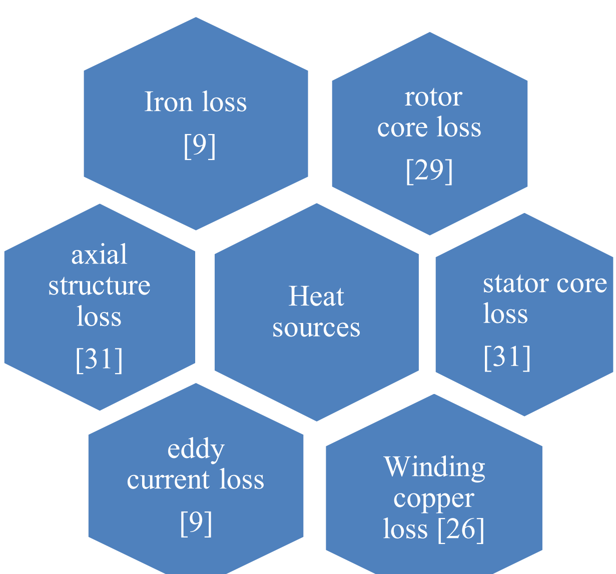

Fig. 5. Different type of losses acting as heat sources.

2.2. Temperature distribution in an induction motor

The temperature distribution in the induction motor is not uniform and there is a risk of local overheating. The **winding** is a main heat source and its insulation is thermally sensitive, so reducing the winding temperature rise is the key to the improvement of the reliability of the motor. Large end winding is required for high electrical loading and for the high torque density. The nature of the low speed, high torque application means that the losses in the machine are dominated by those from the winding [33,34]. Fig. 6 shows the temperature distributions inside an induction motor.

The maximum torque of a motor is directly proportional to the flux produced by the magnets. By keeping the working temperature of the magnets low, higher power density can be achieved [21]. Using cast copper instead of cast aluminum as rotor bars and end rings can reduce the temperature of rotor effectively [18]. The influence of temperature on the relative permeability of iron core material can be obtained. Thermoelectric materials allow converting a temperature gradient into electricity [35]. The material properties of the motor impose the temperature limit. The maximum limit of temperature is linked to silicon properties [10]. The thermal model explains the temperature distribution inside the induction motor, to give a precaution about problems which will occur during the operating conditions, like the **induction motor insulation**.

2.3. Computer aided analysis to find losses

Fig. 7 shows the computer aided analysis and modelling techniques used by different researchers during the past 10 years.

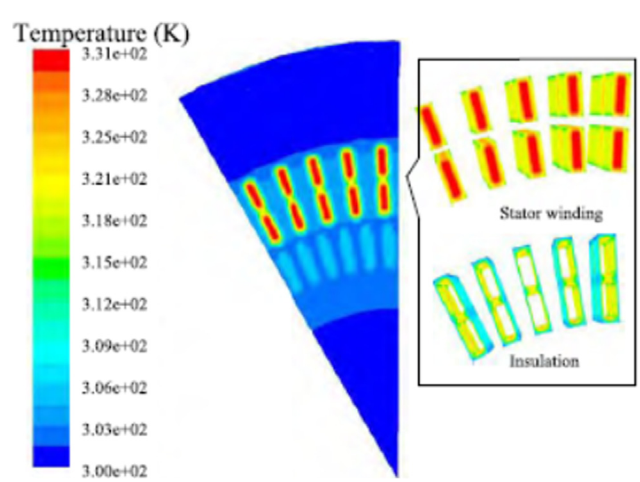

Fig. 6. Temperature distributions inside the induction motor [36].

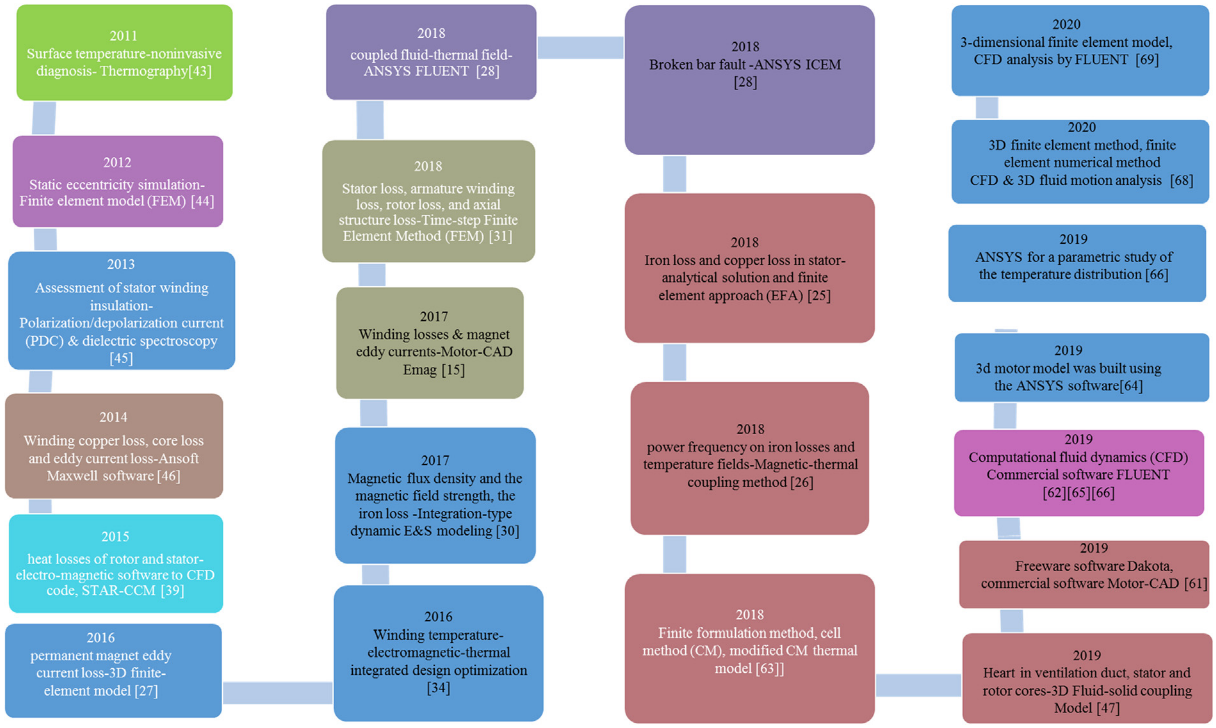

Fig. 7. Computer aided analysis to find losses.

The following techniques were used: Thermography, Simulation using FEM, PDC & dielectric spectroscopy, Ansoft Maxwell software, dynamic E&S modelling, design optimization, CFD, Motor CAD Emag, ANSYS FLUENT, ANSYS-ICEM, FEA method, SOLIDWORKS, commercial software Motor-CAD, cell method (CM), modified CM thermal model, 3D motor model using the ANSYS software, 3D fluid motion analysis and software Dakota. Taguchi methods are utilized to optimize the models.

3. Cooling methods

Motor cooling depends on conduction of lamination stacks, slot windings and end windings. It also depends upon the performance of the cooling jacket [37]. In thermal model, directions of the heat flows in the induction motor are important.

1. heat flow from the rotor bars through the air gap towards the stator winding and then to the stator iron then finally to the ambient through the round frame by convection.
2. heat flow from the stator end-winding and the rotor bars sides towards the end-cap air by convection and then to the ambient through the side frame by convection.

3.1. Cooling techniques for improving efficiency

Efficient cooling systems are essential to minimize the operating temperatures of the motor hot spots, and in particular of the copper windings. Thus, an accurate thermal modelling of the motor and of the coupled cooling system is important to optimize the thermal management of the engine. Water jacket cooling system removes more than 99.5% of the heat generated while the remaining portion is removed by natural convection [61]. By convection, heat is transferred from solid to either gas or liquid through the surface layer and can be either natural or forced convection [38]. The optimal flow rate for cooling is determined through an unsteady state analysis to predict according to the insulation grade [39]. A liquid-cooling system is often adopted where a cooling fluid (usually a 50% mix of water and glycol) is pumped into the components to be cooled and in a liquid–air heat exchanger, forced air cooled by means of cooling fans [40]. Oil spraying technique is used to cool the magnets in a safe operating temperature, increase their performance and also reducing their manufacturing cost. The oil-spraying cooling system, was designed to spray oil on the inside of the rotor of the electrical machine. Due to the high rotational speed the oil forms a thin film that absorbs the heat generated by the magnets [21].Water-ethylene glycol (WEG) circulated through three cooling channels within the cooling jacket [41]. The main technologies used in cooling electric motors include forced air cooling, direct water cooling, alternative cooling fluids, immersion cooling, heat pipes, phase change materials, vapour compression refrigeration, thermo electric cooling and Stirling cycle cooling. The novel cooling systems such as Malone refrigeration, pulse tube refrigeration, thermo ionic cooling, thermo acoustic refrigeration, magnetic refrigeration and ejector expansion refrigeration are still being studied or at research status [42]. Thermal diagnostics of motor windings, stator windings and temperature distribution inside the electric motors are presented [43–45]. Analysis of temperature rise, thermal losses and thermal performance are carried out in detail [46–48]. Forced convection on enhanced surfaces, different oil cooling systems and cooling of traction motors by combination of methods are reviewed [49–51]. Heat pipes are effectively used in thermal management of electric motors which simplify the system structure and save more space compared with the other methods [62]. Rotor is cooled using spiral stator water jacket that uses forced convection with water ethylene glycol mixture (50–50%) and oil spray cooling system. A new ventilation Cooling structure of the radial–axial mixed ventilation system is designed to safeguard the structure of the motor [63]. Temperature-rise rate of oil-cooled motor under rated working conditions viz. same electromagnetic structure, is slower than that of water-jacketed cooled motor and can work for longer periods. The oil-cooled method is one of the best methods to cool sta-

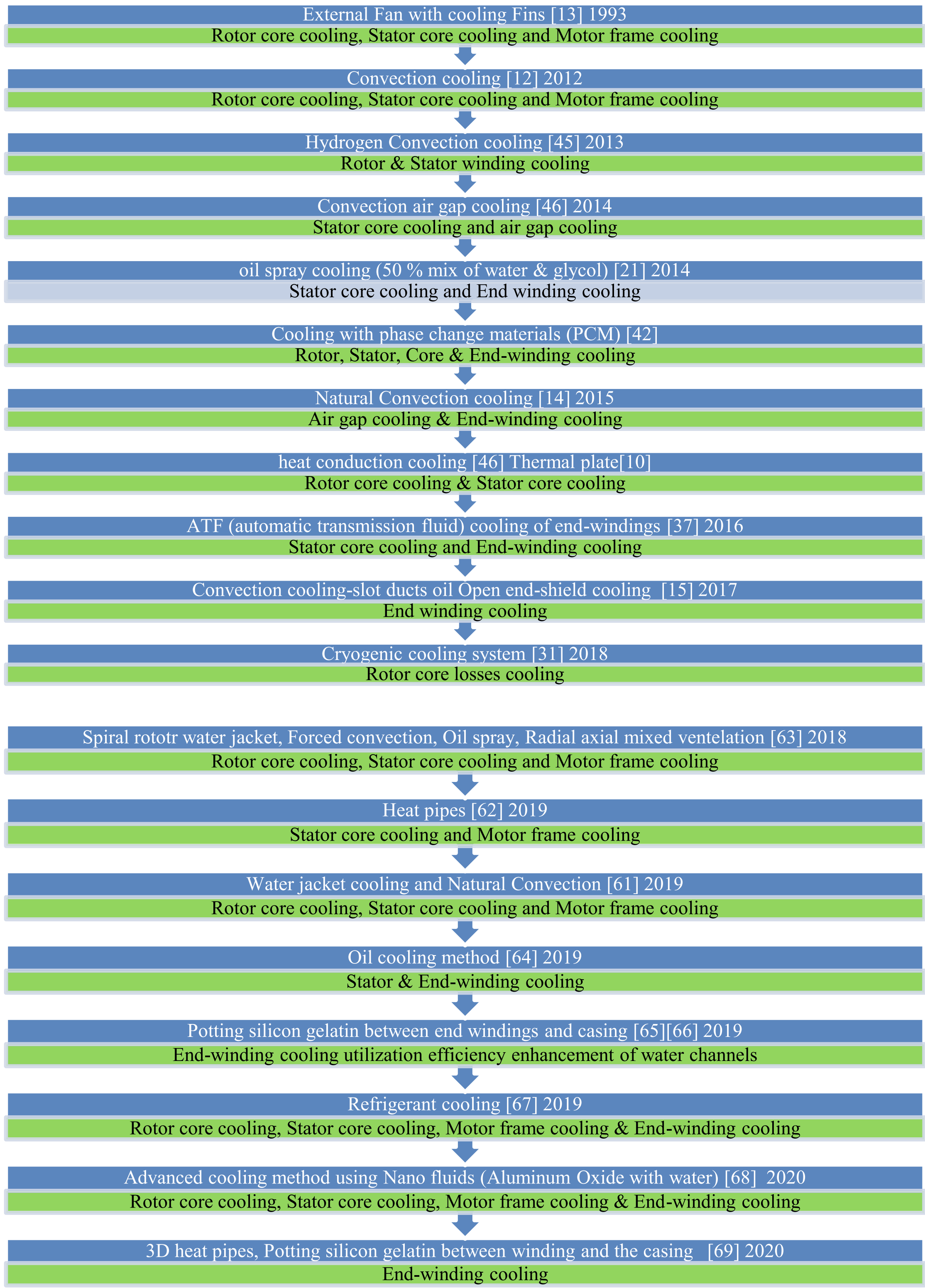

Fig. 8. Applied cooling methods.

tor and a direct oil-cooling method is proposed in the cooling the end winding with oil immersion [64]. Potting silicon gelatin is encapsulated in the gaps between the end windings and the casing to dissipate the heat generated in the end windings quickly and to enhance the utilization efficiency of the whole water channels [65,66]. In the recent research, the exprimental results predict higher cooling performance of electric motor with a refrigerant. Obtained rated torque with a refrigerant cooled motor is around 60% higher than that of water cooled motor [67]. Recently nanofluids are used as advance coolants in order to increase the heat transfer capability of the cooling system and to keep the temperature of the electric motor at operational level. A 4% of nanoparticle of

Aluminum-oxide with base fluid (pure water) increases the heat transfer capability of the cooling system up to 40% [68]. A very recent research is on introducing 3-dimensional heat pipes into the gap between the winding and the casing. Potting silicon gelatin is used to fix the heat pipes which also increase the contact area and the heat pipes with the combination of potting silicon gelatin can effectively improve the heat dissipation efficiency of the water-cooling. This technique is one of the best solution to solve the problem of high winding temperature [69]. A review on increasing efficiency of electric motors using cooling methods, lightweight materials and novel manufacturing processes is available [70]. Fig. 8 shows the applied cooling methods.

4. Research gap and future directions for research

In this review it is observed that thermal mapping tempature at various parts of the motor is not very clear. All the researchers pointed out ther there is rise in temperature but quantitative analysis is missing. High Temperature Superconductor (HTS) technology has to be investigated to improve efficiency of motors. Further study is required to find the arrangement of HTS tape in iron core to reduce losses. Vector control system of electric motors can be explored to reduce losses. Secondly, various cooling methods are studied but comparison of results and quantitative analysis are not explicitly mentioned. Further research can be done in Cryogenic cooling method, Hydrogen cooling method and cooling using phase change materials (PCM)/Heat pipe. Experimental studies are to be done on the novel cooling systems such as Malone refrigeration, pulse tube refrigeration, thermo ionic cooling, thermo acoustic refrigeration, magnetic refrigeration and ejector expansion refrigeration. Even combinations of various cooling methods for the parts of the motor may be applied since the parts of the motor are not equally stressed thermally. Hence, by adopting appropriate cooling methods, the temperature in the motor can be controlled which will enhance torque and efficiency of the electric machines. Optimized thermal management is required to be studied to visualize the electromagnetic effects brought by geometric changes dictated by thermal considerations. The selection of Grade F insulation material has to be studied further to meet the requirements of the motor for short-term temperature rise. Also, Impacts of adding three different amount of nanoparticles in the base fluid has to be studied to predict the thermal performance of the cooling system. An optimized efficient electric motor is the need of the hour for high torque transport applications leading to the mitigation of the effects of climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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