Thermal Analysis of a Permanent Magnet Synchronous Machine at Different Supply Voltage Levels

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***Abstract*—Compact high torque/power density motors are needed for electrical vehicles in modern electric cars, this calls for effective temperature control of the electric motors. The voltage level in automotive spans a large range, usually between 96Vdc and 800Vdc, which asks for flexibility in the development of the powertrains in general, and of their electrical machines in particular. This paper's primary objective is to evaluate the thermal analysis of a Permanent Magnet Synchronous machine at different voltage levels of the power supply.**

Keywords—electric vehicles, permanent magnet synchronous motors, thermal analysis, FEM analysis

I. Introduction

Modern times have seen a significant increase in interest in electrical vehicles (EV). This is primarily because of pollution restrictions brought on by the use of existing internal combustion engines. Current EVs experience an increasing energy consumption, which is due not only to the propulsion system, but also to the numerous auxiliary subsystems, such as heating and ventilation, battery thermal management systems, steering system, etc. A wider social acceptance of e-mobility requires performances optimization, both from the point of view of exploitation, but also from the point of view of charging. Increasing the voltage level represents the most efficient way to optimize performance. By increasing the voltage, the same power can be transmitted with a lower current, which can lead to a reduced cost and size of the electrical power equipment and lower charging time[1].

The development of electric powertrains is a current topic since almost all manufactures have started prototype production of EVs. There are different powertrain concepts, in terms of the type of electric drive and/or of the power source voltage level. Therefore, a tailored and scalable design process of the electric drive so that it meets the customers' requirements is an important asset for any EV powertrain components' producer.

The electrical machine (EM) is one of the key components of an EV powertrain. Its design process involves a multiphysics approach, in which magnetic, thermal and mechanical phenomena are analyzed taking into account their interdependence. There are several approach scenarios, based on the application and technological constraints. Each constraint, either geometrical, dimensional or technological reduces the number of degrees of freedom in designing or redesigning the machine. As the power source voltage ranges from $96\,V_{dc}$ to $800\,V_{dc}$, the EM manufacturer has to adapt the design for the defined voltage level, without a negative impact on the manufacturing costs. A feasible solution is to keep the same magnetic circuit and resize the winding [1].The present paper addresses the impact of the power source voltage level on the losses and thermal behavior.

Section II of the paper addresses the theoretical support for winding dimensioning in an AC machine. After the main losses in electrical machines are described (Section III), Section IV presents the topology of the machine under study, while the results of the analysis for five voltage levels of the power supply are analyzed in Section V. Section VI presents the conclusions and perspectives of the work.

II. Winding Redesign Procedure

When designing an AC EM winding, the first step to take is choosing the winding type and configuration. Single versus double layer, concentrated versus distributed winding, series or parallel connections are aspects to be defined. The number of turns per phase, N_{ph}, results from the peak value of the electromotive force (emf):

$$E_{ph\max} = \omega \psi_{ph\max} \tag{1}$$

where ω is the pulsation and $\psi_{ph\max}$ represents the total linkage flux given by:

$$\psi_{ph\max} = N_{ph} B_{\delta\max} \frac{\pi D_{is}}{2p} L \tag{2}$$

where $B_{\delta\max}$ represents the magnitude of the airgap magnetic flux density; D_{is}, the interior stator diameter; L, the stack length and p the number of pole pairs.

Finally, by taking into account the winding factor, k_w the maximum induced emf and the expression of the pulsation, results as:

$$E_{ph\max} = k_w \frac{\pi^2}{60} N_{ph} B_{\delta\max} D_{is} L n = k N_{ph} n D_{is} L \tag{3}$$

with

$$k = k_w \frac{\pi^2}{60} B_{\delta\max} \tag{4}$$

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When redesigning the winding for the same magnetic circuit, the main goal is that it develops the same magnetomotive force (mmf) and that it fits in the same slot area.

Considering that the main dimensions of the machine, L and D_{is} cannot be changed, (3) becomes:

$$E_{ph\max} = k_1 N_{ph} n \tag{5}$$

with

$$k_1 = k_w \frac{\pi^2}{60} B_{\delta\max} D_{is} L \tag{6}$$

Thus, the number of turns per phase results as:

$$N_{ph} = \frac{E_{ph\max}}{k_1 n} \tag{7}$$

The number of coils per phase is given by:

$$n_{coil\_ph} = Z_s \frac{n_{layer}}{2m} \tag{8}$$

with Z_s the number of stator slots, n_{layer} , the number of winding layers (double or single) and m , the number of phases. The number of turns per slots results as:

$$N_{slot} = \frac{N_{ph}}{pq} \tag{9}$$

with q the number of slots per pole and phase:

$$q = \frac{Z_s}{2pm} \tag{10}$$

For a DC power supply, the phase voltage for a star connected three-phase machine is:

$$U_{ph} = \frac{V_{dc}}{\sqrt{6}} \tag{11}$$

and it can be written that:

$$u_{ph} = R_{pf} i_{ph} + \frac{d\psi_{ph}}{dt} = k_e u_{ph} + \frac{d\psi_{ph}}{dt} \tag{12}$$

With u_{ph} the phase voltage given by:

$$u_{ph} = \sqrt{2} U_{pf} \sin \omega t \tag{13}$$

R_{ph} and i_{ph} are the phase resistance and current, respectively, $\frac{d\psi_{ph}}{dt}$ the phase-induced emf:

$$\frac{d\psi_{ph}}{dt} = E_{pf\max} \sin \omega t \tag{14}$$

and $k_e < 1$. The phase current results from:

$$I_{ph} = \frac{S}{3U_{ph}} \tag{15}$$

with S the apparent power. For a current paths and w branches in parallel per phase the cross-sectional area of conductor is:

$$s_c = \frac{I_{ph}}{awJ} \tag{16}$$

Based on (7), (14) and (15) the mmf of one phase results as:

$$\begin{aligned} N_{ph} I_{ph} &= \frac{E_{ph\max}}{k_1 n} \frac{S}{3U_{ph}} \\ &= \frac{(1-k_e)\sqrt{2} U_{ph}}{k_1 n} \frac{S}{3U_{ph}} \\ &= \frac{(1-k_e)\sqrt{2} S}{3 k_1 n} \end{aligned} \tag{17}$$

For the same winding factor and imposed maximum magnetic flux density (see Eq. (6)) the mmf depends on the defined rated apparent power and speed of the machine and on phase resistance and current, through k_e .

The area occupied by copper in a slot results:

$$A_{copper} = s_c N_{slot} \tag{18}$$

and it can be considered more or less the same for different voltage levels, as the number of turns per slot increases with the voltage level and the phase current, and implicitly the cross-sectional area of conductor is decreasing with the voltage level. Special attention should then be given to the insulation layers such that the filling factor does not exceed the technologically allowed value.

III. Losses in Electrical Machines

Failure to properly analyze the thermal properties of the electric motoring unit is one of the main problems with electric vehicles. A detailed thermal study of the motoring system aids in lowering the thermal losses linked to the system and, as a result, raising the motor's efficiency[2].

The specifics of how to address the issue of rising temperatures are crucial when attempting to increase a motor's output and efficiency. Since the losses are a source of heat, it is crucial to investigate a magnetic design that lowers the losses themselves, but it is also important to investigate a thermal design that improves heat dispersion and prevents the temperature from rising.

Copper loss in the coils and iron loss in the core are the dominant heat sources, so this analysis is focused on the effects of this heat. Due to the magnet's low heat resistance and significant temperature-related changes in its properties, it is essential to design with operational temperature increases in consideration.

The current flowing through the coil determines copper losses (Joule loss) which is one of the major losses in electrical machines.

$$p_{joule} = \sum_{1}^{m} R_{ph} I_{ph}^2 \tag{19}$$

The second main losses are Iron loss (Eddy currents and Hysteresis loss) which are caused by the magnetic flux that crosses the core and experiences time fluctuations.

The Hysteresis losses generated by the n harmonic of the magnetic flux density can be approximated by:

$$p_H = kVf_n B_{n\_\max}^x \tag{20}$$

where the V represents the volume of the material, f_n and $B_{n\_\max}$ represent the frequency and the magnitude of the n-harmonic of the magnetic flux density. The exponent x varies typically over $[1.5, 2.5]$, k being an empirical constant.

The eddy currents losses can be calculated with:

$$p_{eddy} = \frac{n^2 V f_n^2 \Delta^2 B_{n\_\max}^x}{6\rho} \tag{21}$$

with Δ being the sheet thickness and ρ the sheet material resistivity.

For the rotor permanent magnets (PMs) the Eddy current losses are computed, but only taking into account the slotting and the spatial harmonic field caused by fundamental current. A more comprehensive analysis of eddy currents losses in PM has to include the control strategy influence [3].

The heat generated by these losses transfers to the interior of the motor's structure, raising the temperature of each component of the motor.

IV. Study Case

A. Machine under the study

The machine under the study is a 24/10 poles PMSM with rare earth permanent magnets (NeFeB), which has been optimized to operate at 3000 rpm rated speed fed from a 96 V_{dc} battery. The main specifications of the machine are given in Table I [1].

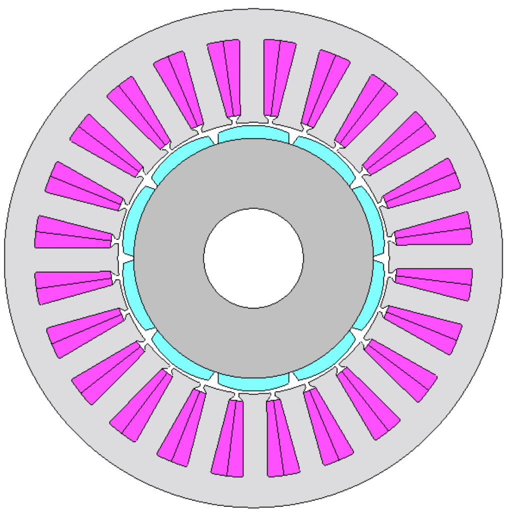

Fig. 1 The PMSM under the study

TABLE I. PMSM Voltage level

Parameter	Unit	Value
Number of pole pairs, p		5
Stator outer diameter , D_{os}	$[mm]$	220
Rotor outer diameter , D_{or}	$[mm]$	117.6
Air gap length , δ	$[mm]$	1.2
Stack Length , L	$[mm]$	40
Rated voltage , V_{dc}	$[V_{dc}]$	96
Rated torque , T_N	$[Nm]$	32
Rated speed , N_N	$[rpm]$	3000

B. Methodology

The study case targets the redesign of the machine winding, so it fits the power source voltage level, V_{dc}, as it is presented in Table II and the analysis of the power source voltage level on the thermal behavior of the machine. For the same topology of the inverter, the rms values of the phase voltage and current are computed and listed in the same table.

TABLE II. PMSM Voltage level

Case	Vdc [V]	Maximum current [A]	Phase voltage [V]	Phase resistance [Ω]
PMSM1	96	127	40	0.00419
PMSM2	120	104	50	0.0045
PMSM3	400	33.7	163	0.044
PMSM4	600	23.8	245	0.085
PMSM5	800	16.6	326	0.18

The methodology to be used in the study case is presented in Fig 2. Based on the electromagnetic model developed in a FEM-based software package an electromagnetic analysis is performed for the rated speed and power, at the power source voltage level given in Table II. The electromagnetic performances and the losses are analyzed, and the former are introduced in the thermal model of the machine developed also in a 2D FEM software package. The evolution of the temperature in the main parts of the machine is extracted and the impact of the voltage level is analyzed.

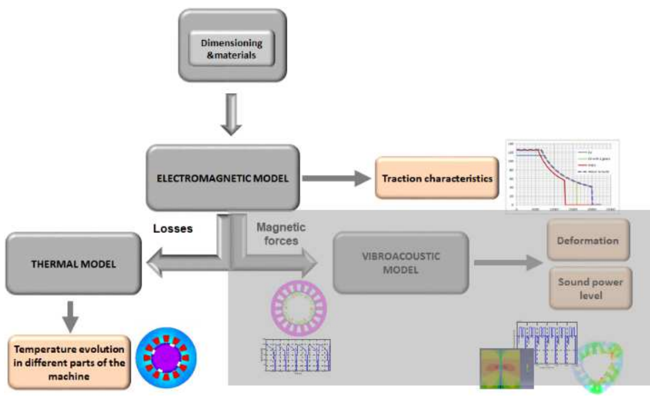

Fig.2 Study case methodology

V. Analysis and Results

A. Electromagnetic analysis and losses computation

The electromagnetic analysis provides information on the electromagnetic and electromechanical performances of the machine, for the considered voltage level in Table II. The electromagnetic torque is depicted in Fig. 3, and the average torque and torque ripple content is presented in Table III [1].

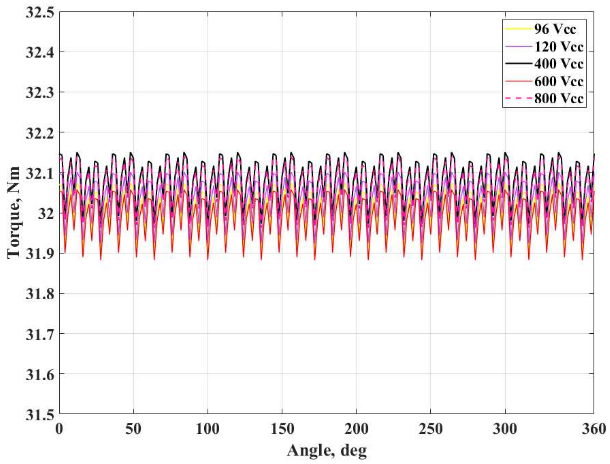

Fig. 3 Electromagnetic torque at rated speed

TABLE III. ELECTROMAGNETIC AND ELECTROMECHANICAL PERFORMANCES

	PMSM1	PMSM2	PMSM3	PMSM4	PMSM5
T_{av} [Nm]	32	32	32	31.99	31.99
Ripple content [%]	0.54	0.55	0.553	0.547	0.553
$B_{\delta\max}$ [T]	1.15	1.15	1.175	1.164	1.175
$B_{\delta rms}$ [T]	0.788	0.7886	0.7886	0.7887	0.7886

The magnetic flux density along the airgap has similar maximum and rms values for all the studied cases. Moreover, as it can be noticed, a different power source voltage level doesn’t have an important impact on the electromechanical performance (average torque and torque ripple content).

For the iron losses computation, the harmonic content of the magnetic flux density is of utmost importance. The magnetic field density in the stator teeth and yoke, as well as in the rotor yoke and permanent magnets are depicted in Fig. 4 for all studied cases. The frequency and magnitude of the main harmonics are given in Table IV.

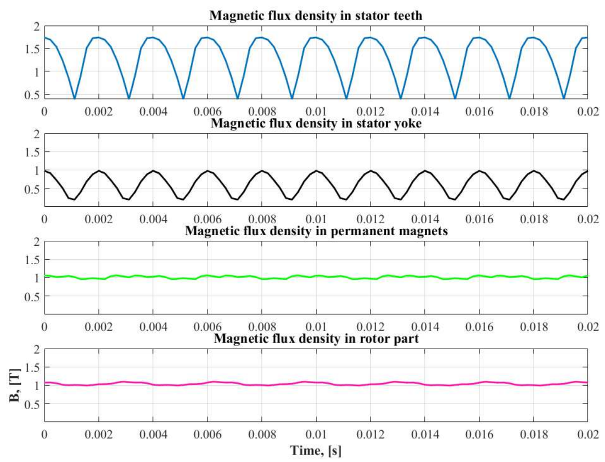

Fig. 4 Magnetic flux density in stator teeth and yoke, as well as in the rotor yoke and PMs

The harmonic content of magnetic flux density can have a considerable impact on electrical machine performance and efficiency. High levels of harmonics, for example, can result in higher Iron losses, increased Copper losses, and decreased machine efficiency. Furthermore, excessive levels of harmonics can cause increased electrical noise and bearing currents, which can affect machine reliability. In the case studied, the magnitude of the main harmonics ($\boldsymbol{B_1}$, $\boldsymbol{B_3}$ **etc.**) depicted in Table IV have slow values which indicates that the waveform is relatively close to an ideal waveform and has minimal deviation. The fundamental harmonic in the stator teeth is the most dominant which illustrates that the stator part is the main heat source of the motor.

TABLE IV. FREQUENCY AND MAGNITUDE OF THE MAIN HARMONICS OF THE MAGNETIC FIELD DENSITY

Parts	Frequency, [Hz]			
Rotor	300	900	1500	2100
	B_1 [T]	B_3 [T]	B_5 [T]	B_7 [T]
	0.0508	0.0020	0.00036	0.00010
PMs	0.00136	0.00088	0.00025	0.0032
	Frequency, [Hz]			
Stator Yoke	250	750	1250	1750
	B_1 [T]	B_3 [T]	B_5 [T]	B_7 [T]
	0.922	0.042	0.011	0.012
Stator Teeth	1.477	0.134	0.043	0.020

It is abnormal when the fundamental harmonic frequency at the rotor portion of an electric machine does not match the fundamental frequency at the stator portion of the machine. This can be the result of a fault with the machine's current supply. The magnetic flux in the motor might be impacted and new harmonics created if the power source is unstable or displays severe distortion.

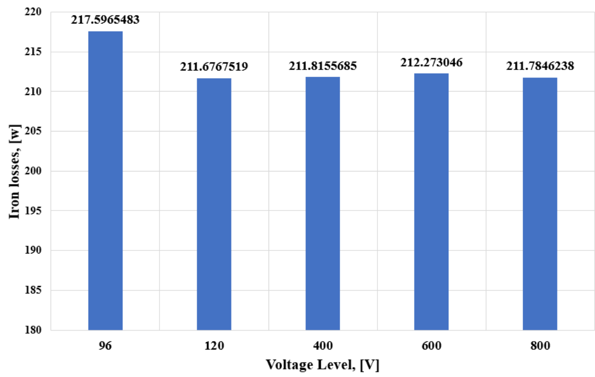

Fig. 5 Iron losses (stator and rotor) in PMSM

Fig. 5 depicts the total Iron losses (stator and rotor losses) for the PMSM at different voltage level supply. The Iron losses in the stator are dominant while in the rotor the values of the Iron losses are around 12 W.

The Joule losses in the coils (total losses) are presented in Fig. 6. While the voltage level increases, the Joule losses in coils decrease because the current’s values are smaller.

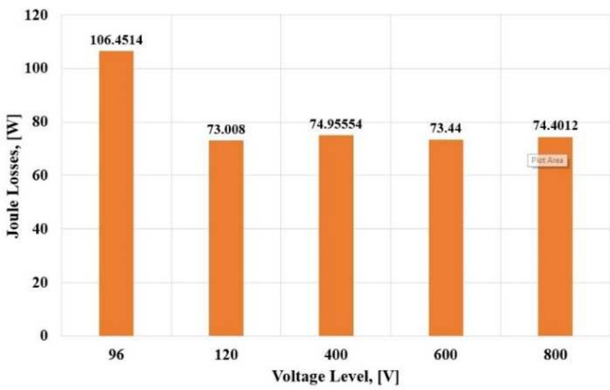

Fig. 6 Joule losses (coils) in PMSM

Even though the current is lower, the phase resistance increases with the number of turns/phase and the losses are maintained at similar values for 120 Vdc, 400 Vdc, 600Vdc and 800 Vdc. A slightly higher Joule losses level corresponds to PMSM1, powered by a voltage level of 96 Vdc.

B. Thermal modelling and results analysis

In steady state, the thermal circuit is made up of thermal resistances and heat sources that are connected between the component nodes [4].

In electrical machines, heat transfer is a combination of conduction within solid and laminated components and convection from surfaces in contact with air or other cooling fluids.

In general, the geometric complexity of an electric machine necessitates a broad thermal network if a solution with high temperature distribution resolution is needed. Instead of employing a huge, complex model, the machine's geometrical symmetries were employed to minimize the model's order [4]. The distributed thermal properties have been combined to produce a smaller thermal network that represents the entire machine, which is illustrated in Fig. 7.

A thermal equivalent circuit is used to evaluate characteristics while taking temperature into account. As heat sources, this circuit employs Copper loss in the coils and Iron loss in the stator core and rotor. The coil resistance and magnet flux are adjusted using the temperature acquired from thermal equivalent circuit calculations. The entry points correspond to the losses computed in the electromagnetic analysis. It is assumed that the machine has no cooling, and the natural convection is taken into consideration. The simulations analysis considered a 20 deg. C ambient temperature.

There are two types of resistances based on the form of thermal exchange between the surfaces of the concentric cylinders they represent: one is convection heat transfer through the surface separating a solid mass from the fluid.

The radial thermal resistance of a hollow cylinder can be computed as follows [4]:

$$R_{conduction} = \frac{\ln(\frac{r_0}{r_i})}{3\pi kL} \quad (22)$$

With r_0 , r_i the outer radius and inner radius of the cylinder, L is the axial length and k represents the thermal conductivity of the material.

If there is temperature exchange due to convection, the heat-transfer rate is proportional to the overall temperature difference between the surface and fluid as well as the convection area and may be computed using (23) [4]:

$$R_{convection} = \frac{1}{hA} \quad (23)$$

where h is called the convection heat transfer coefficient.

The thermal equivalent circuit used in simulations of PMSM presented in this paper is illustrated in Fig. 7.

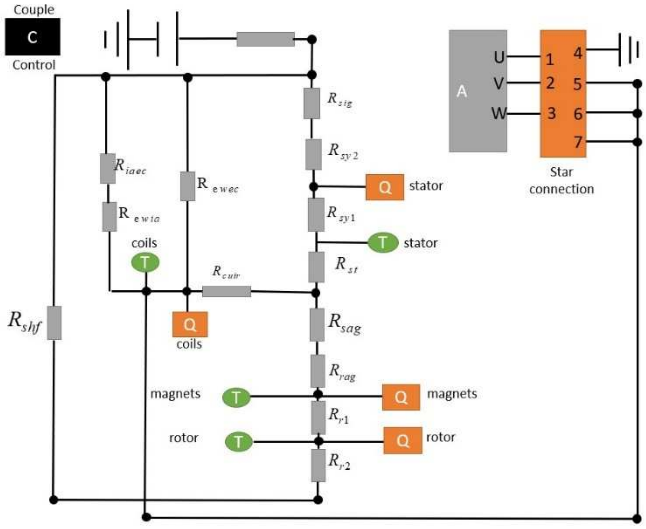

Fig 7. Thermal equivalent circuit

In the table below, the full meaning of the resistances used in the thermal circuit are explained[5, 6].

TABLE V. THERMAL RESISTANCES

	Meaning of the thermal resistance
R_{sy1}	Radial conduction thermal resistance of the Outside Stator Yoke
R_{sy2}	Radial conduction thermal resistance of Inside Stator Yoke
R_{st}	Radial conduction thermal resistance of Stator Teeth
R_r	Conduction thermal resistance of Rotor part
R_0	Natural convection thermal resistance between external case and ambient
R_{ewec}	Convection thermal resistance between Winding and External Case
R_{cuir}	Conduction thermal resistance between Winding and Stator Slot
R_{sig}	Conduction thermal resistance between Stator Core and External Case
R_{sag}	Convection thermal resistance between stator teeth and airgap
R_{rag}	Convection thermal resistance between Rotor and airgap
R_{iaec}	Convection thermal resistance between Internal Air-Endcap
R_{ewia}	Convection thermal resistance between stator winding and Inner air

The values of the temperature during the operation of the machine at rated speed for each of the cases are presented in table below. The values represent the maximum temperature reached in steady state analysis of PMSM.

TABLE VI. MAXIMUM VALUES OF TEMPERATURE IN DIFFERENT PARTS OF THE MOTOR

Parts	**PMSM1 (deg C)**	**PMSM2 (deg. C)**	**PMSM3 (deg. C)**	**PMSM4 (deg. C)**	**PMSM5 (deg. C)**
Stator	171.82	124.123	126.901	124.74	126.110
Rotor	165.148	119.547	122.203	120.136	121.447
PM	165.351	119.687	122.346	120.277	121.589
Coils	190.92	137.225	140.3522	137.918	139.462

The highest level of temperature is found in coils, being determined by the value of the current and by the resistance of the winding.

The temperature decreases from 190 deg C to 140 deg C in the coils once the voltage level increases, but the current value decreases. Therefore, decreasing the values of the current determines a lower temperature in the PMSM.

For the PMSM3, where the voltage level is equal to 400 V_{dc} and the current value is decreased, the temperature in different parts of the is close to the second study. The reason why the temperature is not decreasing even though the value of the current is decreased, it is the increased values of the winding resistance and the increased number of turns/phases in order to maintain the operating condition of the PMSM (same speed and torque).

It can be concluded from Table VI that the highest temperature in PMSM under the study is found in coils, followed by the stator part, which represents also the main heat sources of the machine.

In Fig. 8 the total losses of the PMSM are compared with the voltage level supply.

Iron losses remain constant, and the voltage level does not affect their value. The losses in the coils have higher values at the voltage level of 96 V_{dc} and then they start to stabilize at a certain value even though the voltage level increases.

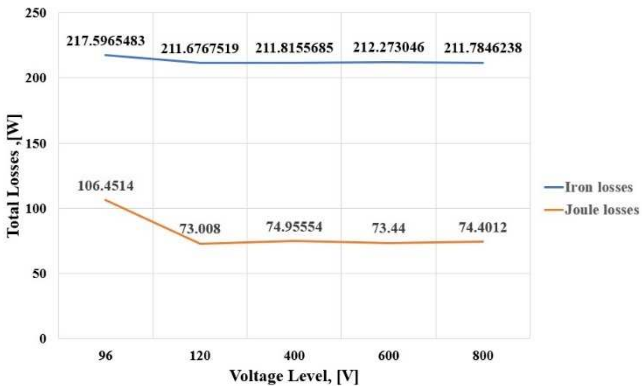

Fig 8. Total losses of the PMSM vs voltage level supply

VI. Conclusions And Perspectives

This paper presents a thermal analysis of a PMSM used for small electric vehicles at different power source levels and shows the impact of the power source level on the losses and thermal behavior.

The temperature decreases while voltage supply level is increased but the temperature is still too high to operate in safe conditions.

The temperature of PMSM may or may not rise when the current in the windings is lower, depending on the specific conditions and operating parameters of the machine.

In general, lower current in the windings will result in lower power dissipation and lower losses in the machine, which may result in a lower temperature of the PMSM.

However, there may be other factors that can affect the temperature, such as the cooling system efficiency, the environmental temperature, and the operating conditions of the machine.

The winding of PMSM is redesigned for every voltage level studied presented in this paper. Thus, this process can affect the temperature of the PMSM. The design of the winding affects the current density and resistance, which are all factors that contribute to the generation of heat in the windings. By optimizing the winding design, it is possible to reduce the copper losses, which can result in lower temperature rise and improved efficiency of the PMSM. For the cases studied the wire size and the number of turns was adapted based on the procedure presented in this paper which caused a reduction in temperature, but subsequently increasing the number of windings caused an increase in resistance, which caused the temperature to remain at similar values.

The maximum operating temperature for Neodymium magnets is around 150 deg C so for the first voltage level supply of PMSM1 (96 V_{dc}) the temperature of the magnets is too high which will determine damage to magnetic properties of the permanent magnets[7].

Rising the voltage supply determines decreasing the current values, which determines smaller losses in the coils but even so, the temperature in coils resulted in analysis still have high values for a good operation of the PMSM.

In future work the methods of cooling the engine will be analyzed in order to lower the temperature in the PMSM.

In the construction of the thermal circuit, radiation was not considered, which can cause errors in the system so in the future work radiation heat transfer needs to be considered, also developing a more accurate thermal circuit for the PMSM will be studied.

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