Transient Lumped Parameter Thermal Model Based Loadability Studies for The YASA Axial Flux Permanent Magnet Synchronous Machines

Abdalla Hussein Mohamed, Hendrik Vansompel, Ahmed Hemeida and Peter Sergeant

***Abstract*—In this paper, the short time duty and the intermittent duty of a 4 kW yokeless and segmented armature (YASA) axial flux permanent magnet synchronous machine (AFPMSM) are calculated based on the transient lumped parameter thermal network (LPTN) model of this machine. The evaluation of these duties is crucial for efficient utilization of the machine in applications where the load is fluctuating or requires high power for a short time. The results show that the 4 kW machine can be loaded up to 2.7 of its continuous rating for 30 minutes and up to 2.5 of its continuous rating for 60 minutes without exceeding the insulation breakdown temperature or the demagnetization temperature of the permanent magnets (PMs). Also, results reveal that for periodic loads of period 10 minutes and duty cycle 0.6 the machine can be loaded up to 3 times its continuous rating and more than that for lower duty cycles.**

***Index Terms*—YASA, AFPMSM, LPTN, Intermittent rating, Transient model.**

I. Introduction

Many types of axial flux permanent magnet synchronous machines exist. These types differ in the number of stators and rotors and the location of them in the machine. Some of these types are axial flux internal rotor (AFIR), toroidally wound internal stator (TORUS), axial flux internal stator (AFIS) and yokeless and segmented armature (YASA) [1]. The absence of the stator yoke in the YASA type makes it more efficient as it means that the staor core has less iron and hence, less core losses. The complete design and optimization of the YASA machine or any other machine needs accurate electromagnetic, thermal and mechanical models for the machine. Two methods for studying thermal modeling exist, the finite element method (FEM) and the lumped parameter thermal network method (LPTN). References [2]–[5] are some of the papers presenting the FEM thermal modeling technique for the YASA machine while [6]–[8] studied the LPTN modeling method. The LPTN method has the advantage of being fast enough while on the other hand the FEM method provides a more detailed temperature distribution in every part but on the cost of the time. The LPTN developed in [8] has the advantage of providing the transient thermal response of the machine that is why it is chosen to study the short time ratings and intermittent ratings of the YASA machine in this paper.

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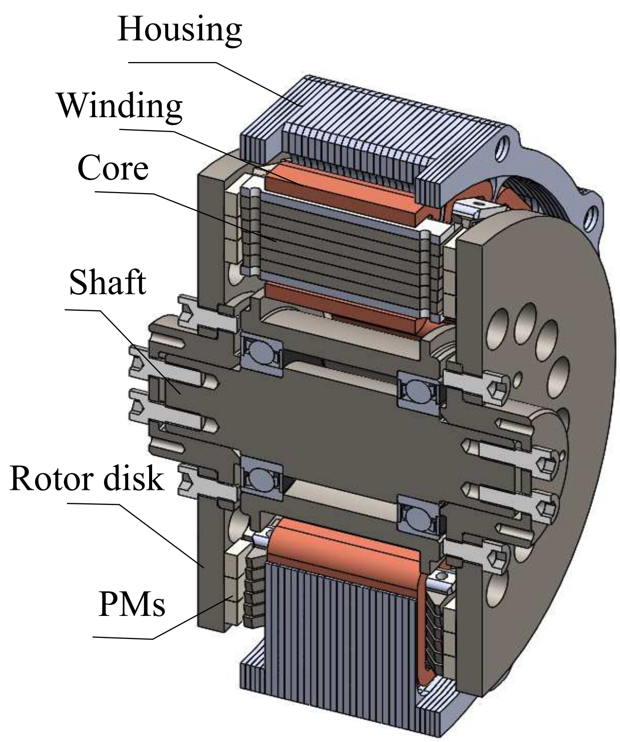

Fig. 1: Cross-section view of the YASA prototype

II. YASA lumped parameter thermal network

A brief description of the lumped parameter thermal model developed by the authors and adopted for studies in this paper is given in this section. The details of that model can be found in [8]. In this model the rotor and the stator are represented by two different networks coupled by the analytical convection heat transfer coefficients in [9], [10]. The lumped parameter thermal network (LPTN) is a network of thermal resistors, capacitors and heat sources. The solution of the network gives the average temperature of each element represented by a node in this network. The values of these resistors and capacitors are driven from the material properties and geometry of the machine under study. The geometry of the YASA machine under study is shown in Fig. 1 while, the material properties are given in Table I.

The heat sources come from the power losses in the machine. The different power losses in the machine are the winding losses, core losses, PM losses and rotational losses. These losses are calculated from the electromagnetic model of the YASA machine in [11],[12] and computational fluid

TABLE I: Material properties.

Material	K (W/mK)	C_p (J/kgK)	ρ (kg/m^3)
copper	385	392	8890
aluminum	167	896	2712
epoxy	0.4	600	1540
nylon	0.25	1600	1140
Nd-Fe-B	9	500	7500

dynamics based model in [13]. The stator and rotor LPTNs are shown in Figs. 2 and 3 respectively.

The reference temperature appearing in the LPTNs represents the temperature of the air near to the convected surface.

III. Temperature Profiles at Continuous rating

The geometrical parameters of the 4 kW YASA axial flux machine under study are listed in Table II. The continuous rated power and speed along with the different power losses at these rated values are listed in Table III.

TABLE II: YASA Geometrical Parameters

Parameter	Value	Unit
number of poles	16	-
teeth number	15	-
outer diameter housing	195	mm
outer diameter active	148	mm
PM thickness	4	mm
rotor outer radius	74	mm
slot width	11	mm

TABLE III: Continuous Rated Values

Parameter	Value	Unit
rated power	4	kW
rated speed	2500	RPM
rated torque	15.27	N.M
copper losses	59.027	W
core losses	44.973	W
PM losses	16.783	W

The winding insulation class is B which breaks down at 130°C [14] while, the demagnetization temperature of the rotor magnets is 150°C [15]. So, at any operating conditions the winding temperature should be kept lower than 130°C and the permanent magnets temperature below 150°C.

The winding T_{wdg}, stator core T_{core} and PM T_{PM} average temperature variation with time at the operating conditions in Table III is shown in Fig. 4 assuming an ambient temperature of 25°C. The steady state average temperature of the winding and the core is 47.5°C while the steady state average temperature of the PMs is 29.5°C.

Many remarks can be deduced from Fig. 4 as follows,

1) The steady state temperature of both winding and PMs is much lower than the critical values which means that the machine can be loaded with a much higher load without thermal problems.
2) The winding and core temperatures are almost the same due to the high thermal conductivity of the core material and the winding material and the good thermal contact between the core and the winding.
3) The thermal time constant of the PM is almost half of that of the winding. This returns to the lower specific heat capacitance of the PMs and the smaller volume compared to the winding.
4) The temperature variation is almost exponential with time.

IV. Evaluation of the short-time duty of the machine

The transient time taken by the machine to reach its final steady state temperature can be utilized by loading the machine with a higher power than its continuous rated one but for a short time. This amount of over power is calculated in a way that the machine doesn't reach its critical temperature after that short time. Usually the short-time duty of the machine is referred to by S2 followed by the allowed short time.

A. S2-60 rating

The flow chart in Fig. 5 shows how the short time duty rating of the machine is calculated for any given short time.

Table IV shows the final calculated load power and different power losses at that load.

TABLE IV: S2-60 rating and losses

Parameter	Value	Unit
load power	10.34	kW
copper losses	384.34	W
core losses	70.836	W
PM losses	89.246	W

As indicated in Table IV, the machine can be loaded up to 2.58 of its continuous rating for one hour without thermal problems. Fig. 6 indicates the temperature variation at the S2-60 rating of the machine.

From Fig. 6, the winding temperature reached its limit after one hour while, the PM temperature is still far from its limit.

B. S2-30 rating

Table V has the S2-30 power rating of the machine along with the power losses at that loading.

TABLE V: S2-30 rating and losses

Parameter	Value	Unit
load power	10.89	kW
copper losses	421.56	W
core losses	73.715	W
PM losses	97.5	W

It is interesting to see from Table V that the S2-30 rating of the machine is only 5.3% higher than that of its S2-60 one. This can be explained by noticing from Fig. 7 the difference in rate of rise of the machine temperature resulting from difference in values of heat sources and reference temperatures.

It worth mentioning that the above two short time ratings are both evaluated at the rated speed of the machine.

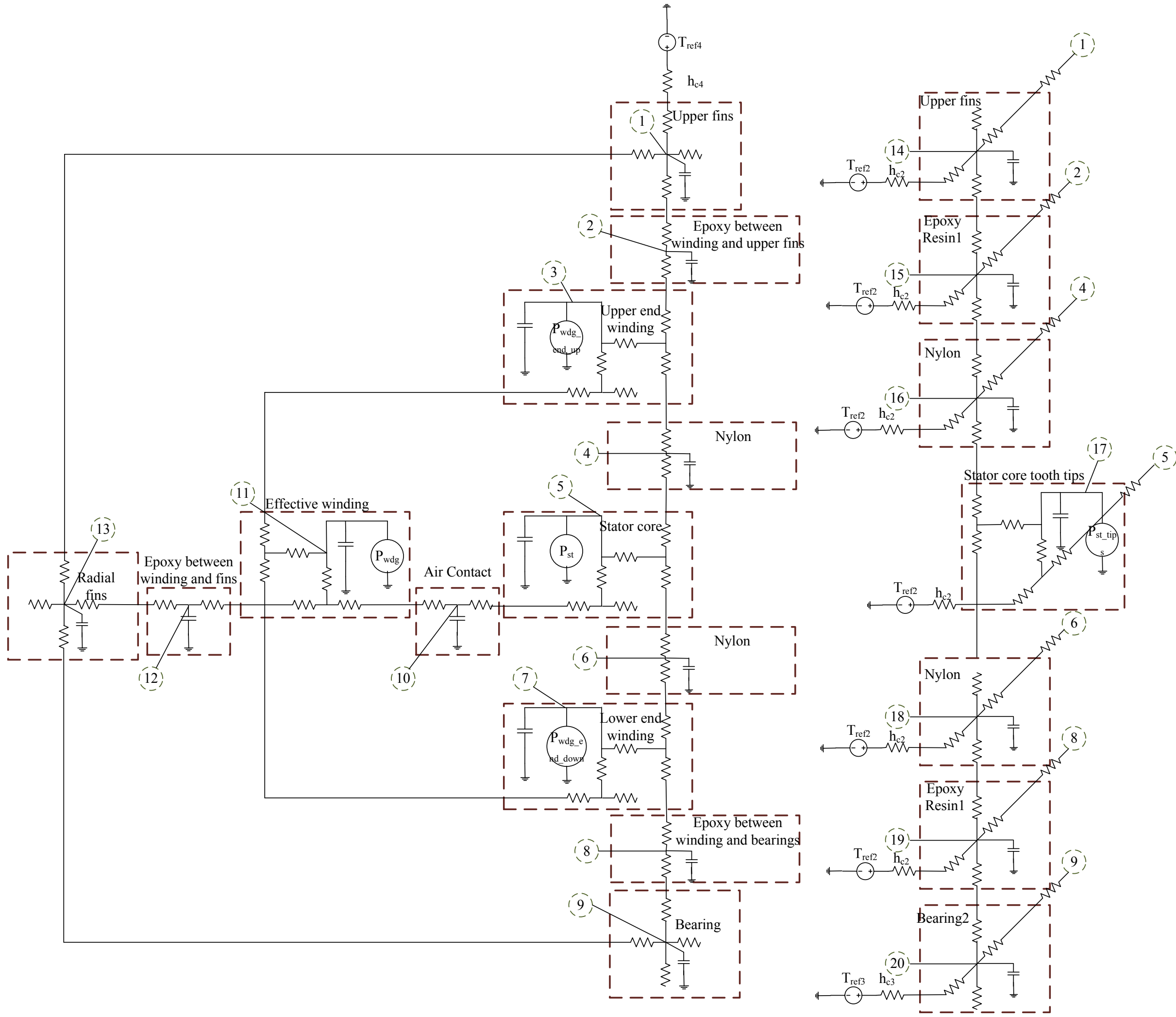

Fig. 2: LPTN of the stator.

V. Evaluation of the intermittent duty of the machine

The intermittent duty is usually referred to by S3 followed by the duty cycle of the operation for 10- minute cycles. Each cycle includes some time of machine operation and some time the machine in rest.

TABLE VI: S3-60% rating and losses

Parameter	Value	Unit
load power	12.295	kW
copper losses	537.37	W
core losses	82.58	W
PM losses	123.16	W

A. S3-60% rating

The flow chart in Fig. 8 describes the method used for calculation of the S3 rating of the machine at any given duty cycle.

At steady state the temperature of the different machine parts oscillates between two fixed maximum and minimum values. Here, the S3 rating is calculated in a way that the maximum temperature of any part doesn't exceed the critical value. Table VI contains the S3-60% rating of the machine and also the different losses.

Fig. 9 shows the winding temperature variation with time along with the copper-loss variation. The temperature fluctuates between 100°C and 130°C.

By inspecting Fig.10 the PM temperature is still below the critical value.

It is useful to mention here that the rate of change of the machine temperature depends on the values of the heat sources, the reference temperatures, the thermal resistances and the thermal capacitances. And, due to the different heat sources, reference temperatures and convection coefficients in case of machine in operation and machine at rest, the rate of temperature rise is different than the rate of temperature fall Figs. 9 and 10.

B. S3-25% rating

The S3 rating at 0.25 duty cycle is also computed to have a feeling of the variation of the intermittent rating with the duty cycle. The S3 25% rating along with the machine losses are listed in Table VII. The 58 % reduction in the duty cycle resulted in 37% increase in the rating.

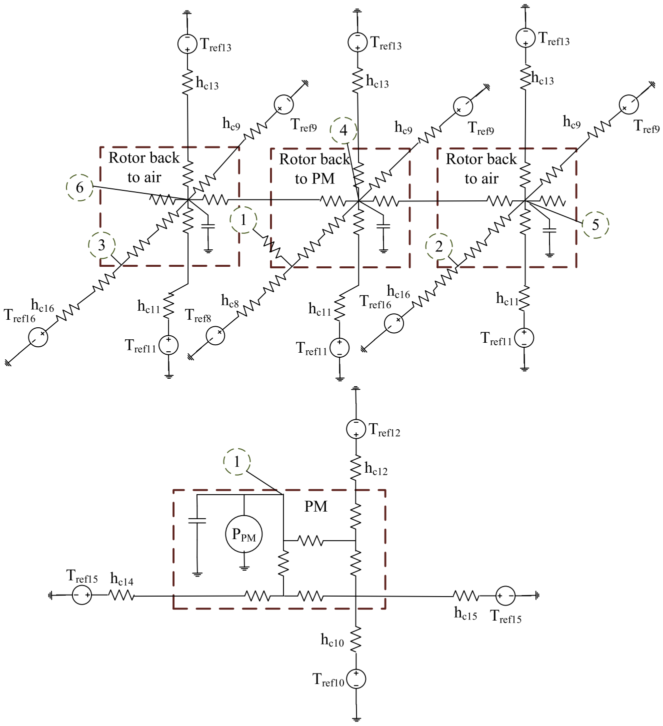

Fig. 3: LPTN of the rotor.

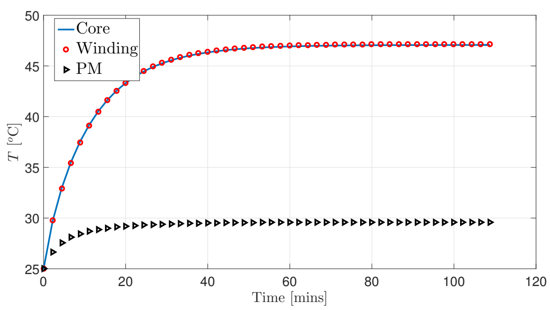

Fig. 4: Winding, Core, PM average temperature variation at rated conditions

TABLE VII: S3-25% rating and losses

Parameter	Value	Unit
load power	16.85	kW
copper losses	1.01	kW
core losses	118.6504	W
PM losses	227.8626	W

VI. Effect of Speed Variation

It is very important to mention that the ratings in the previous sections are calculated assuming that the machine is operating at fixed speed which is the rated one. But, in case of variable speed applications care should be taken when calculating these ratings. Because the reduction of the machine speed has the effect of reducing the core and PM losses and in the same time reducing the convection coefficients. So, at the end this may result in a higher or a lower machine temperature. To clarify this point, Fig. 11 is generated at S2-60 rating reported in Table IV at different speeds. As indicated in the figure, at 16% of rated speed the winding temperature exceeds the critical limit. So, at every short-time and intermittent rating there is a limit on the lowest speed.

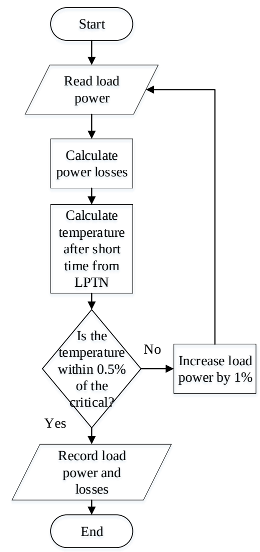

Fig. 5: Flow chart for calculating short-time duty

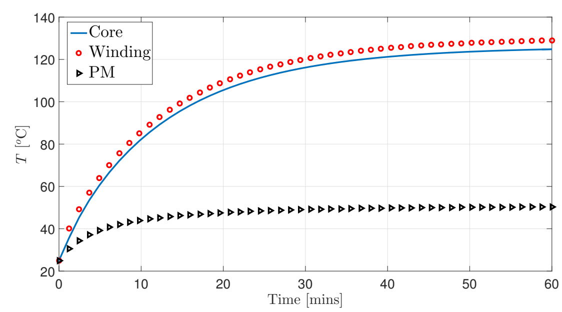

Fig. 6: Winding, core and PM average temperature at S2-60 rating of the machine

VII. Conclusion

In this paper, the transient thermal model of the YASA machine is used in the calculation of the intermittent and short time duties of the machine. Also, the effect of the speed variation on the values of these ratings is clarified and studied for one case. The results show that the machine can be overloaded safely up to 2.5 times its continuous rating for one hour of operation at the rated speed and slightly higher than that for half an hour. And, it is shown also that the intermittent rating for a cycle of 10-minute and duty cycle of 0.6 can be 3 times the continuous rating and slightly higher for lower duty cycles.

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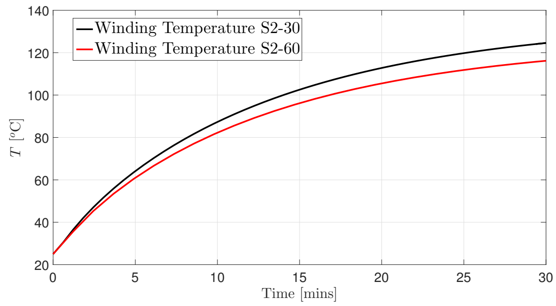

Fig. 7: Winding Temperature at S2-60 and S2-30

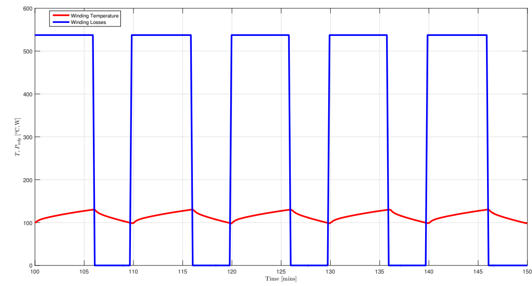

Fig. 9: Winding temperature variation at S3-60% rating along with the copper losses

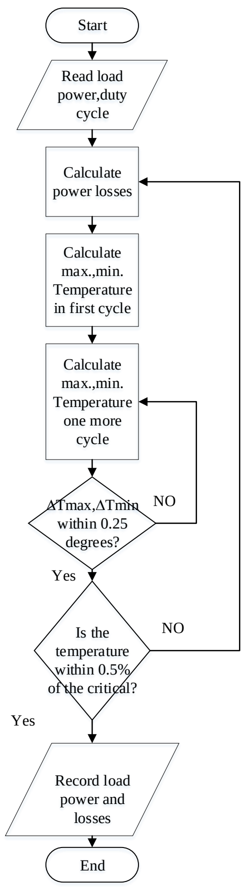

Fig. 8: Flow chart for calculating S3 rating

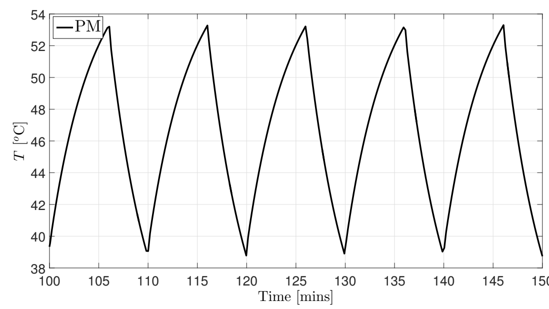

Fig. 10: PM temperature variation at S3-60% rating

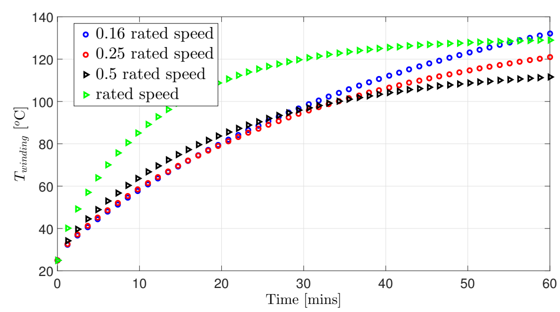

Fig. 11: Winding temperature variation for S2-60 rating at different speeds

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