Evaluation of the Efficiency of Line-Start Permanent-Magnet Machines as a Function of the Operating Temperature

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Abstract—The standard squirrel-cage induction machine has nearly reached its maximum efficiency. In order to further increase the energy efficiency of electrical machines, the use of permanent magnets in combination with the robust design and the line start capability of the induction machine is extensively investigated. Many experimental designs have been suggested in literature, but recently, these line-start permanent-magnet machines (LSPMMs) have become off-the-shelf products available in a power range up to 7.5 kW. The permanent magnet flux density is a function of the operating temperature. Consequently, the temperature will affect almost every electrical quantity of the machine, including current, torque, and efficiency. In this paper, the efficiency of an off-the-shelf 4-kW three-phase LSPMM is evaluated as a function of the temperature by both finite-element modeling and by practical measurements. In order to obtain stator, rotor, and permanent magnet temperatures, lumped thermal modeling is used.

Index Terms—Energy efficiency, finite-element method, induction motors (IMs), magnetic losses, permanent-magnet (PM) machines, synchronous motors, temperature dependence, temperature distribution.

NOMENCLATURE

P_w	Mechanical loss consisting of both friction and windage loss (in watts).
P_{iron}	Magnetization or iron loss (in watts).
P_{joule}	Joule loss (in watts).
P_{SLL}	Stray load loss (in watts).
P_{loss}	Sum of all the losses (in watts).
P_{elk}	Active electrical input power (in watts).
P_{mech}	Active mechanical output power (in watts).
R_T	Resistance at temperature T (in ohms).
α_r	Temperature dependence of R (1/K).

α_{fe}	Temperature dependence of steel (1/K).
I_{RMS}	RMS value of the current (A_{RMS}).
PF	Power factor [–].
$\hat{B}_p$	Peak flux density (in teslas).
f	Supply frequency (in hertz).
γ	Reversible temperature coefficient (in percentage per kelvin).
η	Energy efficiency [–].
σ	Electrical conductivity of stator iron (in siemens per meter).
τ_{temp}	Thermal time constant (in seconds).
R_{cond}	Thermal conductance resistance (in kelvins per watt).
R_{conv}	Thermal convection resistance resistance (in kelvins per watt).
S	Cross-sectional area (in square meters).
S_c	Surface area (in square meters).
l	Length of the body in the heat flow direction (in meters).
k	Thermal conductivity (in watts per millikelvin).
h	Convection coefficient (in watts per millikelvin).
$\mathbf{R}$	Thermal resistance matrix (in kelvins per watt).
$\mathbf{P}$	Segregated power loss vector (in watts).
$\Delta \mathbf{T}$	Temperature rise vector (in kelvins).

I. INTRODUCTION

ACCORDING to [1], it seems unlikely to achieve IE4 (Super Premium) limits [2] in the power range below 7.5 kW while applying the standard three-phase squirrel cage induction motor (IM) technology and still complying to the standard frame sizes, as defined in IEC60034-7 [3]. As high-efficiency line-start permanent-magnet motors (LSPMMs) have evolved from fractional horsepower single-phase motors [4] into commercial three-phase machines in a power range up to 7.5 kW [5]–[8], LSPMMs are being suggested as one of the possibilities to achieve IE4 efficiency. A state-of-the-art review of both practical advantages and limitations of these LSPMMs has been presented in [9].

In [10], the temperature dependence of the energy efficiency of an off-the-shelf 4-kW LSPMM has been evaluated. The measurements indicated an increase in the efficiency of the LSPMM as the temperature reached nominal operating temperature. This effect is uncommon in high-power electromechanical conversion, and in order to explain this effect, the segregated losses

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TABLE I
CONSTRUCTION PARAMETERS OF THE 4-kW LSPMM

LSPMM	
Rated speed [rpm]	1500
Rated torque [Nm]	25
Output power [kW]	4
Efficiency	92%
Frame size	112M
Insulation class	F
Stator winding connection	Δ
Stator windings	copper wound
Rotor bars	poured aluminum
Outer frame diameter [mm]	193
Airgap [mm]	0.4
Rotor diameter [mm]	114.2
Slots per pole and phase	3
Type of magnets	NdFeB
Remanence of PM [T]	1.25

of an LSPMM as a function of the temperature are elucidated in Section II. In Section VI, both the measurement setup and the results from [10] are addressed. However, due to practical limitations, which will be elucidated in this paper, [10] was not able to present the actual temperatures of the different motor parts; subsequently, [10] eliminated the additional stray load losses (SLLs) from the analysis.

One of the key aspects is obtaining the temperature within the different areas of the machine. In Section V, lumped thermal modeling (LTM) is applied to estimate the temperatures of the permanent magnet (PM), rotor iron, stator iron, stator windings, and motor frame. The obtained temperatures in Section VII-A validate the proposed LTM. Consequently, the thermal evaluation of [10] has been fine-tuned by adding the influence of increased temperature of the lamination steel, presenting a more accurate evaluation of the iron losses.

In this paper, finite-element modeling (FEM) is used to validate the SLL. FEM has been also implemented to evaluate the influence of the temperature rise on the iron and rotor bar loss and the resulting overall energy efficiency of the machine. The temperatures obtained by LTM are integrated in the FEM model, and the results obtained by FEM confirm an increase in efficiency with increasing operating temperature.

The machine is depicted in Fig. 9, and the internal winding distribution is presented in Fig. 4. The corresponding motor construction parameters are specified in Table I.

II. FUNDAMENTAL LOSS SEGREGATION OF AN IM AND AN LSPMM

A. Measurement of Losses According to IEC60034-2-1

A totally enclosed fan-cooled (TEFC) LSPMM closely relates to a TEFC IM; they share identical stator winding layout, apart for the PM, a fairly similar rotor construction is noticed, and both machine frame dimensions are built according to IEC60034-7. Consequently, a segregated loss evaluation of an IM as a function of the operating temperature is used as a reference. The electrical losses generated in an IM are stator joule losses, rotor joule losses, and iron losses in both the stator and the rotor. In order to obtain the overall efficiency, mechanical losses caused by friction and windage should be taken into account. Contradictory, the rotor of an LSPMM rotates in synchronism with the magnetic field, and in case of an

ideal field distribution, no currents are induced inside the rotor. The losses are stator joule losses, iron losses in the stator, and mechanical losses.

The Sankey diagram in Fig. 1 lists the segregated losses obtained from measurement of both a 4-kW IM and the tested LSPMM as specified in Table I. In [11], it has been addressed that the indirect measurement method is favored for small power machines. Consequently, the loss segregation for the IM IE1 in Fig. 1 has been executed according to IEC60034-2-1, i.e., the indirect measurement method. However, evaluation of the segregated losses for an LSPMM using the indirect measurement method is prohibited due to technical limitations. The reduced voltage tests are not applicable because the flux of the PM will result in excessive stator currents. A detailed analysis of the indirect measurement method according to IEC60034-2-1 with respect to the LSPMM is presented in [12]. Consequently, for the LSPMM, the stator joule and mechanical losses were determined, as elucidated in Sections III-A and C, respectively, initially assuming that the remaining loss is equivalent to the iron loss. In Fig. 1, the additional SLLs, which are caused by imperfect winding layout within the stator and the rotor, are excluded. For a standard IM, the estimation of SLL according to the indirect measurement method is still a topic of discussion [13], [14], and the indirect measurement method, which is used to determine SLL, is not straightforward applicable for an LSPMM. Consequently, the SLLs are specifically addressed in Section III-D but are initially eliminated within the fundamental loss analysis.

B. Shift of Losses in an IM due to a Temperature Rise

For an IM, friction, windage, and iron losses decrease as the temperature rises [15]. For the vast majority of IMs, the sum of stator and rotor joule losses are dominant, accounting for over 50% of the total loss in the IM [16]. The stator and rotor joule losses increase with a rising temperature; consequently, the overall efficiency changes inversely proportional to the temperature. In Fig. 2, the shift of IM losses is presented as the per unit (p.u.) shift in reference to the losses at an ambient temperature of 40 °C. For an IM up to a few kilowatts, the losses increase approximately 8% between cold and hot stator windings.

III. EVALUATION OF THE INFLUENCE OF THE TEMPERATURE ON THE LOSSES INSIDE AN LSPMM

The goal of this paper is to obtain a similar loss evaluation for an LSPMM as presented for an IM in Fig. 2. In the following sections, the different losses of an LSPMM are evaluated as a function of the temperature. In Section III-A, the stator joule losses are elucidated. Subsequently, the iron losses are addressed in Section III-B, and the mechanical losses, i.e., P_w , are evaluated in Section III-C. SLL is described in Section III-D. As a result, an overall loss analysis as a function of the temperature is obtained in Section III-E.

A. Joule Losses in an LSPMM

If the temperature rises, the internal resistance of the stator coil will rise. This effect is formulated by

$$R_T = R_{20\text{ }^\circ\text{C}} \times (1 + \alpha_r \Delta T) \quad (1)$$

Fig. 1. Fundamental loss analysis for a 4-kW IE1 (a) IM and (b) LSPMM at nominal load condition.

Fig. 2. p.u. shift of windage (P_w), iron (P_{FE}), and stator and rotor winding losses ($P_{s/r}$) in reference to an ambient temperature of 40 °C [15].

where R_T is the value of the stator coil resistance at temperature T , $R_{20^\circ\text{C}}$ is the value of the resistance at a reference temperature of 20 °C, α_r is the temperature dependence of the resistance in (1/K), and ΔT is the temperature rise. Due to the small conductor sections in the coil, both skin and proximity effects are neglected [17]. If balanced conditions are assumed, the joule losses in the stator can be calculated using

$$P_{\text{joule}} = 3 \times R_T \times I_{\text{RMS}}^2 \quad (2)$$

where P_{joule} are the stator joule losses, and I_{RMS} is the RMS value of the phase current. Note that the reactive current demand of an LSPMM is a function of the magnet remanent flux. As this remanent flux changes with the temperature, the joule losses cannot be regarded independently from the iron losses. According to Fig. 1, the actual P_{joule} of an LSPMM has been measured at 3.8% of its nominal input power.

B. Iron Losses in an LSPMM

IMs are designed to work close to the saturation level conditions. This way, the magnetic material is used at its optimum weight/energy ratio. For commonly used magnetic steel, a flux

density of typically 1.5 T is targeted [18]. For a commercial LSPMM, the stator lamination is designed for similar flux density levels. In order to estimate the iron loss, [10] used the following Steinmetz equation:

$$P_{\text{iron}} = C_m \times f^\alpha \times \hat{B}_p^\beta \quad (3)$$

where P_{iron} are the iron losses (in watts), C_m is the first Steinmetz coefficient, f is the frequency (in hertz), α is the second Steinmetz coefficient, $\hat{B}_p$ represents the peak flux density (in teslas), and β is the third Steinmetz coefficient. However, the Steinmetz equation from (3) fails to separate the iron loss into a hysteresis, a classical, and an excess loss. For FEM, the time-domain iron loss model [19] is used as it is more accurate than the Steinmetz formula from (3), particularly in case of nonsinusoidal waveforms. A similar equation as in the cited paper computes the energy loss per cycle W_{fe} for a given waveform $B(t)$, i.e.,

$$W_{\text{fe}}(B, t, T) = aB^\zeta + b(T) \int_0^{T_p} \dot{B}(t)^2 dt + c \int_0^{T_p} |\dot{B}(t)| \left(\sqrt{1 + e(T) |\dot{B}(t)|} - 1 \right) dt. \quad (4)$$

The three terms represent the hysteresis, classical, and excess losses over one electrical period T_p . The coefficients a , ζ , c , and e are to be determined by fitting based on Epstein frame measurements. The fitting procedure is explained in [20], and the coefficients are listed in Table III. The coefficient $b = \sigma d^2/12$ is related to the thickness $d = 0.50$ mm of the material and the electrical conductivity $\sigma = 3.24$ MS/m, making it dependent on the temperature T . As proven in [19, eq. (15)], the excess loss coefficient $e(T)$ is proportional to σ , but the coefficients a , α , and c are not. Because the conductivity depends on the temperature, the coefficients $b(T)$ and $e(T)$ are modified with the temperature by a correction factor $(1 + \alpha_{\text{fe}} \Delta T)$. This factor is similar to (1), but with the temperature coefficient $\alpha_{\text{fe}} = 0.005/\text{K}$ of steel instead of the one for copper α_r . The waveforms $B(t)$ are obtained by a transient 2-D FEM simulation, with rotating rotor (see Fig. 8).

The specific iron loss given by the steel manufacturer is only valid for the steel and does not represent a physical value of the actual iron loss inside a machine. First of all, when evaluating

Fig. 3. Reduction of the peak induction from the PM caused by a temperature rise at identical stator current.

identical steel qualities, a spread from 14% [21] to 25% [18] of the actual losses has been reported between product batches. Second, machines are constructed by lamination resulting in practical imperfections due to mechanical operations such as cutting and stamping, insulation, and physical construction, adding more additional losses [22], [23].

The goal of this section is to evaluate the iron losses as a function of the temperature. As illustrated in Fig. 3, the peak flux density from the magnets is a function of the PM characteristics, the air gap line, and the current in the stator H_{stator} . Since the current in the stator depends on the load ratio of the machine, the resulting flux density is also coupled to the load ratio. It is the vector sum of the magnetomotive force both from the stator and the rotor, which determines the saturation of the machine [24]. This effect is often referred to as armature reaction. In the latter, a constant mechanical output power P_{mech} is assumed, which implies that both the reduction of flux linkage of the magnets and the shift in armature reaction are solely caused by the temperature rise.

If the temperature rises, the PM remanent flux density will reduce as a function of the applied PM according to Table II [25]. These effects are well known [26], and the influence of the temperature rise is illustrated in Fig. 3.

C. Mechanical Losses in an LSPMM

Friction and windage losses, i.e., P_w , mainly depend on the size of the fan and the mechanical speed of the machine. For an IM, these losses can be derived by testing the machine at synchronous speed or by using IEC60034-2-1 [27]. An LSPMM rotates at synchronous speed, and because both an IM and an LSPMM share identical fan size and are constructed according to IEC 60034-7 [3], both friction and windage losses are assumed to be identical. Measurements have been executed on the described LSPMM in Table I in order to validate this assumption.

This paper evaluates the influence of temperature rise on the overall efficiency. According to [15], windage losses are inversely proportional to temperature. Reference [15] reported that pressure and ventilating power vary with air density, which, in turn, depends on air humidity, pressure, and temperature. With a relative humidity of 80% and a normal atmospheric pressure, the windage losses in the considered temperature range decrease approximately 4%–5% for each 10 K of temperature rise. As illustrated in Fig. 1, the mechanical loss for both a 4-kW 1500 r/min LSPMM and IM is 30 W, or 0.75% of the nominal input power. Although temperature rise may have a small influence on the mechanical losses since the rotational speed is constant and the mechanical loss is marginal to other losses, the mechanical loss can initially be assumed to be constant [27]. This simplification will be justified in Section VIII.

D. SLLs in an LSPMM

The fundamental loss analysis of an LSPMM in Fig. 1 has indicated that, at fundamental frequency, there are no rotor losses. However, additional rotor losses do occur due to imperfect winding layout. The measurement of the SSL for an IM has proven to be quite complicated [13]; consequently, normative references such as IEC60034-2-1 give an indication of these losses, which are estimated at 0.5% of its nominal input power [14]. In Section IV, the FEM model is elucidated, and based on FEM, the SLLs are 30 W, which is 0.6% of nominal electric power. The temperature dependence of the SLL will be addressed by FEM and will be discussed in Section VIII.

E. Variation of the Efficiency as a Function of the Temperature

The mechanical power demand P_{mech} is assumed constant and at nominal load. As the temperature rises, the joule losses will increase, whereas the iron losses will decrease. The resulting influence on the losses can be expressed as

$$\frac{dP_{\text{loss}}}{dT} = \frac{dP_{\text{joule}}}{dT} + \frac{dP_{\text{iron}}}{dT} + \frac{dP_w}{dT} + \frac{dP_{\text{SLL}}}{dT} \quad (5)$$

where dP_{loss} is the variation in losses inside the LSPMM due to the temperature shift dT , dP_{joule} is the shift in joule losses in the stator, dP_{iron} is the shift in iron losses in the machine, dP_w is the shift in mechanical losses, and dP_{SLL} is the variation in SLL. If the temperature variation of the loss is positive, the resulting efficiency η will decrease; if the result is negative, the efficiency will increase, i.e.,

$$\eta = \frac{P_{\text{mech}}}{P_{\text{mech}} + P_{\text{loss}}} \quad (6)$$

IV. FEM

A. Introduction

Because a coupled thermal/electromagnetic FEM with computational fluid dynamics (CFD) is highly time consuming [28],

TABLE II
TEMPERATURE EFFECTS OF COMMONLY USED PM [25]

	Ferrite	composite Ferrite	Neoflux	composite Neoflux	SmCo	AlNiCo
Max. Usage Temp (°C)	225	120-150	80-230	160	250	450
Reversible Temp. coefficient γ (%/K)	-0.20	-0.2	-0.9±0.12	-0.08±0.12	-0.03±0.05	-0.03
Reversible Temp. coefficient H_{cJ} (%/K)	+0.2/0.5	+0.3	-0.45±0.85	-0.5	-0.3±0.5	+0.02
Curie Temp. T_c (°C)	460	450	310-380	320	700-800	850

Fig. 4. (a) Rotor geometry [29]. (b) Finite-element mesh of the 4-kW LSPMM.

Fig. 5. Induction distribution of the 4-kW LSPMM.

this is not used for thermal modeling of the LSPMM, as will be elucidated in Section V. However, in order to correctly estimate the SLL in Section III-D and to evaluate the influence of the temperature rise on the segregated losses, including iron and rotor bar losses, FEM of the LSPMM according to the constructional parameters from Table I has been executed. The magnets are NdFeB magnets, with temperature-dependent remanance as listed in Table II. The mesh and the corresponding induction are plotted in Figs. 4 and 5, respectively. The FEM is a 2-D transient FEM, which is coupled to an electrical circuit. The end-winding resistance and inductance are taken into account by an impedance in series with the active part of the winding that is modeled by the 2-D FEM. In addition, for the rotor bars, the electrical circuit adds the resistance and the inductance of the rotor end ring and makes the short circuit between the 28 rotor bars.

The transient simulation starts with the rotor at synchronous speed (1500 r/min) and at nominal load torque. However, at $t = 0$, the load angle is arbitrarily chosen, and the induced currents in the rotor are still zero. Therefore, transient phenomena occur (variation in speed, strong variation in currents and torque) during about 0.7 s. The simulation is run up to 0.84 s with a time step of 0.1 ms. The results presented in Figs. 6–8 are taken during the last period, where the machine is in steady state.

Fig. 6. Stator current for several temperatures of the machine obtained by FEM.

Fig. 7. Rotor current in a bar obtained by FEM and a spectrum averaged over all rotor bars for several temperatures of the machine.

Fig. 8. Induction waveforms in the yoke (almost sinusoidal waveform) and in the tooth tip (more distorted waveform) for several temperatures of the machine obtained by FEM.

TABLE III
LOSS COEFFICIENTS AND RESULTS OBTAINED BY FEM. THE LAST
SIMULATION ASSUMES DRAMATICALLY DECREASED MAGNET
REMANENCE (−14% REMANENCE FOR 74 K TEMPERATURE RISE)

Magnet temperature	20°C	61°C	94°C
Property	$B_{\text{rem}} = 1.24 \text{ T}$	$B_{\text{rem}} = 1.19 \text{ T}$	$B_{\text{rem}} = 1.07 \text{ T}$
Iron loss coeff. a [J/T]	0.0353	0.0353	0.0353
Iron loss coeff. ς	1.789	1.789	1.789
Iron loss coeff. b [J/T]	1.0979e-5	9.265e-6	7.818e-6
Iron loss coeff. c [J/T]	1.876e-2	1.876e-2	1.876e-2
Iron loss coeff. e [sec/T]	2.4808e-4	2.094e-4	1.767e-4
Stator current [A_{RMS}]	3.786	3.852	3.903
Power factor	0.9488	0.9384	0.9106
Stator joule loss [W]	139.1	144.0	169.1
Stator iron loss [W]	109.3	102.0	95.3
Rotor joule loss [W]	34.3	36.5	38.7
Ventilation loss [W]	30	26	22
Total loss [W]	312.7	308.5	325.0
η	0.9218	0.9229	0.919

B. Evaluation of the Temperature Dependence on the Overall Energy Efficiency by FEM

Three FEM simulations were executed in identical conditions of supply voltage and load. The only difference was the higher temperature, resulting in reduced magnet remanence by 0.1% per kelvin, and increased rotor bar and stator winding resistances. In the postprocessing, all losses were computed in the same way. For the iron loss, the coefficients b and e were corrected for a temperature rise of 41 K (see Table III). The reason to choose a temperature rise of 41 K is explained further in this paper.

The results presented in Table III indicate a possible increase in efficiency as the induction increases; however, the obtained results from the FEM analysis will be discussed in detail in Section VIII.

V. LTM

In the thermal loss analysis, knowledge of correct temperatures of the different motor parts is of key value. As an LSPMM contains PM, this machine cannot easily be dismantled to insert temperature sensors inside. Monitoring of PM surface temperature would be challenging because the magnets are inset PMs. Although FEM and CFD should result in accurate estimations, a lot of effort and computation time is still needed to obtain temperature estimations. LTM has been suggested during the latest decade to reduce the computation time and efforts and still obtain fairly good estimations of temperatures in different parts of the machine [28], [30]–[33]. In LTM, the heat transfer is modeled analytically using calculated conduction and convection thermal resistances [34]. Because the stator is constructed from laminated steel, $\pm 70\%$ of the generated heat is transferred in a radial direction via the stator housing. Particularly in TEFC machines, the heat transfer from the stator housing is dominating for the resulting temperatures. The convection R_{conv} and conduction resistances R_{cond} of the components can be obtained by

$$R_{\text{conv}} = \frac{l}{S_c \times h} \quad (7)$$

$$R_{\text{cond}} = \frac{l}{S \times k} \quad (8)$$

TABLE IV
DOMINANT THERMAL RESISTANCES FOR A
4-kW IM AND A 4-kW LSPMM

	IM	LSPMM
Ambient to Frame [K/W]	0.0322	0.0305
Frame to Stator Yoke [K/W]	0.0072	0.0072
Stator Coil to Stator Yoke [K/W]	0.0141	0.0141
Airgap to Rotor Yoke [K/W]	0.2933	0.2933

TABLE V
MEASUREMENT ACCURACY

Quantity	IEC 60034-2-1 limit	Test setup
Electrical	0.2%	0.1%
Torque	0.2% Full Scale	0.1 % Full Scale
Speed	0.1% or 1 rpm	1 rpm
Temperature	1 K	0.14 K

Fig. 9. General test setup.

where l is the length of the body in the heat flow direction, k is the thermal conductivity, S is the cross-sectional area, S_c is the surface area, and h is the convection coefficient. The studied machine is divided into several components, such as frame, stator yoke, stator coils, air gap, rotor tooth, rotor winding, rotor yoke, shaft, and in the case of an LSPMM, additional rotor mounted PM. Within the resistance matrix $\mathbf{R}$, each node is coupled with its neighboring nodes. Because the physical construction of an LSPMM closely relates to an equivalent IM, an equivalent thermal resistance matrix $\mathbf{R}$ is assumed for an LSPMM. A detailed deduction of an IM LTM has been presented in [35], and this model has been tuned to a 4-kW machine. Slight modifications were needed to fine-tune the model into an LSPMM in order to include the PM, the different speed of the fan, and the adjusted rotor bars. According to Fig. 17, 83% of the heat is generated inside the stator; consequently, the most important thermal resistances are listed in Table IV.

Note that the mechanical speed of the fan increases if an IM and an LSPMM are compared. Not only does this influence the mechanical losses, according to Table IV, the absence of slip results in a $\pm 3.3\%$ decrease in thermal frame-to-ambient resistance. Subsequently, the power losses can be segregated to the different areas in the machine and inserted into the loss matrix $\mathbf{P}$. The combination of the resistance matrix and the loss matrix results in actual temperature estimations for each node. The temperature rise $\Delta \mathbf{T}$ for each node is calculated by solving

$$\Delta \mathbf{T} = \mathbf{R} \times \mathbf{P}. \quad (9)$$

Fig. 10. Outer frame temperature as a function of the time.

Contradictory to the similar resistance matrix $\mathbf{R}$ is the segregated loss matrix $\mathbf{P}$, completely different between an IM and an LSPMM, as has been illustrated in Fig. 1.

VI. MEASUREMENTS

A. Measurement Setup

The efficiency at nominal operating conditions is measured according to IEC 60034-2-1 using the direct method [27]. For the measurement of the electrical input power P_{elk} , a calibrated power analyzer is used. Currents were measured directly over the internal shunt with a current range of $30 A_{\text{peak}}$. The output torque and the speed of the machine are measured to determine the mechanical output power, and the efficiency is the ratio of the output/input active power. Both the minimal limits, as stated in [27], as the accuracy levels of the used equipment in the actual test setup are listed in Table V.

The practical test setup is depicted in Fig. 9. The LSPMM in Table I is used as a motor and is loaded at constant nominal load with a controllable dc generator system in closed-loop torque control with speed limitation. The dc generator is in torque control mode, and because LSPMMs are synchronous machines, P_{mech} is also constant. The motor is started up at ambient temperature and is loaded at constant nominal load until steady-state temperature is reached; no additional temperature rise is enforced. As the temperature increases, both the dc machine and the LSPMM are monitored. The mechanical output power remains constant during heating, and consequently, the temperature dependence of the speed and torque transducer are eliminated. The shift in efficiency is calculated based on a constant P_{mech} and varying P_{elk} . Accordingly, the measurement accuracy of the dP_{loss}/dT is only a function of the used power analyzer. The temperature is measured by means of thermocouples on the flanges, the ventilator, and the stator housing. The ambient temperature is measured and used as reference. The temperatures are checked with a calibrated measurement device to ensure the accuracy (see Table V).

B. Measurement Results

During the test, the temperature is monitored, and results of stator housing temperature are given in Fig. 10. As the

Fig. 11. Frame temperature obtained by thermal imaging of a 4-kW LSPMM at nominal load.

temperature rise can be modeled by a first-order thermal circuit consisting of thermal capacitance and a thermal resistance, the temperature rise can be formulated by (10). From the measurements, the thermal time constant τ_{temp} can be derived.

The ambient temperature T_0 is equal to 20 °C; at steady state, the outer housing temperature is 42.5 °C. At an initial time, the interval is equal to τ_{temp} , and the temperature rise is equal to 63% of the steady-state temperature or, thus, 14 K. Therefore, τ_{temp} is equal to 31 min, i.e.,

$$T = T_0 + (1 - e^{-t/\tau_{\text{temp}}})\Delta T \quad (10)$$

where T_0 is the reference temperature, τ_{temp} is the thermal time constant, and ΔT is the temperature increase of the frame. In order to confirm the frame's temperature rise, thermal images were taken and plotted in Fig. 11. As noticeable in Fig. 12, the efficiency increases as the LSPMM reaches the nominal operating temperature. Similar to (10), the time constant of the efficiency variation can be calculated from Fig. 12. As the same time constant τ_{temp} is obtained as in (10), this leads to the conclusion that the measured effect is solely caused by the temperature rise.

Fig. 12. Efficiency as a function of the time.

Fig. 13. I_{RMS} as a function of the time.

Fig. 14. PF as a function of the time.

The efficiency increases as the temperature increases, and this effect is opposite to the IM. In order to explain this effect, an in-depth loss analysis is presented, which is based

on FEM (see Section IV) and on the measurement results (see Section VII-B). Additional measurements needed for Sections IV and VII-B are plotted in Figs. 13–15.

Fig. 15. Active and reactive power as a function of the time.

Fig. 16. Estimated temperatures of rotor iron, stator coil, and stator frame of a 4-kW IM and a 4-kW LSPMM.

TABLE VI
TEMPERATURE MOTOR SECTIONS IN DEGREES CELSIUS

	IM		LSPMM	
	LTM	[15]	LTM	Measured
Stator Yoke	115.9	120	53.3	-
Stator Coil	120.8	120	55.8	57
Rotor Yoke	134.2	150	59.9	-
PM	-	-	60.8	-

VII. LOSS ANALYSIS

A. Validation of the LTM

Before discussing the influence of temperature on the overall efficiency of an LSPMM, the LTM should be validated. In Fig. 16, the comparison between a 4-kW IM and a 4-kW LSPMM is presented. The results were obtained using (9), and the power distribution was obtained according to Fig. 1, including SLL. The obtained temperatures of the IM correspond very well to the values listed in [15], validating the model for the IM. The correspondence between the model and the measurements is shown in Table VI.

The actual coil temperature can be recalculated from the measurement of hot and cold stator resistances using (1). At

a frame temperature of 20 °C, a stator resistance of 2.839 Ω was measured and, subsequently, 3.264 Ω at a stator housing temperature of 42 °C. The α of copper is equal to 3.910^{-3} Ω/K , and consequently, a stator coil temperature of 57 °C is obtained. The LSPMM stator coil temperature obtained by LTM differs 1.3 K to the calculated value, and the LSPMM outer stator frame temperature estimated by LTM differs 2.5 K from the values obtained by infrared measurement in Fig. 11.

In addition to a small amount of SLL, no loss is induced inside the rotor. This often results in the approximation that the temperature of the rotor and the PM could be set identical to the temperature of the stator coils [24]. The LTM indicates that there is a 5-K difference between the stator coil and the PM. Accordingly, the obtained PM temperature of 61 °C can be used to estimate the PM temperature. In [12], it was hinted that the LSPMM is a cool running machine in reference to a similar IM, and the obtained results confirm these conclusions.

B. Loss Analysis Using the Measurement Results

A segregated loss evaluation based on the practical measurements as a function of the frame temperature is presented in Fig. 17.

Fig. 17. Loss evaluation as a function of the frame temperature.

All calculations are done with actual measurement results. In this analysis, the mechanical loss, with an absolute value of 30 W, and the SLL were assumed to be independent of the temperature. From the overall measured losses, the calculated joule loss, mechanical loss, and SLL obtained by FEM were subtracted, assuming that the resulting losses represent the iron losses. Note that the reference temperature is the temperature measured at the frame and not the real temperature of windings and rotor.

In Fig. 13, the current is plotted as a function of the time. The current shifts about 10 mA with increasing temperature, which is barely measurable and noticeable. As the joule losses are a function of I_{RMS}^2 , this minor shift in current does not influence the stator joule losses significantly. This is explained due to the fact that, although the reactive power increases, the active power decreases (see Fig. 15).

Within Fig. 14, it is noticed that the PF has the same τ_{temp} . This leads to the obvious conclusion that the PF also is a function of the temperature. As the supply voltage remains constant, the peak induction in the machine is nearly constant. With the remanence of the PM decreasing for increasing temperatures, an increased magnetizing current from the stator is needed. This explains the increase in reactive power consumption of the LSPMM. Subsequently, the efficiency of the LSPMM does slightly increase. For the same amount of active output power P_{mech} , this does imply a decrease in active electric power consumed by the machine.

VIII. REMARKS AND DISCUSSION

A. Mechanical Loss and SLL

In the measurement analysis, both the mechanical loss and the SLL are excluded. For mechanical losses, the increased temperature results in a reduced viscosity of both the bearing lubricant and the cooling air flow. For the IM, it is reported that there is a reduction in windage losses of 5% per 10 K [15]. In Fig. 2, it is observed that concerning the actual mechanical losses, this effect is not negligible. For a 4-kW

TABLE VII
COMPARISON OF FEM AND MEASUREMENTS

	FEM		Measured	
Stator coil temperature [°C]	20	57	23	57
Stator current [A_{RMS}]	3.786	3.852	4.021	4.035
Power factor	0.9488	0.9384	0.899	0.885
Stator joule loss [W]	139.1	144	140.46	155.7
Total loss [W]	312.7	308.5	385	345.7
η	0.9218	0.9229	0.910	0.917

LSPMM, the mechanical losses will reduce from 30 to 26 W when reaching the nominal operating temperature. However, the SLLs are within the same order of magnitude of the mechanical losses. Because SLLs are mainly harmonic losses, the SLL will increase with increasing rotor bar resistance and, hence, with increasing temperature. This is observed from the FEM simulations in Table III. Because the mechanical losses decrease and the SLLs increase with increasing temperature, these effects compensate each other partially.

B. FEM Evaluation of I_{RMS} , PF, and Efficiency

A comparison between the results obtained by FEM and the measurements is listed in Table VII.

The FEM model does result in slightly higher values of the PF in reference to the actual PF. The reason may be that the machine has a slightly lower remanent magnet flux than given by the manufacturer specifications. The measurements also indicated that the RMS current remains almost constant because the reactive power increases with temperature and the active electrical power reduces a bit. The latter is because of the decreasing losses and the constant mechanical power. FEM proves this result: The reactive power increases also in FEM, and the PF decreases. Evidently, the active power remains constant in FEM (and equal to the mechanical power) because the losses are computed *a posteriori* in FEM.

Nevertheless, FEM does confirm that there is a slight increase in energy efficiency as the temperature rises. FEM also illustrates that this effect is not to be extrapolated. The third

column in Table III indicates that, at an excessive reduction in the PM remanent field, the efficiency does tend to reduce due to excessive stator loss. Consequently, there is an optimal temperature at which the LSPMM does operate at maximum efficiency.

IX. CONCLUSION

As a segregated loss evaluation of a three-phase LSPMM according to IEC60034-2-1—the indirect method—is prohibited due to technical limitations, this paper has used FEM to address the individual loss mechanisms. All the losses are a function of the temperature, of the implemented permanent magnets, and the resulting stator current. As the operating temperature increases, the iron losses reduce, and the joule losses increase. If the decrease in the iron loss is dominant, the overall energy efficiency can increase. This effect has been validated by FEM and, consequently, confirms the measurements presented in [10].

However, before a thorough evaluation of the temperature effect can be presented, both partial loading and different power ratios of the LSPMM should be taken into account. The effect of the temperature rise on the overall efficiency is a function of the relative ratio between the segregated losses. Should the joule losses become dominant, it is possible that the overall efficiency will drop, and consequently, the conclusion of efficiency increase should not be generalized. The latter is a subject of future research.

Temperatures of the individual machine parts are essential knowledge; these are estimated using LTM. This paper suggests that slightly modified thermal models of IMs can be used to estimate temperatures inside industrial three-phase LSPMMs.

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