Extrapolation of Losses and Efficiency in Field Weakening and Overload Range for Delta- and Star-Connected Electrical Machines Based on IEC 60034-2-3

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Abstract. An accurate knowledge of the power dissipation and efficiency of an inverter-fed electrical machine is essential, whereas a precise measurement with a high resolution of measurement points is very time consuming and cost intensive. In the IEC standard 60034-2-3 for rotating electrical machines, seven standardized measuring points are used to determine the losses and efficiencies throughout the whole base speed range of an electrical machine. However, the used correlation is not applicable to the field weakening and overload range, whereas those regions are of enormous importance for a speed-variant drive system. In this contribution, we present an extension to the existing interpolation approach in IEC 60034-2-3 to estimate the losses and efficiencies between stand-still and twice the rated speed as well as between no-load operation and twice the rated torque. The approach is based on the seven standardizes measurement points and no additional measurement is needed. Furthermore, the influence of a switching from a star-connection to a delta-connection and to a double star-connection is investigated. The new approach is validated experimentally.

Keywords: Electrical machines, IEC 60034-2-3, Losses, Star-connected machines, Delta-connected machines, Efficiency determination, Analytical calculation, Overload, Field weakening.

1 Introduction

This article presents an interpolation procedure to calculate losses and efficiencies in the whole operating range of induction motors including field weakening and overload. It is based on the latest IEC 60034-2-3 ED1 standard [1], which describes a procedure using a formula with seven coefficients, obtained from seven standardized measurements. However, this method is limited in speed and torque. Only the losses from stand-still to the rated speed and from no-load operation to rated torque can be calculated. For certain applications, operating the motor in the overload or in the field weakening area is required.

The standard approach is analyzed in section 2 and afterwards extended for overload and field weakening range in section 3. The application to star-, double-star- or delta-connected machines is described in section 4. The new approach has been validated experimentally. Therefore, efficiency and losses were measured in a dense mesh of operating points. The results were compared to the interpolation result, which is based on the seven standard measurements. The results are shown and discussed in section 5.

2 IEC 60034-2-3 ED1 interpolation procedure

The formula to interpolate base load and base speed machine losses according to IEC 60034-2-3 ED1 is given by

$$P_{\mathrm{L}}(n,T) = \boldsymbol{c_1} + \boldsymbol{c_2} \cdot n + \boldsymbol{c_3} \cdot n^2 + \boldsymbol{c_4} \cdot n \cdot T^2 + \boldsymbol{c_5} \cdot n^2 \cdot T^2 + \boldsymbol{c_6} \cdot T + \boldsymbol{c_7} \cdot T^2 \qquad (1)$$

Therein $\boldsymbol{c_{1\ldots7}}$ describe the coefficients, which can be calculated from seven standardized measurements. The various terms in eq. (1) are derived from the existing loss mechanisms [2].

Ohmic losses or $\boldsymbol{I^2R}$-losses are occurring in the stator and rotor windings and are independent of the frequency and change with the square of the current, respective torque. However, it must be taken into account that even in no-load operation a magnetizing current I_0 has to be considered e.g., in case of an induction machine.

The following formula can be used to interpolate the stator losses P_{LS} in the defined range at each torque T and speed n:

$$P_{\mathrm{LS}}(n,T) = P_{\mathrm{LS}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot \left(\left(\frac{I_0}{I_{\mathrm{N}}}\right)^2 + \left(1 - \left(\frac{I_0}{I_{\mathrm{N}}}\right)^2\right) \cdot T^2\right) \qquad (2)$$

Therein, n_{N} is the rated speed, T_{N} the rated torque and I_{N} the rated current. Rotor losses only depend on torque, which is proportional to rotor current. Accordingly, the rotor losses P_{LR} can be interpolated by

$$P_{\mathrm{LR}}(n,T) = P_{\mathrm{LR}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot T^2 \qquad (3)$$

These losses are taken into account by coefficients $\boldsymbol{c_1}$ and $\boldsymbol{c_7}$ in (1).

Iron losses P_{Lfe} can be divided into three components – hysteresis, eddy current and excess losses [2,3] – whereby in the standard the excess losses are included in the load-dependent additional losses. The corresponding losses are thus divided into hysteresis losses, which are proportional to the frequency and eddy current losses, which are proportional to the square of the frequency:

$$P_{\mathrm{Lfe}}(n,T) = c_{fe} \cdot P_{\mathrm{Lfe}}(n_N,T_N) \cdot n + (1 - c_{fe}) \cdot P_{\mathrm{Lfe}}(n_N,T_N) \cdot n^2 \qquad (4)$$

Here the value for c_{fe} is a motor-specific weighting factor between hysteresis losses and eddy current losses at the rated operating point. If the exact distribution of both components is unknown, a weighting factor of $c_{fe} = 0.5$ should provide a sufficiently good result. It should also be added that in the base speed range the magnetic flux is kept constant. Therefore, the losses in the base speed region do not depend on the magnetic flux density in the iron. Iron losses are considered by coefficients $\boldsymbol{c_2}$ and $\boldsymbol{c_3}$ in (1).

Additional load losses include losses that occur in the supporting structure and other losses, such as cross currents between rotor bars and eddy currents in permanent magnets [8]. Additional load losses can be divided into two parts. Losses proportional to the frequency and the square of the torque and losses proportional to the square of the frequency and the square of the torque exist.

$$P_{\mathrm{LL}}(n,T) = c_{LL} \cdot P_{\mathrm{LL}}(n_N,T_N) \cdot T^2 \cdot n + (1 - c_{LL}) \cdot P_{\mathrm{LL}}(n_N,T_N) \cdot T^2 \cdot n^2 \tag{5}$$

If the exact distribution c_{LL} of the two shares is not known, the equivalence relationship can be used as for the iron losses. Additional load losses are considered by coefficients $\boldsymbol{c_4}$ and $\boldsymbol{c_5}$ in the interpolation formula (1).

Friction and windage losses can also be divided into two parts [4-7]. Friction losses, which are proportional to the rotational speed and fan losses, which are proportional to the third power of the rotational speed should be regarded.

$$P_{\mathrm{Lfw}}(n,T) = c_{\mathrm{fw}} \cdot P_{Lfw}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot n + (1 - c_{\mathrm{fw}}) \cdot P_{\mathrm{Lfw}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot n^3 \tag{6}$$

If the exact distribution c_{fw} is not known, a table provided in the standard can be used, which gives recommended values for different speeds. Friction losses are also represented by coefficient $\boldsymbol{c_2}$. Windage losses are not considered for the base speed interpolation, since a corresponding term has proven to be unpractical and prone to measurement errors [1].

Further high frequency losses are caused by the PWM switching of a frequency inverter [9]. The PWM generates switched voltages with high harmonic content, which cause high-frequency current components. Also, stator slotting produces harmonic current components. The harmonics in the phase currents lead to increased iron losses and also increased I^2R losses. Experiments have shown that the high-frequency losses are predominantly constant over the entire speed and torque range, provided that the inverter frequency remains unchanged. These losses are therefore independent of the speed and torque and are considered by coefficient $\boldsymbol{c_1}$.

To enhance the quality of interpolation, eq. (1) contains another torque-dependent term, which does not represent any loss mechanism. It is weighted by coefficient $\boldsymbol{c_6}$.

3 Machine loss extrapolation

The interpolation described in section 2 will now be extended to the field weakening and overload range. The calculation of the losses in the new ranges is to be carried out exclusively with the seven known measuring points and the respective coefficients. Therefor eq. (1) will be extended by analyzing the impact of overload and field weakening on the loss equations (2)-(6).

3.1 Overload

In the overload range, the relation of currents and magnetic flux densities to speed and torque are equivalent to the standard range. In addition, industrial motors are built in such a way that magnetic saturation is negligible even at high torques. However, due to the increasing currents, the temperature increase must be taken into account. The associated increase in resistance causes the losses to rise disproportionately. The consideration of this increase in resistance can vary greatly from motor to motor. Furthermore, this data is not known. Only the seven total losses at the seven measuring points are available. For this reason, eq. (1) is still considered valid in the overload range.

3.2 Field weakening

Field weakening does have a significant impact on the machine losses. Thus, equations (2)-(6) must be accordingly adapted.

As the magnetizing current is inversely proportional to the frequency, the stator and rotor winding losses vary with speed and torque. It should be noted that the maximum torque of the machine decreases inversely proportional to the machine speed.

Stator and rotor winding losses in field weakening can thus be calculated by

$$P_{\mathrm{LS}}(n,T) = P_{\mathrm{LS}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot \left[\left(\frac{I_0}{n \cdot I_{\mathrm{N}}}\right)^2 + \left(1 - \left(\frac{I_0}{n \cdot I_{\mathrm{N}}}\right)^2\right) \cdot (T \cdot n)^2\right] \tag{7}$$

$$P_{\mathrm{LR}}(n,T) = P_{\mathrm{LR}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot (T \cdot n)^2 \tag{8}$$

The magnetic flux density (B-field) is proportional to the magnetizing current and therefore decreasing inversely proportional to the frequency. In a first approximation, the iron losses are proportional to the square of the magnetic flux density. Hence, the iron losses are now given by

$$P_{\mathrm{Lfe}}(n,T) = c_{\mathrm{fe}} \cdot P_{\mathrm{Lfe}(n_{\mathrm{N}},T_{\mathrm{N}})} \cdot \frac{1}{n} + (1 - c_{\mathrm{fe}}) \cdot P_{\mathrm{Lfe}}(n_{\mathrm{N}},T_{\mathrm{N}}) \tag{9}$$

The additional losses in the field weakening range will change as the maximum machine torque decreases inversely proportional to the speed.

$$P_{\mathrm{LL}}(n,T) = c_{\mathrm{LL}} \cdot P_{\mathrm{LL}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot T^2 \cdot n^3 + (1 - c_{\mathrm{LL}}) \cdot P_{\mathrm{LL}}(n_{\mathrm{N}},T_{\mathrm{N}}) \cdot T^2 \cdot n^4 \tag{10}$$

Friction and windage losses are mechanical losses and are not dependent on electromagnetic parameters. Therefore, the same formulas as for the base speed region can be applied. Also, the PWM losses are constant over the whole speed and torque range.

3.3 Extrapolation formula

The extrapolation formula for overload is the same as the interpolation formula (1), with the range of the normalized torque being $T = 0 \ldots 2$. The interpolation formula for the field weakening range is adapted from the interpolation formula (1) of the base speed region. The seven known loss coefficients can be used, but two additional coefficients c_{WHf} and c_{BH} are required.

According to the different loss scaling in the field weakening range, the following interpolation formula can be obtained

$$P_{\mathrm{L}}(n,T) = \boldsymbol{c}_{\mathbf{L1}} \cdot \left(c_{WHf} \cdot \frac{1}{n'^2} - c_{WHf} \cdot T^2 + T^2 \cdot n'^2 + \left(1 - c_{WHf}\right)\right) \tag{11}$$

$$+\boldsymbol{c}_{\mathbf{L2}} \cdot \left(c_{BH} \cdot n + (1 - c_{BH}) \cdot \frac{n_{\mathrm{FW}}}{n'}\right) + \boldsymbol{c}_{\mathbf{L3}} \cdot n_{FW}^2 + \boldsymbol{c}_{\mathbf{L4}} \cdot n'^2 \cdot n \cdot T^2$$

$$+\boldsymbol{c}_{\mathbf{L5}} \cdot n'^2 \cdot n^2 \cdot T^2 + \boldsymbol{c}_{\mathbf{L6}} \cdot T \cdot n' + \boldsymbol{c}_{\mathbf{L7}} \cdot T^2 \cdot n'^2$$

Herein, n_{FW} is the normalized speed above which field weakening is required. The range of the normalized speed is $n = n_{FW} \ldots 2$. The relative field strength is defined as $n' = n - (n_{FW} - 1)$.

The coefficient c_{WHf} describes the loss separation of the windage losses due to the magnetizing current (c_{WHf}) and the high frequency losses $(1 - c_{WHf})$. If a detailed loss separation is not known, the value of 1 should be chosen for c_{WHf} as the high frequency losses can normally be neglected in comparison to the I^2R-losses of the magnetizing current.

The coefficient c_{BH} describes the loss separation of the bearing losses (c_{BH}) and the hysteresis losses $(1 - c_{BH})$. If a detailed loss separation is not known, an equal loss separation should be chosen ($c_{BH} = 0{,}5$).

4 Star- and delta-connected machines

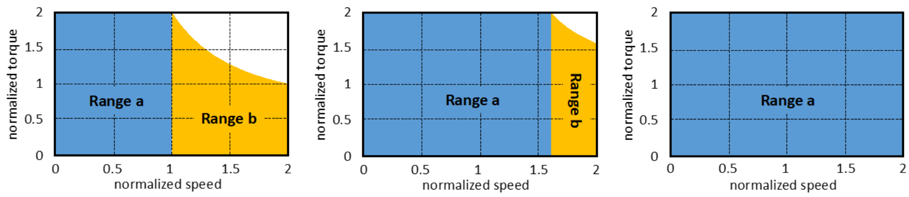

Fig. 1. Operating ranges of a Y- (or Δ-) connected machine (left). Operating ranges of a Y → Δ-connected machine (center). Operating ranges of a Y → YY-connected machine (right). Range **a** covers base speed, range **b** covers field weakening operation.

When a machine is operated with a different connection, the operating ranges are shifted. Since the overload extrapolation is equivalent to (1), only the influence of the shifted field weakening range, as shown in **Fig. 1**, must be taken into account. Therefore, an additional coefficient c_{con} is introduced to adjust the normalized field weakening threshold speed based on the star-connection threshold speed $n_{FW,Y}$

$$n_{FW} = c_{con} \cdot n_{FW,Y} \tag{12}$$

The possible values of c_{con} can be taken from **Table 1**. The fact, that the type of connection has no influence on mechanical losses is considered in (11).

Table 1. Values of c_{con} considering an original Y-connection

Connection type	Value of c_{con}
Y	1
Δ	$\sqrt{3}$
YY	2

5 Experimental validation

To validate the novel extrapolation method, efficiency measurements of several machines have been taken and compared to efficiencies calculated by means of (11). Therefore, the seven required coefficients have been calculated from the same measurements as the comparison is performed. The measurements consist of more operating points than required for coefficient calculation. The comparison is performed, comparing the respective measurement points to the values resulting from (11). **Fig. 2** presents the resulting comparisons as interpolated maps.

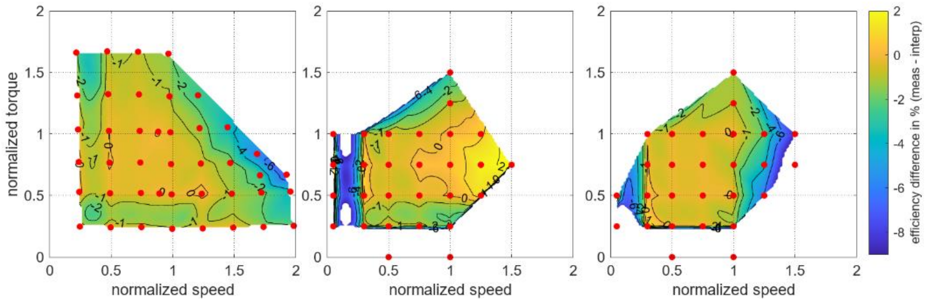

Fig. 2. Difference between measured and interpolated efficiencies for a 15 kW IE3 machine (left), a 3 kW IE3 machine (center) and a 7,5 kW IE5 machine (right).

The deviation in efficiencies is below 2% in a broad range of the speed-torque map. Larger deviations occur at the operating boundaries of the machine. In these operating points the machine is operated at the voltage limit and the current harmonics increase significantly leading to higher iron losses for example. At the measurement points at low speeds or low torque, the output power is comparably small leading to a major influence of the measurement uncertainty to the measurement result itself. Due to the small differences in a broad range of the efficiency map, the novel correlation for extrapolating the losses and efficiencies based on the seven standardized measurement points can be assumed valid.

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