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Performance assessment tool based on loadability concepts

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Abstract. In order to choose electric machines for transport applications, i.e. automotive, aerospace, railway and naval, a tool that can make quick tradeoffs of high specific torque electric motors has been developed. The level of the different technologies involved in an electrical machine can be quantified using the loadability concepts developed by experienced designers. After recalling these concepts, magnetic, electric and thermal balances are used to calculate the main sizes of an electric motor according to some targets. Specific power or specific torque can then be quickly assessed. The proposed approach is validated by applying the tool to some known high torque industrial motors.

Keywords: Loadability, specific power, specific torque

1. Introduction

Useful loadability concepts have been developed by electric motor experienced designers [1]. For instance the effectiveness of magnetic and electric technologies to produce torque can be assessed by the magnetic shear stress [2]. In this work, these concepts are exploited to develop a tool to evaluate quickly available electric machine technologies such as winding, cooling or magnetic technology. This tool based on analytical calculation helps to make rapid tradeoffs on high specific torque motors for instance. Among the output data of this tool, there are the main sizes of different parts of the electric machine and its specific power or specific torque. On the other hand many assumptions are done. The tool is evaluated by comparing its results with the performance of industrial machines [4]. As these industrial machines have a relatively low speed, the iron loss can be neglected in front of Joule loss in the winding. For the same reasons the effect of eddy currents in Joule loss are not taken into account.

The main loadability concepts are recalled first from the analytic expression of the torque of an ideal sinewave synchronous motor and the Joule loss in electric motors. After giving the input and output data of the tool, magnetic, electric and thermal balances are presented to calculate the main sizes of electric motors. Finally the performances obtained from the developed tool are compared to some known industrial performances.

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2. The loads of an electric motor from the torque and Joule loss expressions

The magnetic and electric loads are useful concepts presented in many text books [1]. The assumptions of the proposed approach are presented. An ideal sinewave electric motor is defined by two sinewaves: the airgap radial magnetic flux density B and the surface current density K . These two waves are supposed to be localized on the stator bore of axial length, L , and radius, R . Applying Laplace and the action re-action laws, the expression of torque applied on the rotor of a synchronous motor [3] is:

$$T = 2\pi LR^2 K_{rms} B_{rms} \quad (1)$$

K_{rms} and B_{rms} are the rms values of the two waves.

The torque expression (1) defines two load notions, the airgap flux density which is B_{rms} and the magnetic shear stress σ defined by:

$$\sigma = K_{rms} B_{rms}. \quad (2)$$

The rms current per unit length A_{rms} around the stator bore is linked to the surface current density wave by the winding factor k_w [3]:

$$K_{rms} = k_w A_{rms}. \quad (3)$$

Using the classical expression of resistance, the Joule loss can be expressed as:

$$P_j = \rho_c k_{wh} 2\pi R L A_{rms} j_{rms}. \quad (4)$$

With: ρ_c the resistivity of copper at the winding temperature and k_{wh} the winding head coefficient. This expression of the Joule loss defines one of the most important load notions which is the product $A_{rms} j_{rms}$ of the rms values of the current per unit length A_{rms} and the current density j_{rms} . In [1], it is demonstrated that this product is independent of the size of the machine and depends only on the effectiveness of the cooling of the machine.

3. Input and output data of the assessment tool

From the previous defined loads and the magnetic, electric and thermal balances defined in next section, a tool has been developed to assess the performances of an electric machine. This analytical tool is based on different choices given in Table 1. The model of the motor studied is shown in Fig. 1. The design of an electric motor starts from the main mechanical specifications which are the rated speed and power. The thermal specifications are the ambient temperature and the maximum temperature on the external surface of the stator frame. The levels of magnetic, insulation and cooling technologies are chosen through the previously defined loads. Finally, some geometrical parameters are chosen (Table 1).

One of the aims of the assessment tool is to roughly calculate the main sizes of the motor and the mass of the motor from the input data. The main dimensions calculated are: the external stator radius R_{out} , the radius bore R , the axial active length L , the slot height h_s , the stator yoke height h_y , the slot width l_s and the teeth width l_t at the bore radius. From the input data and the output data, specific torque and specific power can then be calculated.

Table 1
Input data of the assessment tool

Mechanical specifications	Thermal specifications
Mechanical power, P	Ambient temperature, T_{amb}
Base rotational speed, N	Allowable heating, ΔT
Choice of load levels	Geometrical Parameters
Magnetic shear stress, σ	Pole pairs, p
Airgap magnetic radial flux density, B_M	Rotor form coefficient, $\lambda = \frac{2l}{R}$
Current density, j_{rms}	Winding head coefficient, k_{wh}
Magnetic flux densities allowed in stator teeth B_t and yoke B_y	Slot fill factor, k_{fill}

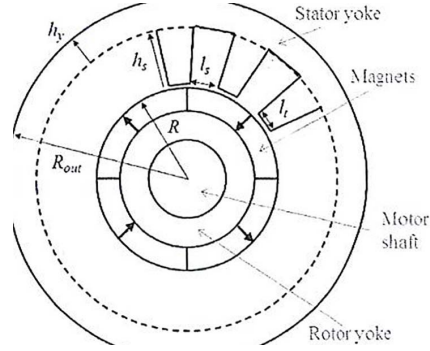


Fig. 1. Main dimensions of the motor studied.

4. Magnetic, electric and thermal balances

Neglecting the reaction flux, the magnetic flux conservation law between the flux per pole and the flux in the stator yoke leads to the yoke thickness:

$$h_y = \frac{\sqrt{2}}{pB_y} RB_{rms}. \quad (5)$$

The magnetic flux conservation law between the flux per pole and the total absolute flux in the teeth allows to obtain the total circumferential length of teeth:

$$N_t l_t = \frac{4\sqrt{2}}{B_t} RB_{rms}. \quad (6)$$

The relations (5) and (6) define two magnetic loads: the mean magnetic flux densities in the yoke B_y and in the teeth B_t . Given these loads, without knowing the number of teeth, N_t , key sizes of the stator iron can be known.

In our model, we consider slot of rectangular form of radial height h_s and circumferential width l_s . Considering that the fill factor of slot is k_{fill} and the number of slots is N_s (equal to the number of teeth

N_r), the ampere turns balance leads to the slot height:

$$h_s = \frac{2\pi R A_{rms}}{N_s l_s k_{fill} j_{rms}} \quad (7)$$

The relation (7) defines A_{rms} and j_{rms} as loads. Given these loads, without knowing the winding, one key size of slots can be known.

In the example in the last section, only low speed electric motors are considered. Thus only Joule loss in winding are taken into account. It is assumed that the electric motor is cooled only from the external stator surface. This surface, with external radius R_{out} , has a convective coefficient transfer, h_{cv} . If radiation transfer is neglected:

$$h_{cv} = \frac{P_j}{2\pi R_{out} L \cdot \Delta T} \quad (8)$$

The relation (8) defines the cooling effort to be done. The coefficient transfer can be used to compare the cooling effort between motors of different performances and sizes.

5. Loads and technological limitations

Performances of electric motors are mainly limited by thermal constraints in insulation materials of windings. From their experiences, designers have defined the loads that have been presented in the previous section. They may be used to know the technological limitations of electric motor. The permitted levels of loading presented below are extracted from [1]. The magnetic shear stress level (2) measures the capability of electric machines to produce torque and depends on the cooling system efficiency. One knows that fixing shear stress level is the starting point of the sizing of an electric motor. Table 2 gives limitation levels of the magnetic shear stress in synchronous motor independently of their sizes and according to the cooling technology and their types.

The product $A_{rms} j_{rms}$ of the rms current per unit length and the rms current density (4) gives the level of Joule loss according to the cooling technology. They measure the level of insulation technology to support thermal constraints. Indeed Table 2 is given from present insulation technology but it may change with the technology progress.

The airgap flux density appears in the expression of the magnetic shear stress (2) and the stator dimensions (5–6).

For the same level of shear stress and current density, the highest is the airgap flux density, the lowest the Joule loss. The airgap flux density measures the level of the magnetic technology. Table 3 gives its permitted level according to the type of electric motor.

6. Validation of the assessment tool

The assessment tool allows to evaluate torque, Joule losses and powers of an electric motor for given set of technology levels. The main advantage is that it needs a few data: for instance the stator and the rotor is not described completely to make these calculations. In order to calculate the specific torque or power torque, it is necessary to find data on electric motors for a wide range of power. The tool is based

Table 2
Permitted values of magnetic shear stress, RMS current per unit length and surface current density in synchronous motor

		Synchronous machine type			
		Salient-pole synchronous machines or PMSMs	Non salient-pole synchronous machines		
			Indirect cooling		Direct water cooling
		Air	Hydrogen		
σ (N.m ⁻²)	Min	21000	17000	51000	85000
	Average	33500	36000	65500	114500
	Max	48000	59500	81500	148500
A_{rms} (kA/m)		35–65	30–80	90–110	150–200
j_{rms} (A/m ²)		4–6.5 × 10 ⁶	3–5 × 10 ⁶	4–6 × 10 ⁶	7–10 × 10 ⁶
$A_{rms} \cdot j_{rms}$ (A ² /m ³)		14–42.25 × 10 ¹⁰	10.5–40 × 10 ¹⁰	36–66 × 10 ¹⁰	105–200 × 10 ¹⁰

Table 3
Permitted values of magnitude of the airgap radial magnetic flux density waves

	Asynchronous machines	Salient-pole synchronous machines	Non salient-pole synchronous machines	DC machines
$B_M(T)$	0,7 – 0,9	0,85 – 1,05	0,8 – 1,05	0,7 – 1,1

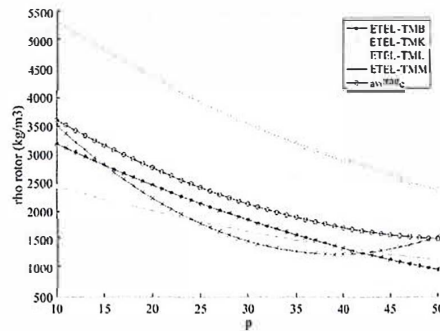


Fig. 2. Rotor density of ETEL motors vs. pole pairs number.

on a statistical study of industrial motors [4], in order to get data on the volume of housing and the rotor densities.

A benchmarking of TML, TMM air cooling and TMB, TMK water cooling torque ETEL motors has been done. In [4], the geometric data of one hundred motors of these series are given. When the number of pole pairs p increases, the total rotor density decreases and the structure becomes hollow or annular. The benchmarking of these motors having a wide number of pole pairs gives us an idea about the variation rules of the rotor density. Figure 2 shows the interpolated curves of this rotor density ρ_{rot} as a function of the number of pole pairs p .

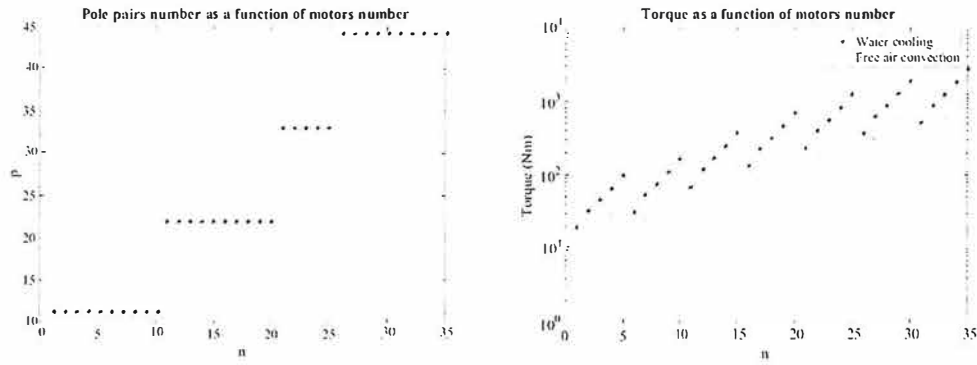


Fig. 3. Number of pole pairs and continuous torques extracted from the data sheet of 35 TMB ETEL motors [4].

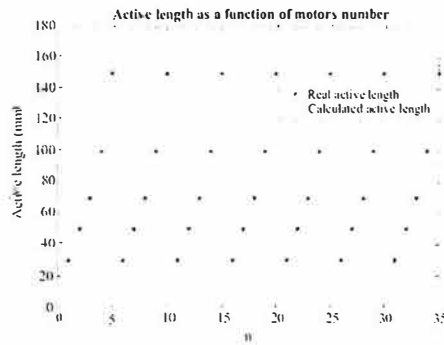


Fig. 4. Comparing the active length calculated to the data sheet of TMB ETEL motors [4].

The equation of the average curve of the rotor density of the four ETEL types for $p > 10$ is:

$$\rho_{rot} = 1.09p^2 - 117.45p + 4681. \quad (9)$$

For $1 \leq p \leq 10$, we interpolate linearly the rotor density between 7500 (which is the approximated homogenized value at $p = 1$) to 3615 kg/m³:

$$\rho_{rot} = -431.67p + 7932. \quad (10)$$

Thus, the weights of the rotor can be calculated. On the same way, the benchmarking of ETEL motors allows us to estimate the volumes and the weights of the housing.

The proposed tool is validated by analyzing the high torque permanent magnet TMB ETEL motors [4]. For each motor, two types of cooling modes are available: free air convection and water cooling. For each cooling mode, the continuous torque and the main sizes of each motor are given in the data sheets.

The number of pole pairs and the continuous torques of the 35 analyzed motors are given according to the two cooling modes (Fig. 3). After adjusting the input data of the assessment tool to ETEL motor data sheets (Table 4), the performances calculated with the tool from these data are compared to the real performances of the motor. The sizes of each part of the motor are calculated by the tool.

For instance, the active length (Fig. 4), the rotor and the external stator radius (Fig. 5) calculated are compared to the values on data sheets. From these sizes, the mass and the specific torque of the motor can be estimated (Fig. 6).

Table 4
Input data of the assessment tool suitable for ETEL TMB motors

	Free air convection	Water cooling
Thermal specifications		
T_{amb} (°C)	40	40
ΔT (°C)	120	120
Load levels		
σ (N.m ⁻²)	25000	50000
j_{rms} (A/m ²)	3.5×10^6	7×10^6
B_M (T)	1.05	1.05
B_y (T)	1.7	1.7
B_t (T)	1.7	1.7
Deduced Values		
A_{rms} (kA/m)	37	74
$A_{rms} \cdot j_{rms}$ (A ² /m ³)	13×10^{10}	51.8×10^{10}

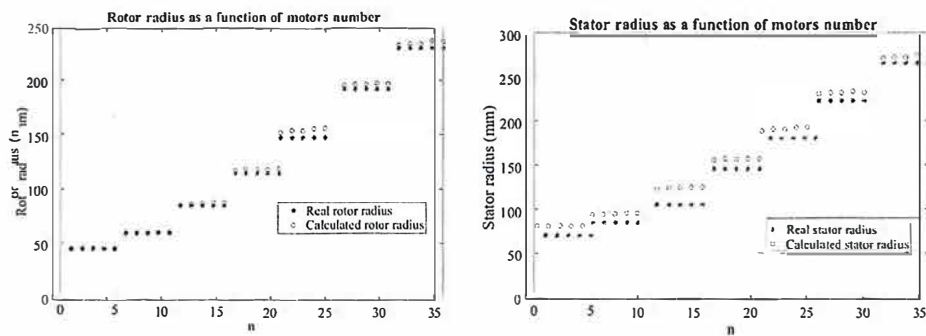


Fig. 5. Comparing the rotor and the stator radius calculated to the data sheet of TMB ETEL motors [4].

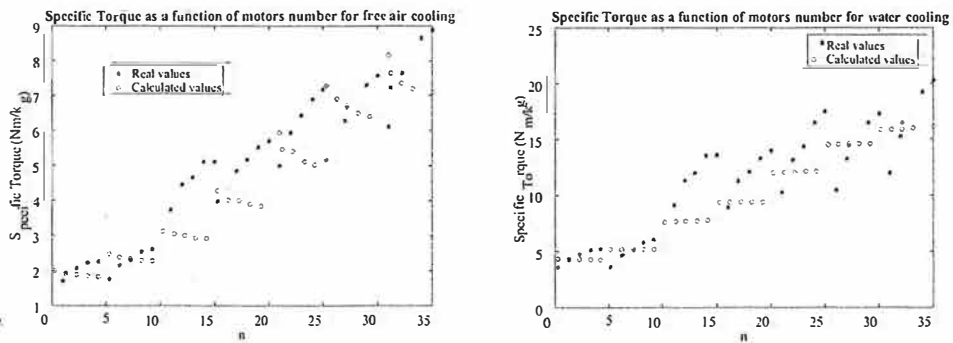


Fig. 6. Comparing the specific torque calculated to the data sheet of TMB ETEL motors [4].

From Figs 3 to 5, it can be seen that for this type of torque motors, the increase in the torque is done by increasing continuously the length for a given rotor radius and a given number of pole pairs.

Due to the assumptions made, differences can be observed between the specific torque calculated and the one from the data sheet. Nevertheless one may conclude that the specific torque is calculated with enough accuracy and the variation of the specific torque with motor number follows correctly the variation evaluated from the data sheet (Fig. 6). Only the mass of the active parts are taken into account. That is why the specific torque is so high. Results on Fig. 6 show that water cooling allows to double the specific torque (magnetic shear stress is twice for water cooling than for air cooling).

7. Conclusions

A tool based on loadability concepts has been developed. By means of some additional balance equations, the tool can quickly size a low speed electric motor. The tool has been evaluated from the data sheet of high torque TMB ETEL motor. The results show that the specific torques are calculated with enough precision to make rapid tradeoffs of high torque electric motors. The loadability concepts seem to be very useful to evaluate the levels of the set of, magnetic, electric and cooling technologies and assess the performance of electric motors. The main advantage of this tool is that it needs very few data: for instance the stator and the rotor are not described completely to make these calculations. The results can then be assessed for many types of electric machines without saliency.

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