Rapid Electric Motor Sizing Estimation for Automotive Application with Statistical Approach Using Catalog Values

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***Abstract*— This paper presents a rapid sizing method for electrical machines estimating the length, rotor and stator diameter using only the maximum torque, the maximum speed, the maximum power and efficiency as input parameters. The method allows the calculation of separately excited synchronous (SSM), asynchronous (ASM) and permanent synchronous machines (PSM). To calculate the missing parameters needed for the estimation, a pre-compiled database of motors is considered. These parameters can be calculated using statistical interpolation methods. The proposed method combines these statistically calculated parameters with physical relations. Advantages of this method include the possibility to estimate the volume of the electrical motor as well as to use the interpolated data to scale the dimensions of the engine, which enables integrating the motor in a constrained space. To prove the validity of the method, different motors not present in the interpolated database are redesigned with the proposed method. This comparison shows that the model can display a divergence in a range of -6% to +10% in the estimation, which depends on the type of motor. This is small enough to be applied in the automatized design method of automotive transmission. The computational time of 1-2 s per motor design proves that the algorithm operates fast enough.**

***Index Terms*—Electric motor design, hybrid vehicle, parameter estimation, transmission synthesis**

I. Introduction

The automotive industry is facing increasingly strict regulations concerning fleet-CO_2 and pollutant emissions, which require innovative drive systems. To meet these requirements, a fleet containing a mix of conventional, hybrid and purely electric vehicles seems to be one likely answer. To handle the space challenges that the adding of electrical components produces, transmission synthesis tools have been developed. They are successfully applied by the industry to synthesize transmissions for purely electric, conventional and hybrid powertrains. A full evaluation of the transmission concept, however, requires design drafts. Therefore, automatizing the transmission design process is the content of current research, which is focusing on a fast generation of design drafts for multiple transmission topologies found by the transmission synthesis. In particular, the automated design of electric axle systems or dedicated hybrid transmissions, comprising the optimal design of the electrical components and their geometrical integration into the system has not been formally addressed so far. Due to the massive amount of time needed for the design draft, a rapid machine design method is required to meet the accuracy requirements only based on the few information available at that early stage of development. The design of a motor depends on multiple parameters (e.g. lamination thickness, conductor diameter, power factor, starting current, frame sizes, etc. etc.). However, some of them might not be available during the first dimensioning of the system. For this reason, a database with over 130 engines was built to create functions that relate size and characteristics.

II. Torque Density

The first factor estimated via database is the torque density, also known as torque per rotor volume, defined as the ratio between the torque and the size of the rotor as presented in Equation (1), where L_k is the active length and D_{Rotor} the diameter of the rotor [1] [2] [3].

$$T_d = \frac{\text{Torque}}{\text{Volume}} = \frac{\text{Torque}}{L_k \frac{D_{\text{rotor}}^2 \pi}{4}} \tag{1}$$

The mean value of the torque density is calculated among the three types of motors in the database: ASM, PSM, and SSM. Fig. 1, Fig. 2 and Fig. 3 represent the variation of the torque density within the database, where the green line represents the mean value. Table I lists the mean of the three different motors.

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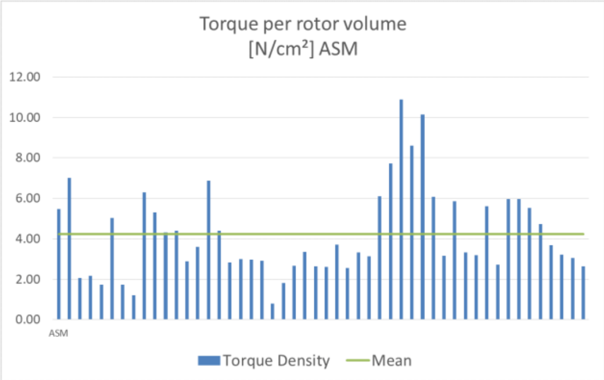

Figure 1. Torque per rotor volume ASM

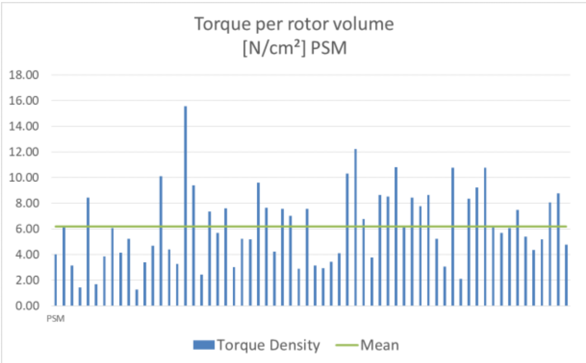

Figure 2. Torque per rotor volume PSM

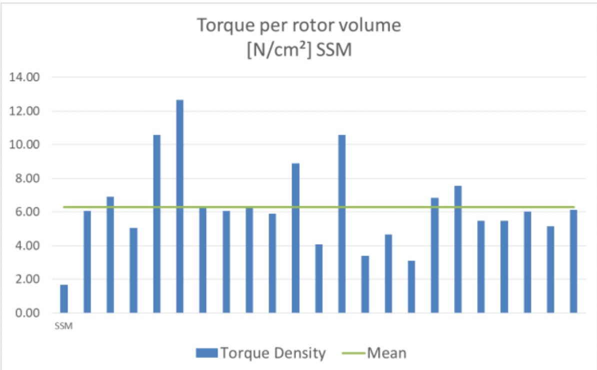

Figure 3. Torque per rotor volume SSM

TABLE I. TORQUE DENSITY MEAN

Type	Mean
ASM	4.22
PSM	6.20
SSM	6.29

III. ROTOR FACTOR

The rotor factor r_f is the second parameter estimated via database. It is the ratio between the stator and rotor diameter, and it is presented in Equation (2).

$$r_f = \frac{D_{rotor}}{D_{stator}} \tag{2}$$

Since the rotor factor is related to the torque [4] [5] [6], it is possible to create a function that relates the torque to the rotor factor by a trendline within the database data. Fig. 4, Fig. 5, and Fig. 6 show the performed interpolations.

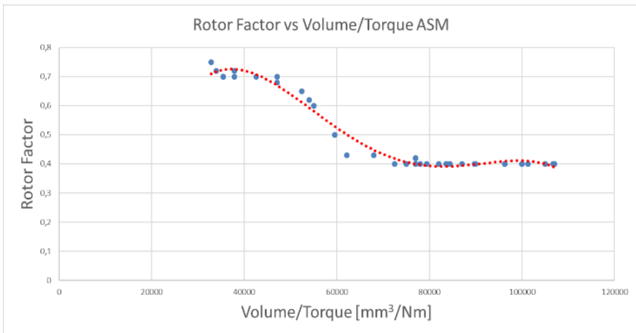

Figure 4. Rotor factor ASM

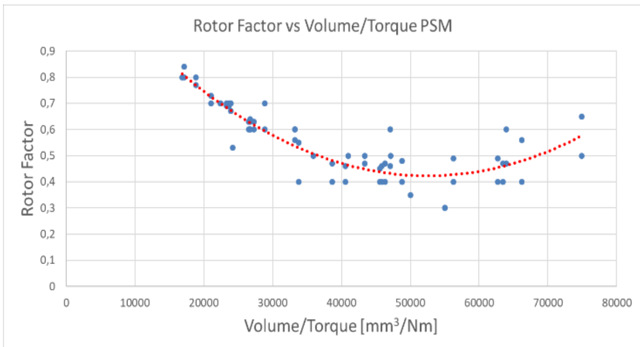

Figure 5. Rotor Factor PSM

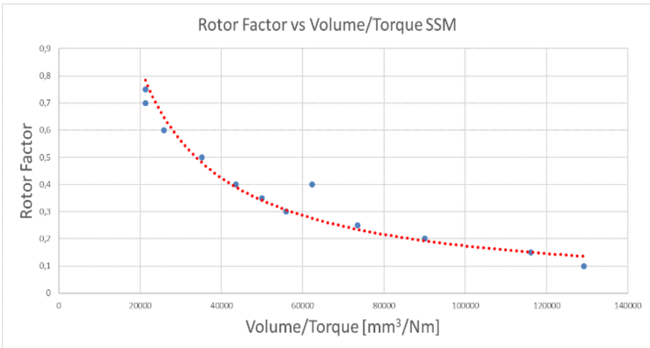

Figure 6. Rotor factor SSM

The trendlines are shown in Equation (3) where x is the ratio between Volume and Torque expressed in mm^3/Nm.

$$\begin{aligned} &\text{ASM} && r_f = -10^{-19}x^4 + 4\cdot10^{-14}x^3 - 4\cdot10^{-9}x^2 + 4\cdot10^{-4}x - 1.53 \\ &\text{PSM} && r_f = 3\cdot10^{-10}x^2 - 3\cdot10^{-5}x + 1.233 \\ &\text{SSM} && r_f = 16548x^{-0.997} \end{aligned} \tag{3}$$

IV. Cooling Height

After designing the leading dimension of the stator, the length of the cooling system is further added to obtain the final size of the motor, as shown in Fig. 7.

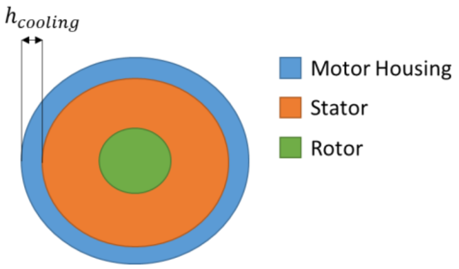

Figure 7. Cooling height and the stator diameter

The cooling area is expressed as a function of the stator diameter D_{stator} as presented in Equation (4).

$$A= \frac{\pi}{4} \cdot (D_{stator}+ 2\cdot h_{cooling})^2 - \frac{\pi}{4} \cdot D_{stator}^2 \tag{4}$$

Equation (5) represents the relation between the dissipated power and the characteristics of the fluid, where Q is the heat released from the motor, m the mass of cooling liquid, c_p is the specific heat capacity, f_d is the fluid density, and ΔT is the difference between the inlet and outlet temperature. A rough estimation of the heat released by the motor can be calculated using the engine efficiency and power.

$$\frac{dQ}{dt} = \frac{dm}{dt} c_p \Delta T = \frac{d(f_d \cdot L \cdot A)}{dt} c_p \Delta T \tag{5}$$

Equation (5) can be then re-arranged as Equation (6), where $\dot{Q}$ is the dissipated power, $\dot{m}$ the mass flow rate and v the velocity of the fluid.

$$\dot{Q} = \dot{m} c_p \Delta T = f_d \cdot v \cdot A \cdot c_p \cdot \Delta T \tag{6}$$

By combining (4), and (6), it is possible to evaluate the cooling height as a function of the stator diameter (7)

$$h_{cooling}=0.5\cdot \left(\sqrt{D_{stator}^2 + \frac{4\cdot \dot{Q}}{f_d \cdot v \cdot c_p \cdot \pi \cdot \Delta T}} - D_{stator} \right) \tag{7}$$

According to the power of the motor, air or a mix of water and ethylene glycol can be considered as the cooling fluid [7] [8] [9].

In this study, the fluid characteristics of the glycol have been taken from the literature [10].

V. Method

As already explained, the inputs for the algorithm are the nominal voltage and current, the maximum torque, maximum speed, and efficiency. Fig. 8 shows how the motor has been modelled in terms of total, stator, and rotor diameters.

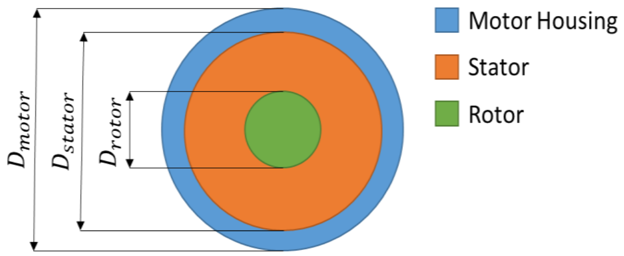

Figure 8. Model of the motor

With this model, the outer rotor diameter and the internal stator diameter correspond.

The rotor diameter depends on the maximum rotational speed and the maximum radial acceleration, which depends on the application.

The rotor diameter can be evaluated with Equation (8), where a is the radial acceleration.

$$a=\omega_{max}^2 \frac{D_{rotor}}{2} \tag{8}$$

The radial acceleration at the air gap diameter can be found in the literature and it is presented in Table II [11].

TABLE II. Radial Acceleration

Type	a (m/s^2)
ASM	95954
PSM	95954
SSM	99381

Alternatively, the rotor diameter can be evaluated via stress analysis [12].

Equation (9) shows how to find the active length L_k, using the maximum torque and the rotor diameter, where T_d is the torque density explained in Section II.

$$L_k = \frac{Torque}{\frac{\pi \cdot D_{rotor}^2 \cdot T_d}{4}} \tag{9}$$

From the active length, the total length of the machine can be calculated with Equation (10), where f_{wc} is the winding coil factor

$$L_{total} = \frac{L_k}{1+ f_{wc}} \tag{10}$$

The winding coil factor is defined in Equation (11), where l_{wc} is the winding coil length as presented in Fig. 9.

$$f_{wc} = \frac{2 \cdot l_{wc}}{L_k} \tag{11}$$

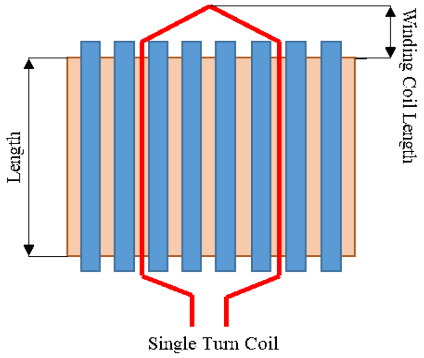

Figure 9. Winding coil length

The winding coil length can be roughly estimated as $l_{wc} \approx 1.2 t_s$, where t_s is the stator pole width [13] [14], and it can be calculated using the geometry of the electric motor [15].

However, the winding factor can be considered as constant and can be estimated via database, as presented in Fig. 10, Fig. 11, and Fig. 12. Table III shows the mean of the winding factor.

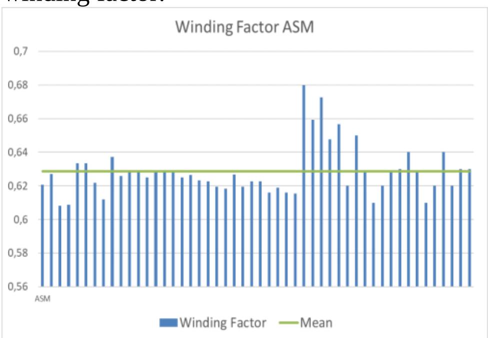

Figure 10. Winding factor ASM

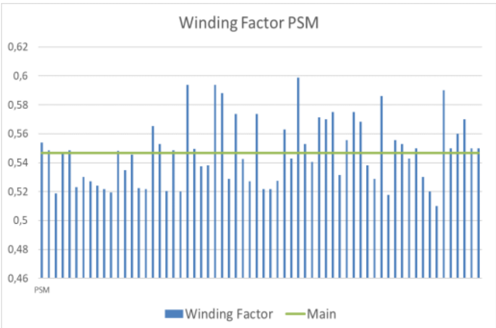

Figure 11. Winding factor PSM

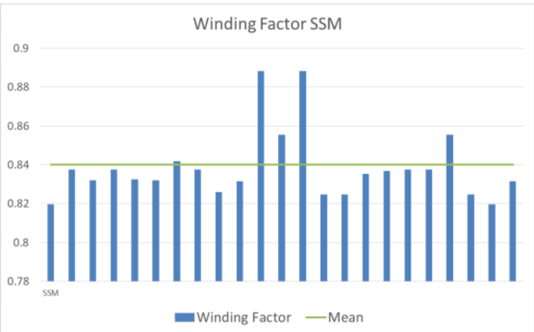

Figure 12. Winding factor SSM

TABLE III. TORQUE DENSITY MEAN

Type	Mean
ASM	0.63
PSM	0.55
SSM	0.84

From the rotor diameter, it is possible to calculate the stator diameter with Equation (2).

The total diameter of the motor is evaluated in Equation (12).

$$D_{motor} = D_{stator} + 2 \cdot h_{cooling} \tag{12}$$

The main steps of the design procedure are summed up in the flowchart of Fig. 13.

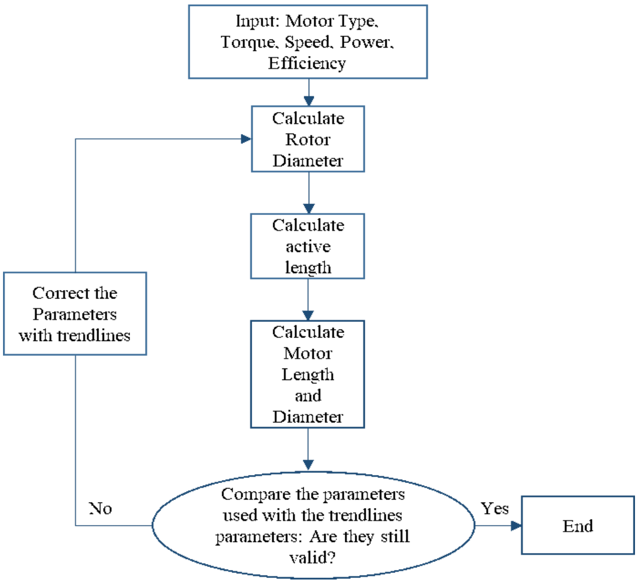

Figure 13. Proposed designing method flowchart

The algorithm is an iterative one that automatically corrects the parameters by sequentially calculating the size of the electric motor. The algorithm makes a first evaluation of the volume using a starting point. At the beginning, the rotor diameter is calculated. Next, the active length is calculated. Finally, the diameter and the total length are calculated. It then checks whether the parameters obtained from the estimated size are close to the values used for the calculation. If they are not, the program modifies the parameters and recalculates the volume. This cycle ends when the parameters of the calculated geometry are, under a user-defined tolerance, close to the parameters evaluated with the engine volume.

The starting values for the rotor and winding factor as well the cooling height are summed up in Table IV.

TABLE IV. PARAMETERS INITIALIZATION

Parameter	Motor		
	ASM	PSM	SSM
Cooling height	8 mm	8 mm	8 mm
Rotor factor	0.2	0.6	0.2
Winding Factor	0.6	0.5	0.8

VI. Results

In order to validate the algorithm, different motors excluded a priori from the database have been analyzed.

Table V lists the results obtained. The percentage errors e_D and e_L, which represent the error on diameter and error on length respectively, are calculated subtracting the catalog value from the computed value, dividing by the catalog value and then multiplying by 100%. As expected, the interpolation of the data can cause errors in excess or defect. The type of technology used for the motor influences the error.

TABLE V. Torque Density Mean

Motor	Type	Diameter [mm]	Length [mm]	Obtained Diameter [mm]	Obtained Length [mm]	e_D	e_L
Curtis 1238-7601 HPEVS AC-50	ASM	228	356	245	350	7.45%	-1.68%
Zytek 55kW	PSM	242	392	237	387	-2.06%	-1.27%
Chevrolet Volt	PSM	204	380	204	400	0%	5.26%
Brusa SSM1-6.17.1	SSM	270	245	299	230	10.7%	-6.12%
Nissan Leaf (EV)	SSM	329	259	349	250	6.08%	-3.47%
Renault Fluence	SSM	240	370	241	364	0.42%	-1.62%

VII. Conclusions

In this study, an algorithm that can estimate the length and diameter of an electric motor was implemented. A correct size estimate requires many factors ranging from the electrical sector to the materials sector. These factors are often not available during the preliminary analysis of the transmission, where the parameters involved are purely mechanical, such as speed, torque and efficiency. To get around this obstacle, a database was built consisting of motors currently on the market and interpolating the parameters necessary for sizing. By doing so, the interpolations obtained represent a link between the performance of the engine and the parameters that manufacturers can currently provide. To validate the algorithm, the results obtained were compared with some drivers not included in the database and therefore considered as a benchmark. According to the obtained results, the difference between the model and a real motor oscillates between -6% and +10% not exceeding 30 mm, which is a reasonable estimation in the first dimension. A strong point of the algorithm is its speed for calculating the size of the motor, which is around 1-2 seconds due to its level of abstraction and its simple model. By increasing the number of samples inside the database, it could be possible to decrease the error. However, due to interpolations, a small deviation will always occur. The algorithm also adapts well to future developments in the automotive field. With increasing performance, it will be enough to add motors with new technologies and possibly remove the older ones to adapt the algorithm.

Conflict of Interest

The authors declare no conflict of interest.

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