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EFFICIENCY MAPS FOR AN EV BLDC MOTOR USING ANALYTIC CALCULATION AND SIMULATION

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Abstract. In an EV (Electric Vehicle), the more tractive force produced by the electric powertrain in fact requires more electric current from the battery. The question is how efficiently the stored energy is used, as for modern EVs, the ability to move over a greater distance represents an important issue. Of course, it can be best confirmed by physical measurements on the vehicle, but before, the analytic calculations and the simulations are important to certify the choices. In this context, the actual paper presents the analysis of the capabilities of a BLDC motor powertrain. A new method is used in the determination of the number of identical motors needed to participate in the powertrain, based on the efficiency map of the individual motor.

1. INTRODUCTION

Being known for more than 100 years [1], Electric Vehicle (EV) topics continue to be investigated following sustained research activities in order to accelerate the transition to green mobility. Improvements in the capabilities to have more onboard electric energy continue in parallel with more efficiency on the powertrain. The physical dimensions and the control possibilities of the electric motors allow for the integration of multiple motors on the same powertrain [2-6] giving new opportunities for energy efficiency compared to an equivalent single-motor powertrain [7] and higher performance [8-9].

Induction motors [10-12] preserve an important potential for propulsion systems. At the same time, the usage of permanent magnets [13-15] offers a substantial advantage in electric powertrains. Using multiple mechanical power sources on the same vehicle generates complex individual torque control [16-18] to preserve the vehicle's stability searching performance and energy efficiency [19]. For supplying the multiple motors, the direct current (DC) from the onboard energy storage must be adapted for each motor phase via the inverter [20-22] following the strategy given by the motor's controls [23-29]. Using simulation [30] different control strategies can be explored. Solutions to obtain a first physical confirmation on a test bench are already explored [31]. The activities could be realized at a reduced scale, depending on the platform's capabilities [32].

Different scenarios of torque repartition between the multiple motors of the powertrain had already been investigated [33] and show real opportunities to improve the efficiency in the usage of the onboard electric energy. In this context, the actual paper continues to investigate the capabilities of permanent magnet motors. If control improvements like the usage of phase advance and dwell control generate better performance in terms of speed [34] and energy efficiency [35], in this case, the investigation concerns the usage of a BLDC (brushless DC) motor in a multi-motor powertrain. In [7] the analysis regards the usage of multiple smaller motors instead of a single motor covering the whole operating points. In complement, the present paper presents a new method in powertrain construction using multiple identic motors, starting the analysis with a single motor, and building and investigating its efficiency maps to establish the number of identical motors in the powertrain. The analysis is based on a

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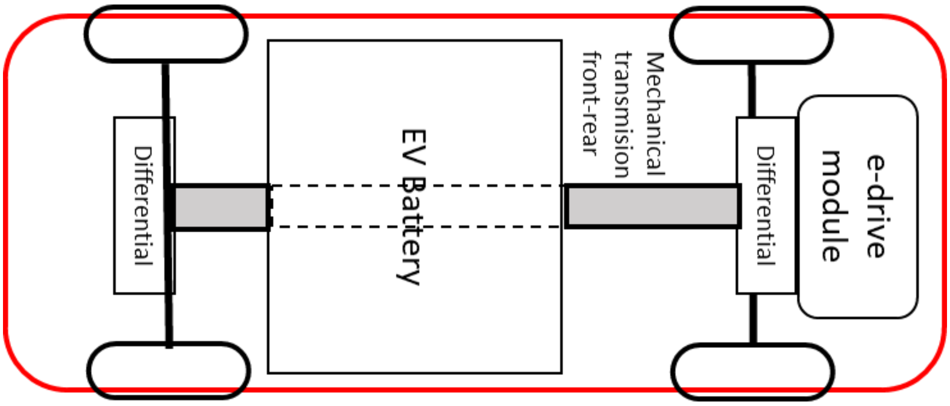
normalized testing cycle giving the evolution of the vehicle speed request and thus obtaining the evolution of the torque request for the powertrain.

2. CONFIGURATION OF THE VEHICLE

2.1 Classic vehicle configuration

Modern vehicles dispose of all-wheel driving capabilities. The mechanical power provided by the propulsion system must be dispatched to the vehicle's wheels, as shown in Fig. 1.

Fig. 1. – Initial vehicle configuration



In [36] is explained that there is mechanical power lost in the transmissions (1% in the clutch, 3 to 5 % in each pair of gears, and 1 to 2% in each bearing and joint). One advantage of electric motors is that in the same vehicle, the powertrain can integrate multiple motors. An important question is how many motors are needed to be integrated into the powertrain and how the vehicle will be configured.

2.2 Vehicle data

To continue the investigation, vehicle data are required, Table 1.

Table 1. Characteristics of the vehicle

Characteristic	Value	Measurement Unit
Vehicle mass	400	kg
Wheel radius	0.3	m
Aerodynamic drag coefficient	0.46	-
Frontal area	0.92	m^2

Based on vehicle characteristics, a normalized testing cycle is used to build the torque request for the powertrain, a WLTC. In [33] is explained how the speed profile of the testing cycle is transformed into a tractive effort profile required for the powertrain. The tractive effort coefficient is considered 0.8, enabling the calculation of the maximum tractive effort supported by the wheels, and the rolling resistant coefficient, 0.013, helps to calculate the rolling resistant force. The operating points to be covered by the powertrain are generated in the torque-speed plane.

2.3 Motor data

The BLDC motor from [35] is considered for the investigations, with the main characteristics shown in Table 2.

Table 2. Individual Motor Data

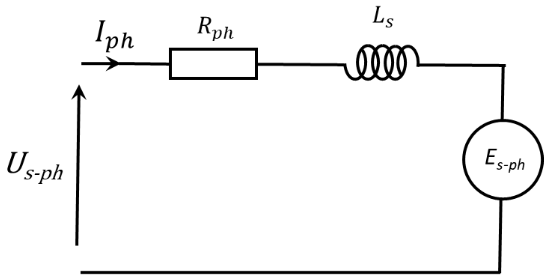
Characteristic	Value	Measurement Unit
Rated / Maximum Power	3 / 5.4	kW
Voltage supply	72	V
Number of pair poles	20	-
Rated current	68 / 136	A
Transmission rapport motor to wheel	1	-
Torque constant	0.78	Nm/A
Phase Resistance	0.027	Ω
Phase Inductance	0.15	mH
Calculated equivalent static torque	0.89	Nm
Calculated equivalent coefficient of viscous friction	0.021	Nms

3. INVESTIGATION OF THE MOTOR CAPABILITIES

3.1 Analytic calculation

The three phases of the BLDC motor are star connected and supplied applying the DC voltage between two phases. The equivalent circuit is represented in Fig. 2, where U_{s-ph} is the source voltage applied to a motor phase, R_{ph} is the phase resistance, L_s, the leakage inductance, as the difference between the self-inductance of the winding and mutual inductance, and E_{s-ph} is the back-EMF induced in the winding.

Fig. – 2. Phase equivalent circuit of the motor



The electromagnetic torque, T_E, is the product between the torque constant, k_T, and the motor phase current, I_{ph},

$$T_E = k_T I_{ph}, \tag{1}$$

and the back-EMF is the product between the speed of the motor, Ω, and the back-EMF constant, k_E.

$$E_s = k_E \Omega \tag{2}$$

The current passing the motor phase results from the rapport between the real voltage applied on the phase and the phase resistance:

$$T_E = k_T \frac{U_{s-ph} - k_E \Omega}{R_{ph}},\quad (3)$$

where k_T is the torque constant.

The electric power requested by the motor is:

$$P_e = P_E + R_{ph} I_s^{\,2},\quad (4)$$

where P_E is the electromagnetic power

$$P_E = T_E \Omega \cdot\quad (5)$$

At the motor shaft, the resulting torque is

$$T_{shaft} = T_E - T_{f0} - F_v \Omega,\quad (6)$$

where, T_{f0} is the equivalent static torque, and F_v is the viscous friction coefficient previously calculated using two measurements when running the machine without load at two different speeds.

A first approximation for the mechanical characteristic of the motor is to consider that the maximum torque and maximum power curve give the superior limitation.

The iron losses are computed using equation (7),

$$P_{iron} = \left(T_{f0} + F_v \Omega\right) \cdot \Omega,\quad (7)$$

the total losses are the sum of Joule losses and iron losses, and the output power is the product between the torque at the shaft from equation (6) and the speed, Fig. 3.

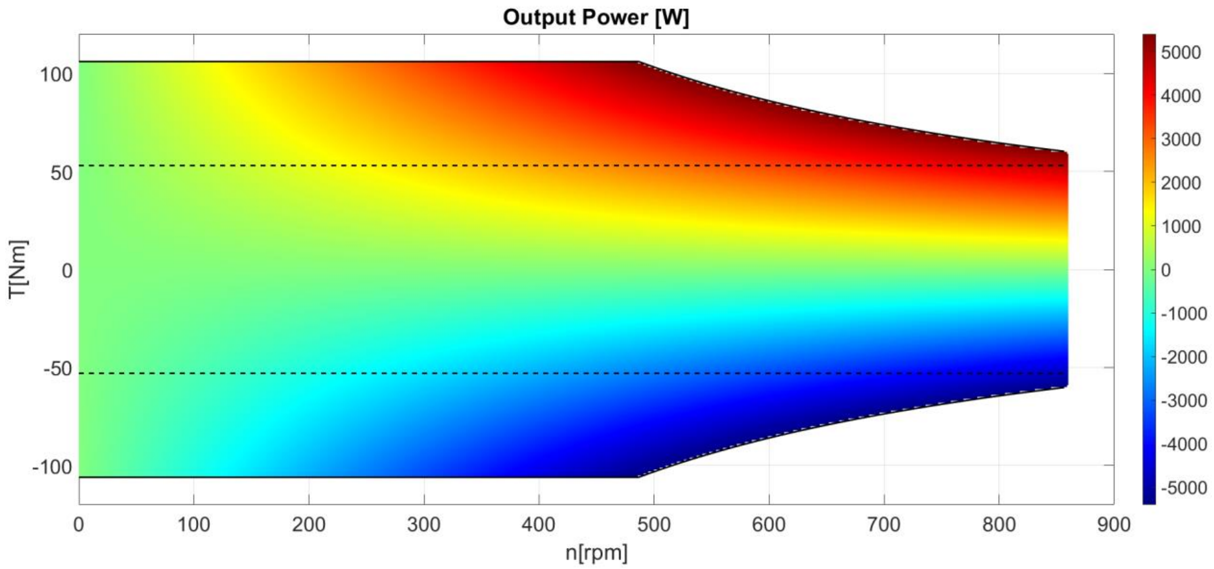


Fig. 3 –. Mechanical power at shaft

The input power results from the output power adding the total losses, Fig.4

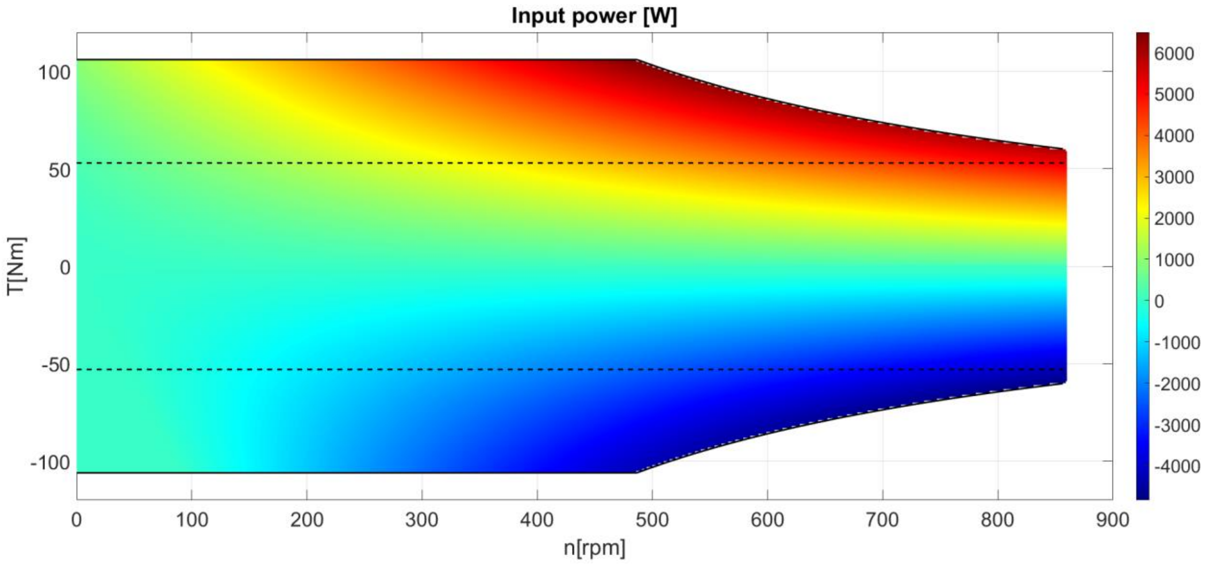


Fig. – 4. Electrical power consumption

The resulting motor efficiency profile, as the rapport between the delivered mechanical power at the motor shaft and the electrical power received, is shown in Fig. 5.

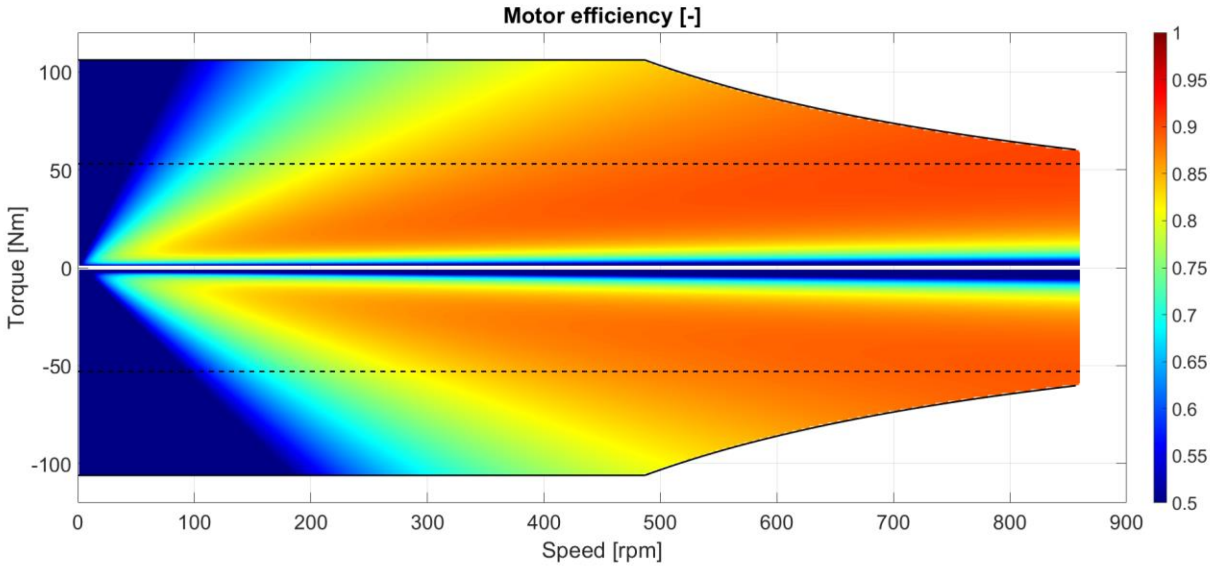


Fig.5. – Efficiency map of the motor

3.2 Motor investigation using simulation

Figure 6 presents the model implemented in MATLAB-Simulink to determine the motor characteristic.

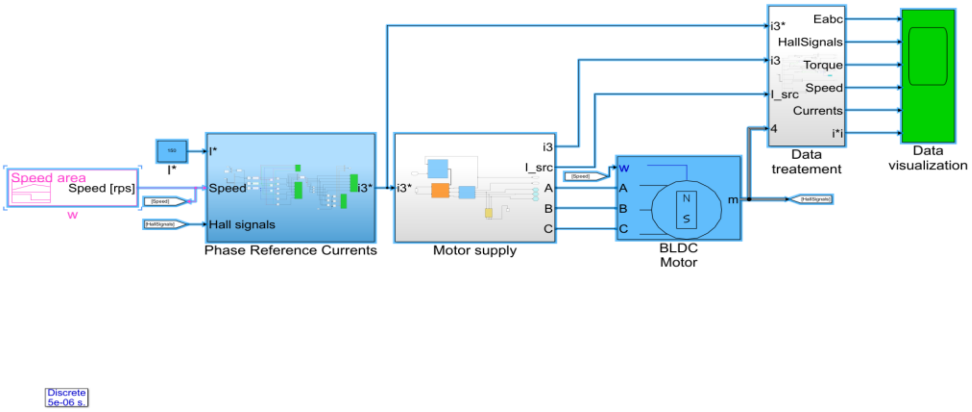


Fig. 6. – Model for motor capabilities investigation [35]

The "w" block generates different speed levels to investigate all operational areas of the motor. Depending on the speed, the "Phase Reference Currents" block creates the rectangular shape of the phase currents of the motor, and the "Motor Supply" integrates the DC power source, the commutation pulses generation, and the inverter. The "Data Treatment" block prepares data for computation in the block shown in Fig. 7.

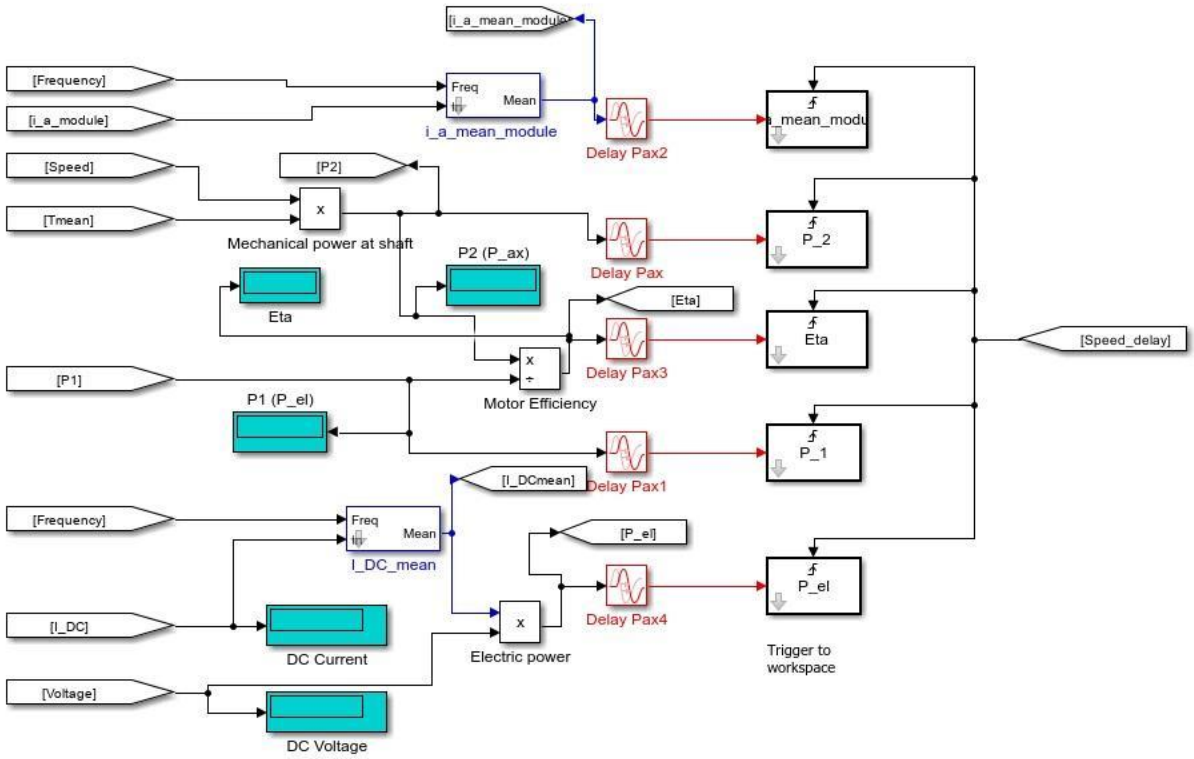


Fig. – 7. Computation of physical quantities under MATLAB-Simulink

For each investigated speed level, different reference current values (I* in Fig. 9) are submitted to simulation. The obtained data request additional treatment. Figure 8 presents a few interpolation methods followed to cover the entire area of the powertrain.

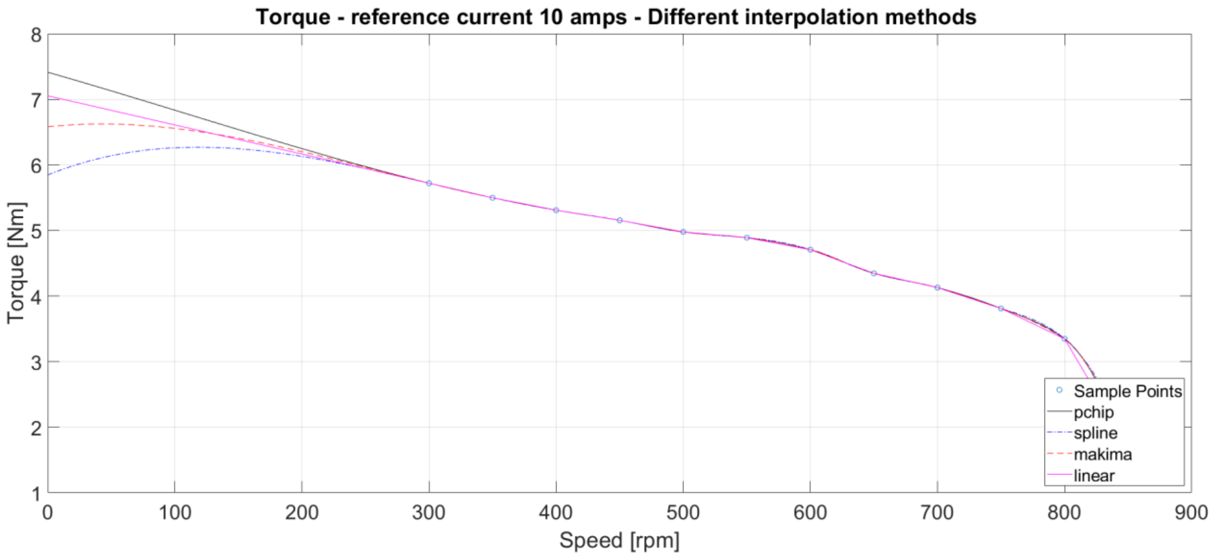


Fig. 8 – Interpolation methods used for torque computation.

Finally, the obtained mechanical characteristic of the motor is presented in Fig. 9.

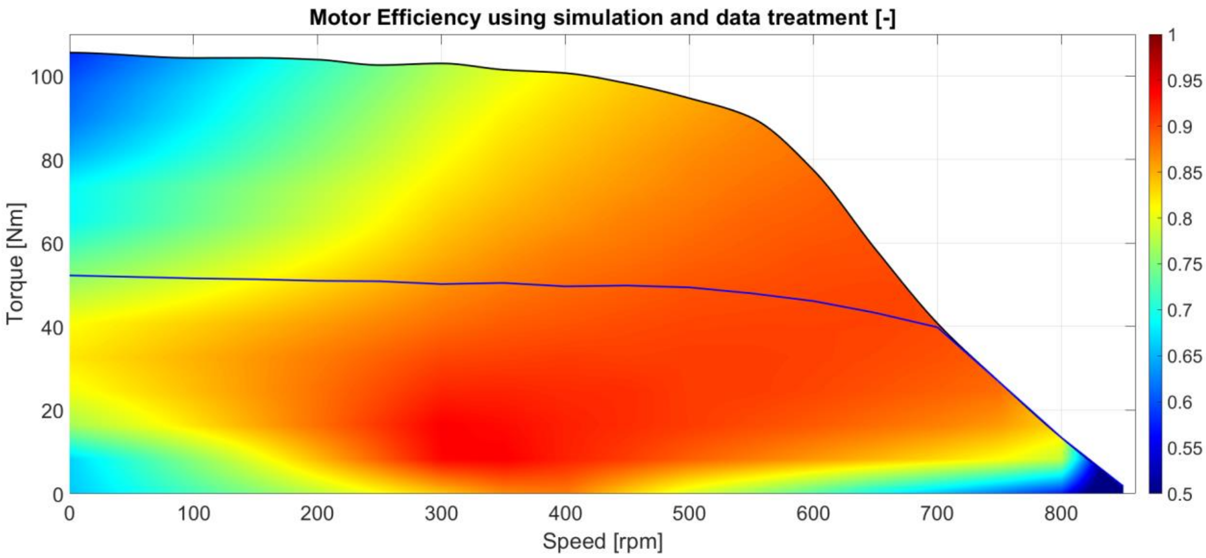


Fig. 9 – Efficiency map of the motor obtained by simulation.

4. RESULTS AND DISCUSSION

4.1 Operating points and number of motors for the powertrain

To calculate the operating points following the example in [33], Fig.. 10 presents the normalized testing cycle, WLTC.

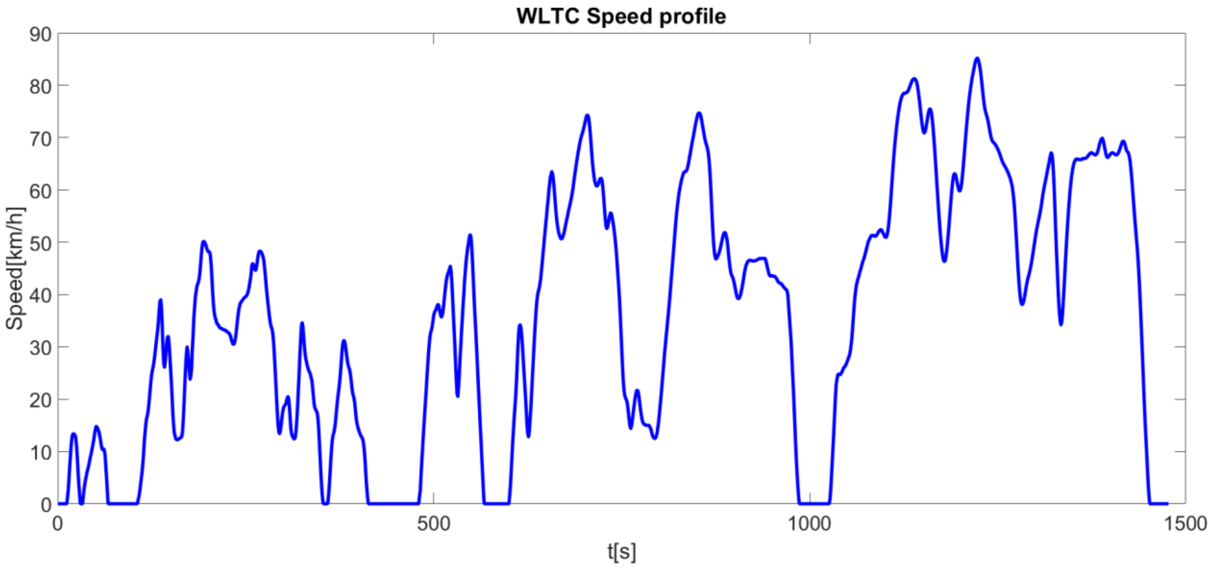


Fig. 10 –. Speed request during WLTC

In Fig. 11 the operating points resulting from the WLTC speed profile as a request for the powertrain are represented in blue. With a continuous line in blue and black are the nominal torque and respectively the maximum torque obtained by simulation and data treatment. In the same colors, the dashed lines represent the nominal and maximum torque used for analytic calculation.

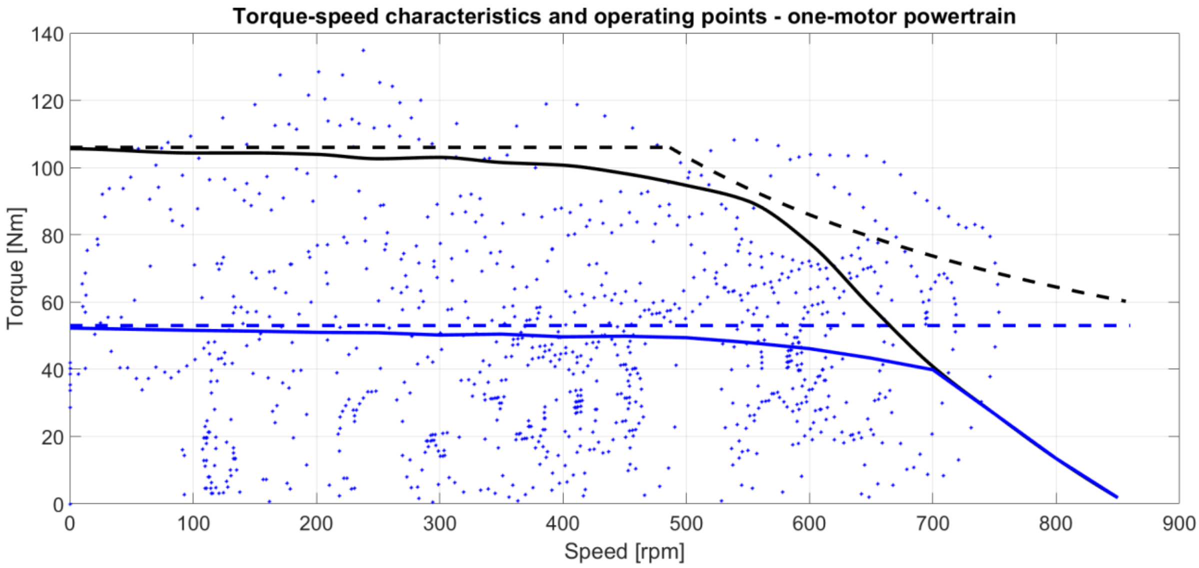


Fig.11 – Operating points and motor characteristics

4.2 Number of motors for the powertrain

One single motor moves the vehicle but is not able to cover all operating points. Not being able to provide enough torque, the vehicle's speed will increase less fast, and it will not be able to offer high speeds.

To preserve the motor in the most efficient area, in the case of a multi-motor powertrain, the motors have to provide torque successively. For example, if the speed is about 350 rpm, one single motor could provide torque between 0 and 35 Nm. For more torque, a second motor could link its shaft to the mechanical transmission of the vehicle. It is important to keep each motor in the most efficient zone.

Following the precedent example:

- three identical motors would be needed to cover the torque request in the high-speed region,
- for the low-speed region, four identical motors would be an interesting solution,
- for the middle-speed area, five identical motors represent a good choice.

In a real case, it is possible to use successively the motors if their shaft can be mechanically connected before dispatching the power to the wheels. If each wheel is powered directly by a single motor, additional strategies had to be integrated.

5. CONCLUSION

The precedent investigations compare the results regarding the efficiency maps of a motor following analytic calculation and simulation. To obtain a rapid result, the analytic calculation is preferred. To obtain a more precise one, the simulation is better but takes more time.

The finer the investigation step is, the longer time is needed for simulation. Practically, there is not possible to avoid an external treatment of the data obtained by simulation, and different methods could be used. In the analyzed case, the maximum iron losses, dependent on speed and square of the speed, are less important than the maximum Joule losses. Also, the Joule losses could be different for the same current but at different temperatures of the windings. The simulation integrates better the behavior of the motor than the analytic calculation.

An analytic calculation provides rapid information about the general coverage of the operating points requested for the motor. It is easier by analytic calculation to confirm or not the possibility of using the motor in the powertrain.

For dipper investigations, such as using multiple similar motors, the simulation is more indicated to give directions for the future powertrain.

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