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Dynamic Modelling and Simulation of a Permanent Magnet Synchronous Motor (PMSM) Applied in a Prototype Race Car and the Comparison of Its Performance with BLDC Motor

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Abstract

Electric vehicles are playing an important role in transport, aided by rapid advances in battery technology. The Faculty of Engineering at the University of Debrecen is also engaged research and development in the field of electric vehicles. To support the development of electric vehicle prototypes, a vehicle dynamics simulation program has been designed. The study presents the modeling and simulation of a permanent magnet synchronous motor (PMSM) in MATLAB/Simulink, which has been integrated into the existing vehicle dynamics simulation framework. The methods used to determine the motor characteristics required for the simulation are described in detail. In addition, the performance of the PMSM is compared with that of a brushless DC (BLDC) motor within the vehicle dynamics simulation program. The developed method allows the selection of the appropriate motor type for the given competition tasks.



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Keywords: PMSM motor; modelling; simulation; MATLAB; Simulink

1. Introduction

Electric vehicles are playing an increasingly important role in road transport today, thanks to the rapid development of modern batteries and electric systems. In addition, a number of other factors are also influencing this trend, such as increasing environmental awareness and the resulting legal regulations, or economic considerations, as more and more manufacturers are now offering a viable alternative to conventional internal combustion engine vehicles in the field of electric vehicles. This means that the entire global vehicle industry is currently undergoing a transformation. One of the main components of hybrid and electric vehicles is the electric motor, for which manufacturers use a variety of different types of motors to power their vehicles [1–3]. These motor types are summarized in Figure 1 [1].

Each type of motor has different characteristics, so when designing a new vehicle, for example, these must be taken into account in order to select the optimum motor for the vehicle. The selection process usually starts with vehicle dynamics simulations [4], the results of which can provide a good basis for the decision. The above facts underline the importance of research into different types of electric motors.

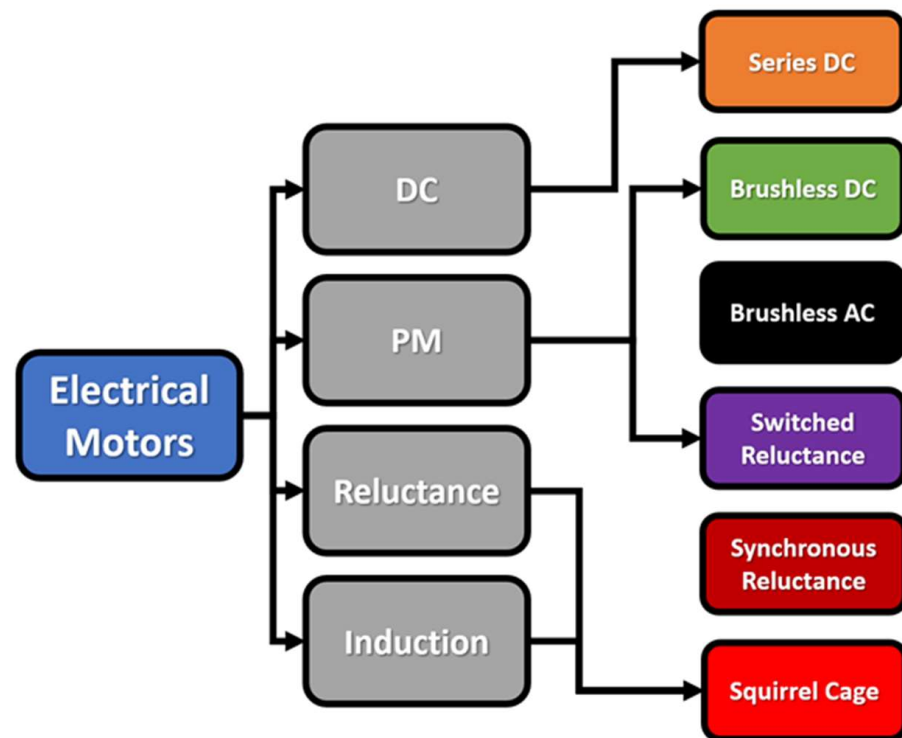


Figure 1. Motor types used in electric vehicles.

The Faculty of Engineering of the University of Debrecen has more than a decade of experience in the development of pneumatic and electric prototype race cars. In order to improve the efficiency and awareness of development and racing, a vehicle dynamics simulation program has already been developed [4]. One element of the above program is the simulation of the electric motor, which has been previously performed for brushless DC (BLDC) and series-wound DC (SWDC) motors and incorporated into the vehicle dynamics simulation program [5]. Since the permanent magnet synchronous motor (PMSM) is often used in electric drive vehicles due to its outstanding properties, in this paper, the model and simulation program of this motor are presented in MATLAB/Simulink (R2022b) and applied to the above vehicle dynamics simulation program. In order to run the simulation program, it is necessary to know the various electromagnetic and dynamic characteristics of the motor, which are often not or only partially provided by the manufacturers. Therefore, methods developed for the experimental determination of the motor characteristics required as input to the simulation program are also presented. Furthermore, the research compares the performance of the PMSM motor with another motor type (BLDC) in the vehicle dynamics simulation program to select the optimal motor type for the competition tasks. The results obtained here may be useful for the design of a Formula Student race car in the future.

Although there are several publications in the literature dealing with the modelling and simulation of PMSM motors [6–11] or the experimental determination or estimation of the motor characteristics [12–14], no comprehensive publication on the above has been found. In this research, after a detailed description of the motor model and simulation, used this motor simulation as a module of a vehicle dynamics simulation program and run it with different type of motors to compare and analyze the results obtained. In addition, present research provide a comprehensive solution for the experimental determination of engine characteristics, building upon extensive prior experience in this field [15–18], which is also novel in the literature.

2. The Applied Vehicle Dynamics Simulation Program

The following section briefly presents a vehicle dynamics simulation program previously developed for prototype race cars in a MATLAB Simulink environment [4]. One of the modules of the program is the simulation of an electric motor, which has been previously implemented and tested for two types of motors (BLDC, SWDC) [5]. In connection with this, in the following sections, present the modelling and simulate the PMSM motor and integrate it into the vehicle dynamics simulation program. In this way, simulation results for different motor types can be compared.

The simulation program mentioned above is based on a proprietary vehicle dynamics model, the structure of which is shown in Figure 2.

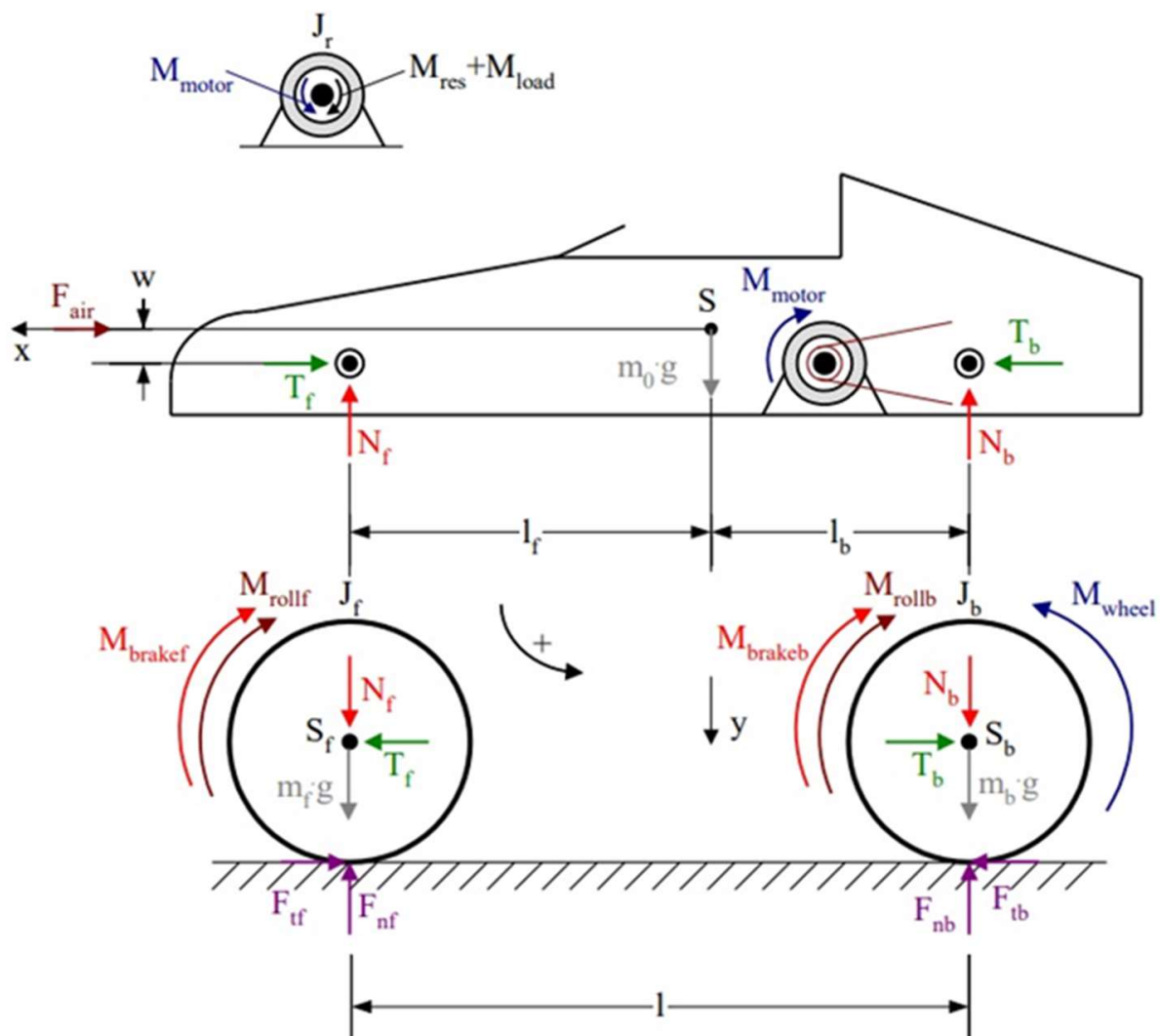


Figure 2. The vehicle dynamics model for the race car together with the forces and torques acting on it [4].

The model was developed for an electric single-seater prototype race car, with a sufficiently rigid frame and chassis, and powered by an electric motor that drives the rear wheels via a chain drive. In the model, the vehicle is divided into 4 structural units, which are the vehicle body, including the motor housing (stator), the rotor of the motor, the freely rotating front and the driven rear wheels with the rotating parts belonging to them. A description of the meaning of the symbols shown in Figure 2 can be found in [4]. Based on the models presented in Figure 2, a vehicle dynamics simulation program in

MATLAB Simulink (R2022b) [4] was created. The modular structure of the simulation program is shown in Figure 3.

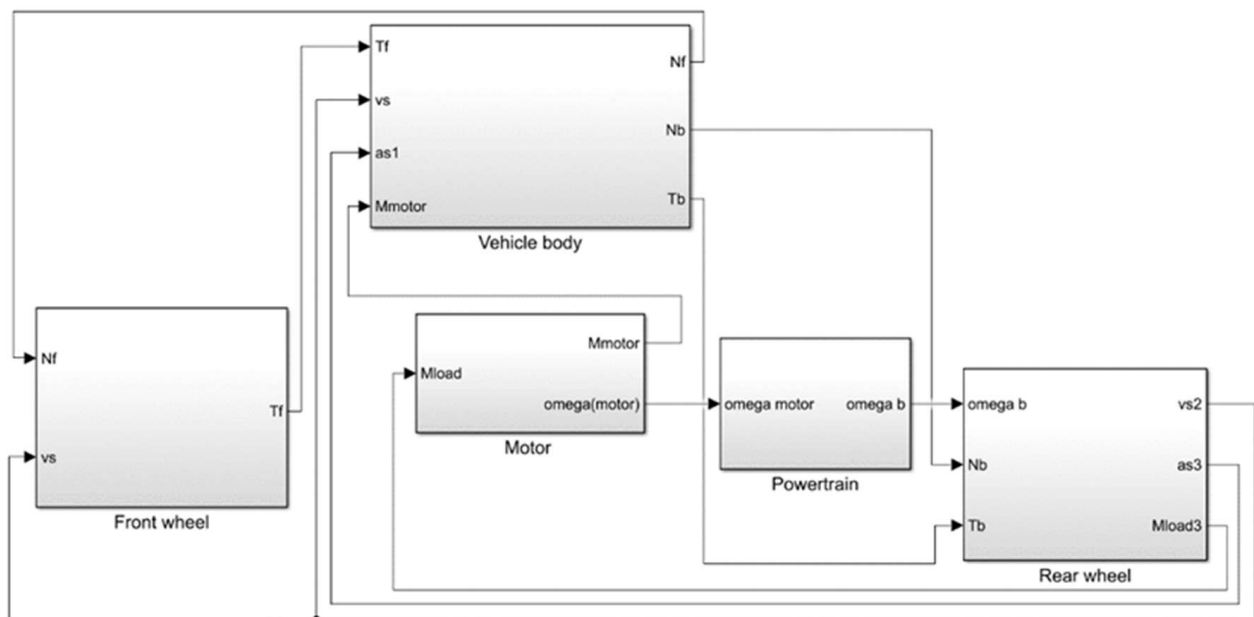


Figure 3. The simulation program developed in MATLAB Simulink [4].

The simulation program, in accordance with the above dynamic model, is built up of five modules: vehicle body, front wheels and related rotating machine parts, rear wheels and related rotating machine parts, motor and powertrain. A detailed description of the structure and operation of the different modules of the program can be found in reference [4]. For the purpose of this publication, the “Motor” simulation module shown in Figure 3 is important, as the PMSM motor simulation module developed in Section 3 can be installed in its place. The input to this module is the load torque (M_{load}) exerted by the vehicle, as well as the electromagnetic and dynamic characteristics of the motor (see Section 3), while its output is the torque delivered by the motor (M_{motor}) and the motor angular velocity (ω_{motor}). So, the motor simulation module is connected to the vehicle dynamics simulation program through these inputs and outputs.

The inputs of the whole simulation program and its output functions are also found in [4]. The input parameters of the simulation program are mainly the technical data and characteristics of the vehicle and motor. Some of the above data can be found in the catalogue of the motor and other machine parts, or in the related scientific literature, but in most cases, they must be determined experimentally [15–20]. Such experiments usually require a complex measurement system [21]. In this case, a unique system was developed and applied, as presented in the referenced work [22].

3. Permanent Magnet Synchronous Motor (PMSM) Modelling and Simulation

3.1. Brief Description and Modelling of the Permanent Magnet Synchronous Motor

Permanent magnet synchronous motors (PMSM) are used by many vehicle manufacturers (e.g., Nissan, Honda, Toyota) to power electric or hybrid vehicles. This is due to the motor’s superior characteristics compared to other types of motors [3], such as high torque and power density (kW/kg) and good controllability. In addition, its small size and mass also give it good torque-to-power and torque-to-volume ratios, making it particularly suitable for direct wheel drive applications [23,24]. However, the main magnetic field of

permanent magnet motors is fixed (due to the permanent magnets), so they can only deliver their high power at low speeds. However, this phenomenon can be greatly improved by field weakening [25–27]. One drawback is that their application is costly, mainly due to the expensive rare-earth permanent magnets, and thus less common in cost-sensitive applications. Figure 4 shows the internal structure of a PMSM motor. [1]

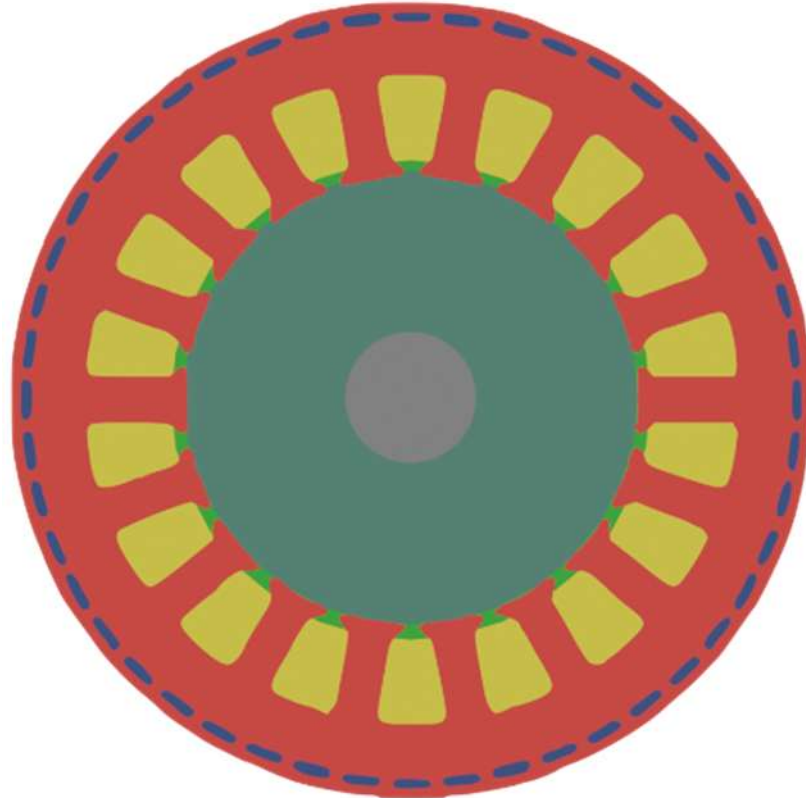


Figure 4. Internal structure of a permanent magnet (PM) motor.

In terms of construction, three-phase AC coils are mounted on the stator of the PMSM motor, while permanent magnets are mounted on the rotor. These magnets are often rare-earth neodymium magnets (NdFeB) to achieve higher performance. The motor's blades are connected to sinusoidal AC current, so the motor is also called a BLAC (brushless AC) motor. If the voltage waveform applied to the motor is rectangular or trapezoidal, it is called a brushless DC (BLDC) motor [1,28].

There are various methods for modelling the PMSM motor in the literature, summarized in reference [29]. There are three main modelling methods: electrical equivalent circuit [EEC]-based methods, magnetic equivalent circuit [MEC]-based methods, and numerical methods [NMs]. Within these main methods, there are further subcategories that affect the achievable accuracy and computational speed. The highest accuracy is generally achieved with numerical methods, but the computational time is also the longest. While the shortest computational time can be achieved with electrical equivalent circuit-based methods, but these are the least accurate methods. The chosen method belongs to the electrical equivalent circuit (EEC)-based methods. We chose this method because the computational time is the shortest with this method, which greatly facilitates the use of our previously mentioned vehicle dynamics simulation program for optimization purposes, where the simulation program is run up to several thousand times during an optimization process [30]. On the other hand, the previously completed BLDC motor simulation [5] was also based on such a method, so the comparison of the two motors is relevant.

Since the design of the PMSM motor is very similar to the BLDC motor, whose modelling and simulation we have previously addressed [5], the modeling of the PMSM motor is based on that earlier model. Figure 5 shows a model of a PMSM motor with a star-coupled stator.

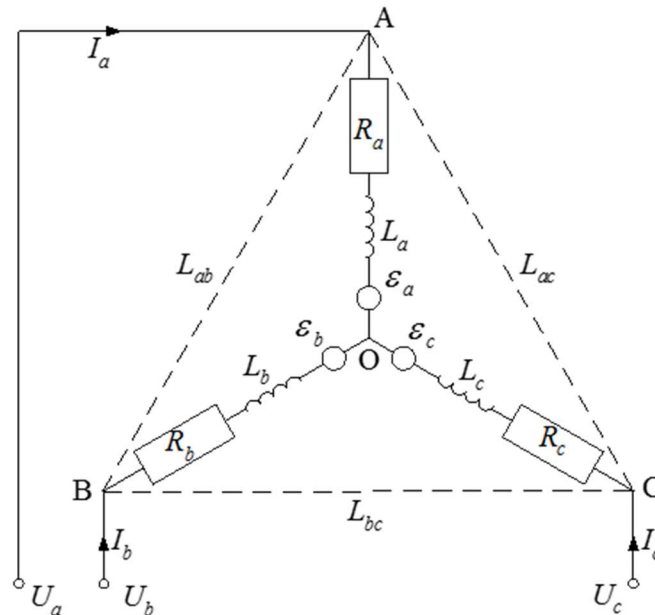


Figure 5. Model of the PMSM motor [5].

Based on the model, the following equations can be written:

$$U_a = R_a \cdot I_a + L_a \cdot \frac{dI_a}{dt} + L_{ab} \cdot \frac{dI_b}{dt} + L_{ac} \cdot \frac{dI_c}{dt} + \varepsilon_a \quad (1)$$

$$U_b = R_b \cdot I_b + L_{ba} \cdot \frac{dI_a}{dt} + L_b \cdot \frac{dI_b}{dt} + L_{bc} \cdot \frac{dI_c}{dt} + \varepsilon_b \quad (2)$$

$$U_c = R_c \cdot I_c + L_{ca} \cdot \frac{dI_a}{dt} + L_{cb} \cdot \frac{dI_b}{dt} + L_c \cdot \frac{dI_c}{dt} + \varepsilon_c \quad (3)$$

where, U_a , U_b and U_c are the electric potential of points A, B and C. The R_a , R_b , R_c , L_a , L_b and L_c are the electrical resistances and self-inductances of each winding, L_{ab} , L_{ac} , L_{ba} , L_{bc} , L_{ca} and L_{cb} are mutual inductances between the pairs of windings, ε_a , ε_b és ε_c are the back electromotive forces (Counter or Back EMF) generated by the permanent magnet rotor in the stator windings.

For one pair of poles and a peak voltage of 2 [V], the voltages applied by the motor control electronics to each winding can be given as a function of the electrical angle (θ_e):

$$U_a = U_0 \cdot \sin(\theta_e) \quad (4)$$

$$U_b = U_0 \cdot \sin\left(\theta_e - \frac{2\pi}{3}\right) \quad (5)$$

$$U_c = U_0 \cdot \sin\left(\theta_e - \frac{4\pi}{3}\right) \quad (6)$$

The electric angle (θ_e) can be calculated from the angular position of the rotor (θ_r) using the following equation:

$$\theta_e = \frac{p}{2} \cdot \theta_r \quad (7)$$

where $\frac{p}{2}$ is the number of pairs of poles of permanent magnets in the rotor. The Figure 6 shows the U_a , U_b and U_c voltages as a function of electrical angle for a peak voltage is 2 [V] and the pair of poles is ($\frac{p}{2} = 1$).

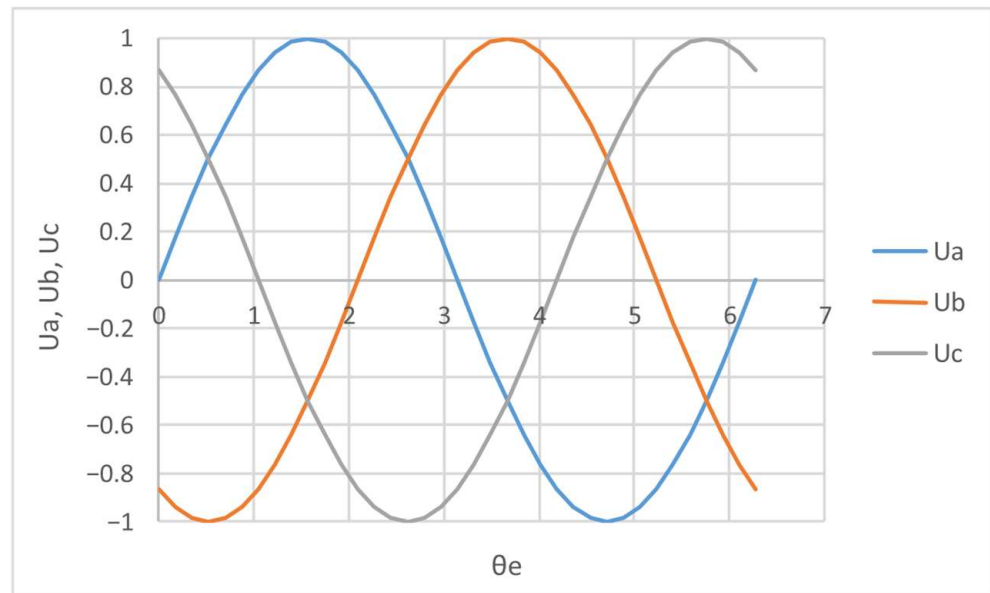


Figure 6. The U_a , U_b and U_c voltages as a function of electrical angle with a peak voltage of 2 [V] and a pair of poles ($\frac{p}{2} = 1$).

The control electronics, including the electronically controlled commutation system, are not described here. The windings are identical in all respects, and a magnetically linear approximation is used in the modelling, i.e., the inductances are constant:

$$R = R_a \equiv R_b \equiv R_c \quad (8)$$

$$L = L_a \equiv L_b \equiv L_c \quad (9)$$

$$M = L_{ab} \equiv L_{ba} \equiv L_{ac} \equiv L_{ca} \equiv L_{bc} \equiv L_{cb} \quad (10)$$

where R and L are the electrical resistances and self-inductances of each winding and M is the mutual inductance between pairs of windings.

In conclusion:

$$U_a = R_a \cdot I_a + L \cdot \frac{dI_a}{dt} + M \cdot \frac{dI_b}{dt} + M \cdot \frac{dI_c}{dt} + \varepsilon_a \quad (11)$$

$$U_b = R_b \cdot I_b + M \cdot \frac{dI_a}{dt} + L \cdot \frac{dI_b}{dt} + M \cdot \frac{dI_c}{dt} + \varepsilon_b \quad (12)$$

$$U_c = R_c \cdot I_c + M \cdot \frac{dI_a}{dt} + M \cdot \frac{dI_b}{dt} + L \cdot \frac{dI_c}{dt} + \varepsilon_c \quad (13)$$

Applying Kirchhoff's nodal law at the star point O (Figure 5) yields the following:

$$I_a + I_b + I_c = 0 \Rightarrow \frac{dI_a}{dt} + \frac{dI_b}{dt} + \frac{dI_c}{dt} = 0 \quad (14)$$

Therefore:

$$\frac{dI_b}{dt} + \frac{dI_c}{dt} = -\frac{dI_a}{dt} \quad (15)$$

$$\frac{dI_a}{dt} + \frac{dI_c}{dt} = -\frac{dI_b}{dt} \quad (16)$$

$$\frac{dI_a}{dt} + \frac{dI_b}{dt} = -\frac{dI_c}{dt} \quad (17)$$

By using this:

$$U_a = R \cdot I_a + (L - M) \cdot \frac{dI_a}{dt} + \varepsilon_a \quad (18)$$

$$U_b = R \cdot I_b + (L - M) \cdot \frac{dI_b}{dt} + \varepsilon_b \quad (19)$$

$$U_c = R \cdot I_c + (L - M) \cdot \frac{dI_c}{dt} + \varepsilon_c \quad (20)$$

The back electromotive forces can be calculated as follows:

$$\varepsilon_a = -\frac{d\Psi_a}{dt} \equiv -\frac{d\Psi_a}{d\theta_r} \cdot \frac{d\theta_r}{dt} \equiv -\frac{d\Psi_a}{d\theta_r} \cdot \omega_r \equiv -k_B \cdot F(\sin(\theta_e)) \cdot \omega_r \quad (21)$$

$$\varepsilon_b = -\frac{d\Psi_b}{dt} \equiv -\frac{d\Psi_b}{d\theta_r} \cdot \frac{d\theta_r}{dt} \equiv -\frac{d\Psi_b}{d\theta_r} \cdot \omega_r \equiv -k_B \cdot F\left(\sin\left(\theta_e - \frac{2\pi}{3}\right)\right) \cdot \omega_r \quad (22)$$

$$\varepsilon_c = -\frac{d\Psi_c}{dt} \equiv -\frac{d\Psi_c}{d\theta_r} \cdot \frac{d\theta_r}{dt} \equiv -\frac{d\Psi_c}{d\theta_r} \cdot \omega_r \equiv -k_B \cdot F\left(\sin\left(\theta_e - \frac{4\pi}{3}\right)\right) \cdot \omega_r \quad (23)$$

In the above equations ω_r is the angular speed of the rotor, and $\frac{d\Psi_a}{d\theta_r}$ is the derivative of the magnetic flux of the winding with angle θ_r , which traditionally given by $k_B \cdot F(\sin(\theta_e))$, where k_B is the Back EMF constant and the function $F(\sin(\theta_e))$ is interpreted by for a pair of poles:

$$F_a = F(\sin(\theta_e)) \quad (24)$$

$$F_b = F\left(\sin\left(\theta_e - \frac{2\pi}{3}\right)\right) \quad (25)$$

$$F_c = F\left(\sin\left(\theta_e - \frac{4\pi}{3}\right)\right) \quad (26)$$

It should be noted here that the theoretically assumed sinusoidal shape of the Back EMF may deviate from the sinusoidal shape in practice due to the effect of permanent magnets. Thus, for a more accurate simulation, it is worth experimentally determining the Back EMF (see Section 3.4.1) and using the measured values in the simulation (e.g., in the form of a “look-up table”).

Equation of motion for the motor rotor:

$$\sum_i M_i = M_{motor} - M_{res} - M_{load} \equiv J_r \cdot \varepsilon_r \quad (27)$$

where M_{motor} is the electromagnetic torque of the motor, M_{res} is the friction (resistance) torque, M_{load} is the load on the motor, J_r is the moment of inertia of the rotor, and ε_r is the acceleration of the rotor.

The electromagnetic torque can be calculated here using the following equation:

$$\begin{aligned} M_{motor} &= \frac{P}{\omega_r} \equiv \frac{\varepsilon_a \cdot I_a + \varepsilon_b \cdot I_b + \varepsilon_c \cdot I_c}{\omega_r} \equiv \frac{-k_B \cdot \omega_r \cdot (F(\sin(\theta_e)) \cdot I_a + F(\sin(\theta_e - \frac{2\pi}{3})) \cdot I_b + F(\sin(\theta_e - \frac{4\pi}{3})) \cdot I_c)}{\omega_r} \equiv \\ &\equiv -k_B \cdot (F(\sin(\theta_e)) \cdot I_a + F(\sin(\theta_e - \frac{2\pi}{3})) \cdot I_b + F(\sin(\theta_e - \frac{4\pi}{3})) \cdot I_c) \end{aligned} \quad (28)$$

where P is the power of the motor.

3.2. Simulation of the Permanent Magnet Synchronous Motor (PMSM)

Based on the model described in Section 3.1, a simulation module for the PMSM motor was created using MATLAB Simulink software (R2022b), which is illustrated in Figure 7.

The internal structure and operation of each module is described in detail below.

The Module I in Figure 8 is calculated the U_a , U_b and U_c voltages and the electrical angle (θ_e) from the angular position of the rotor θ_r and the number of pole pairs ($\frac{p}{2}$) based on Equations (4)–(7) in Section 3.1. The U_a , U_b and U_c voltage waveforms shown in Figure 6, were fitted as a “look-up table” as a function of electrical angle, and then multiplied by the nominal voltage.

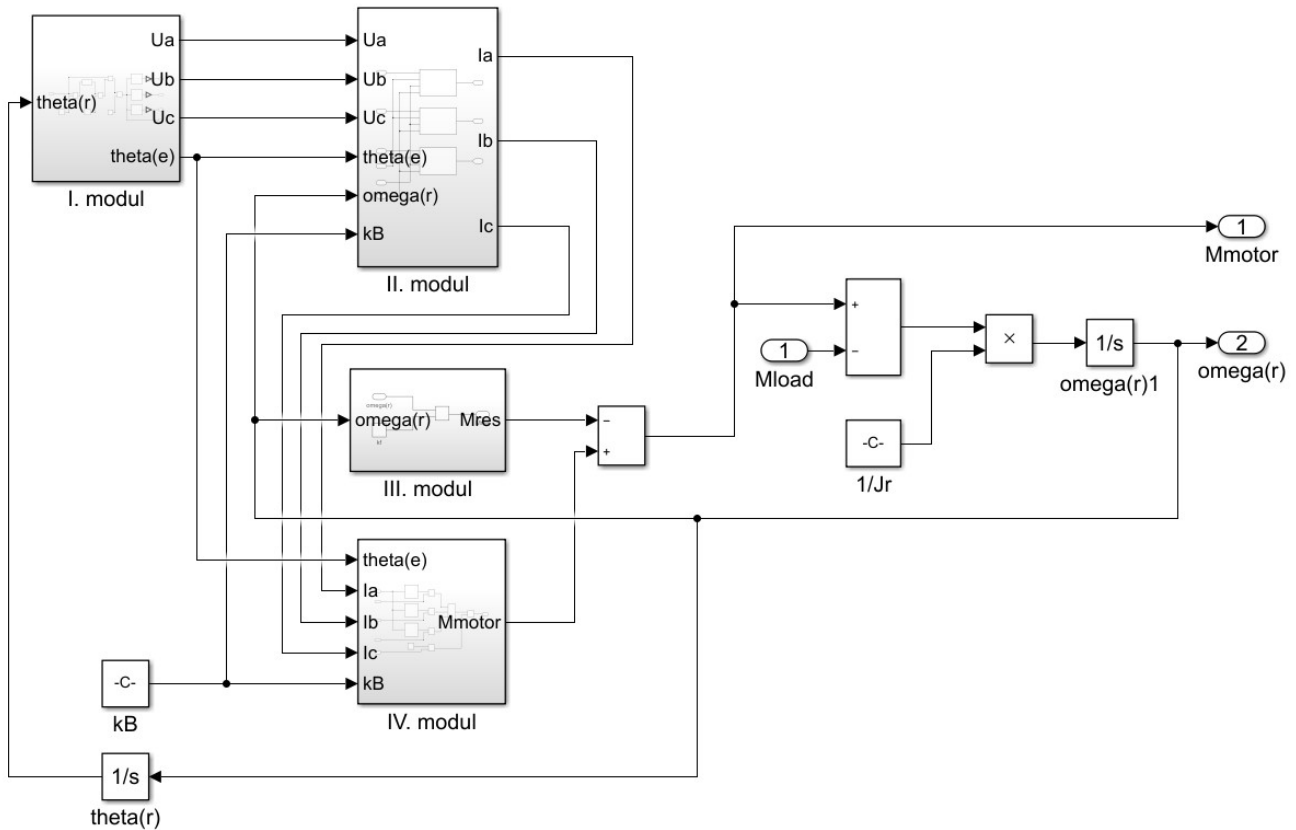


Figure 7. The PMSM motor simulation module.

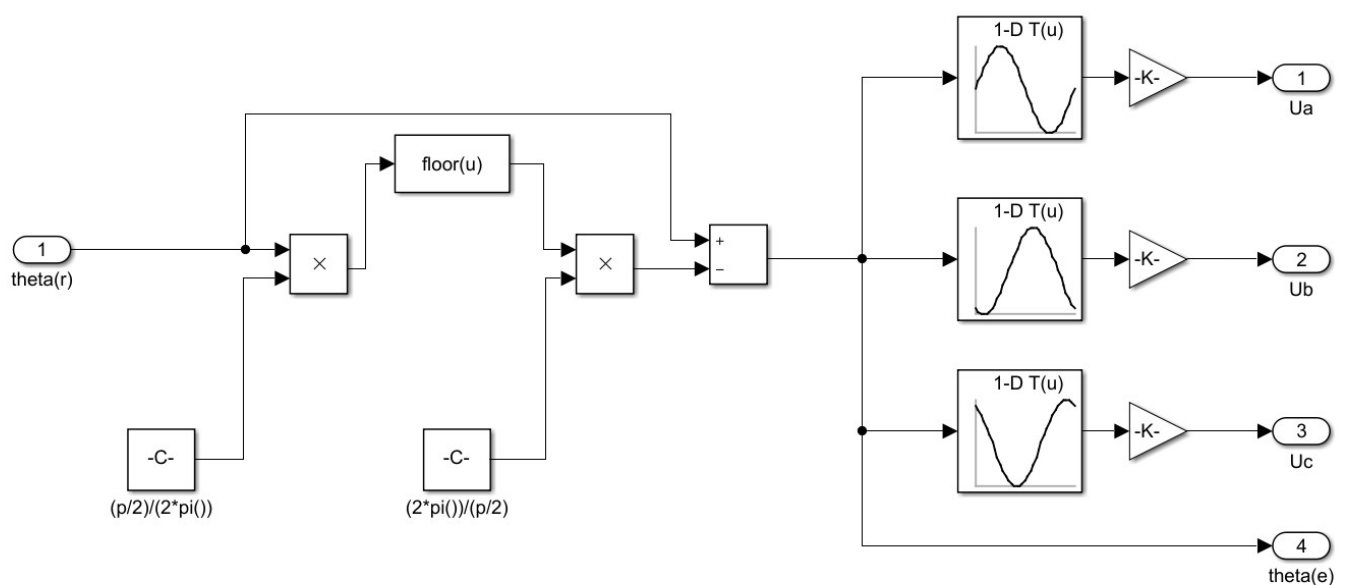


Figure 8. Module I of the PMSM motor simulation.

Description of Module II:

The Module II in Figure 9 is calculate the currents I_a , I_b and I_c from the U_a , U_b and U_c voltages and the electrical angle θ_e , as well as the angular velocity of the rotor (ω_r) and the Back EMF constant (k_B).

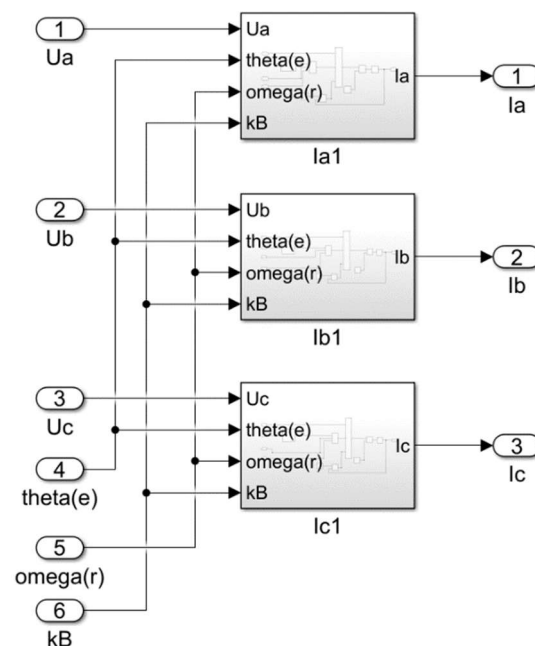


Figure 9. Module II of the PMSM motor simulation.

The currents are calculated in separate internal modules based on Equations (18)–(26) in Section 3.1. Figure 10 shows the structure of the internal module that calculates the current I_a . (For currents I_b and I_c , the modules are similar.)

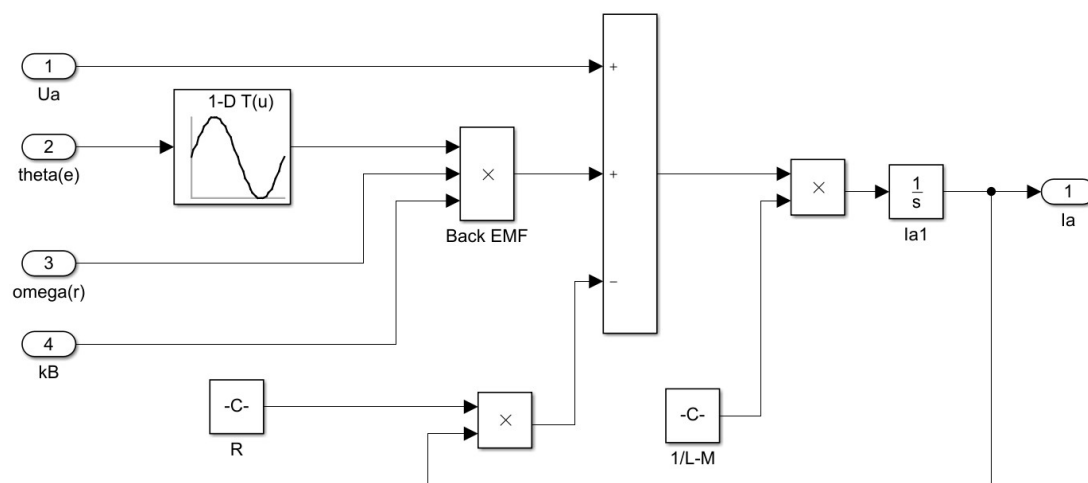


Figure 10. Structure of the internal module that calculates the current I_a .

In the internal module that calculates the I_a current, the sinusoidal function in Equation (24) is incorporated in the form of a “look-up table”, while the other motor characteristics (R , L , M) are in the form of constants.

Description of Module III:

The Module III in Figure 11 calculates the bearing resistance (friction) torque (M_{res}) of the motor from the angular velocity of the rotor (ω_r) and the bearing friction factor (k_f).

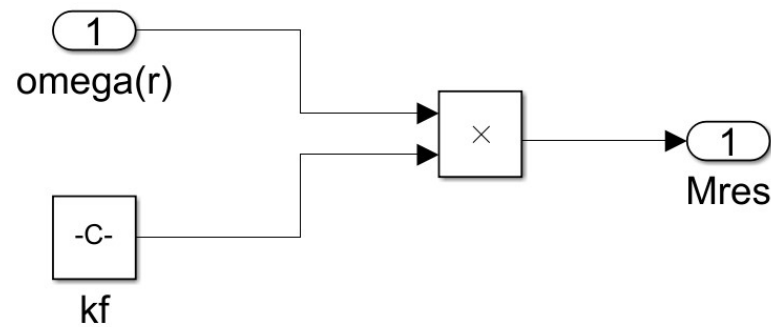


Figure 11. Module III of the PMSM motor simulation.

Description of Module IV:

The Module IV in Figure 12 reads in the current intensity I_a , I_b and I_c , the electrical angle (θ_e) and the Back EMF constant (k_B), and calculate the electromagnetic torque (M_{motor}) of the motor based on Equation (28) in Section 3.1.

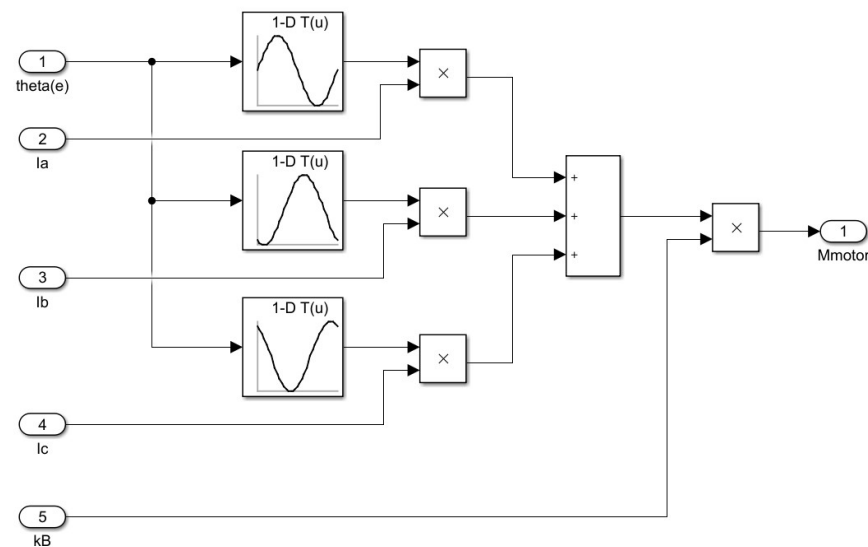


Figure 12. Module IV of the PMSM motor simulation.

The sinusoidal functions in the equation, which give the shape of the Back EMF for each winding, are incorporated in the form of a “look-up table”.

3.3. The Functions Obtained by Simulation

Since the BLDC and PMSM motors are similar in design, and thus the modelling and simulation are similar, simulations were performed with both motors and compared the resulting functions. The input data of the motors were the same in both cases, namely: rated power: 1.4 [kW]; rated DC voltage: 100 [V], phase resistance: 0.28 [Ω], phase inductance: 0.24 [mH], bearing friction factor (k_f): 0.001 [Nms], moment of inertia of the rotor: 0.002139 [kgm²], Back EMF konstans (k_B): 0.0033 [V/(r/min)] [31].

In addition, for both motors the load torque is set to $M_{load} = 10$ [Nm]. A detailed description of the BLDC motor simulation program can be found in [5]. To run the simulation, we used the default settings of Simulink (solver: ode45, with variable step size, automatic minimum, maximum and initial step size, and automatic tolerance). In the case of the “look-up tables”, we used the “Linear point-slope” interpolation method.

Figure 13 shows the simulated voltage-time functions of the motors for one phase in the time interval 0–0.3 s.

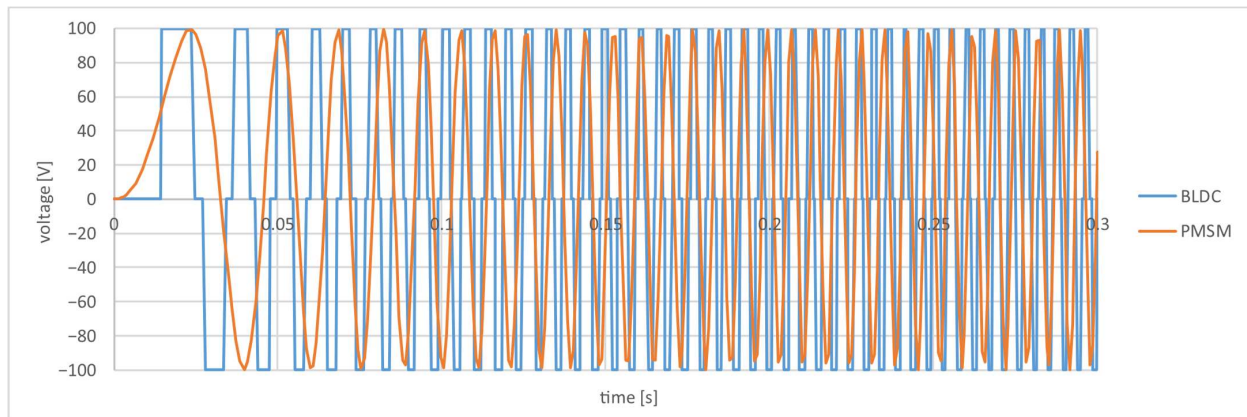


Figure 13. Simulated voltage-time functions of PMSM and BLDC motors.

The Figure 13 shows the voltage waveforms on one phase and shows that the BLDC motor spins up faster at the same load and peak voltage. Figure 14 shows the current intensity versus time function through the motors in one phase.

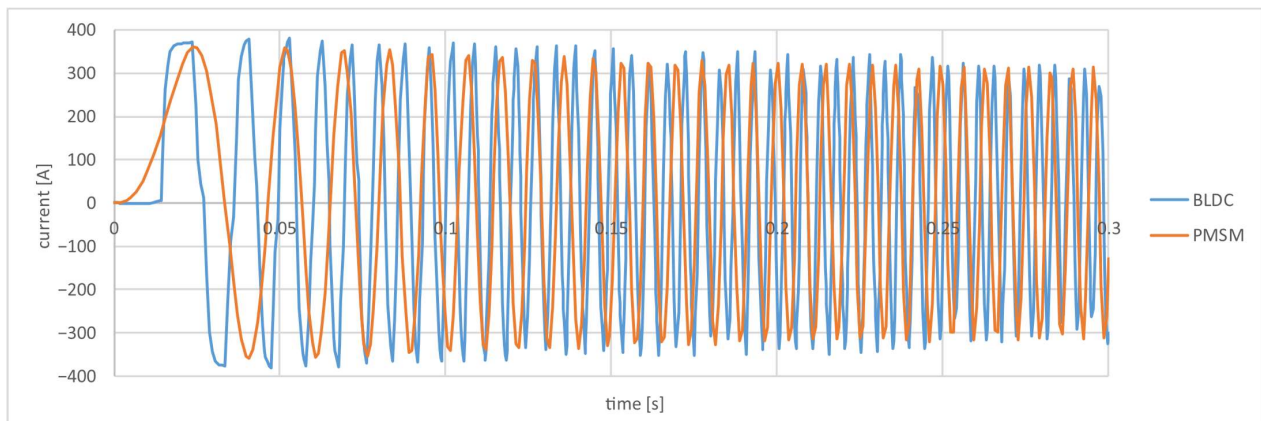


Figure 14. Simulated current intensity-time functions of PMSM and BLDC motors.

The current intensity-time function behaves similarly to the voltage during the simulation. Figure 15 shows the angular speed-time functions of the motors.

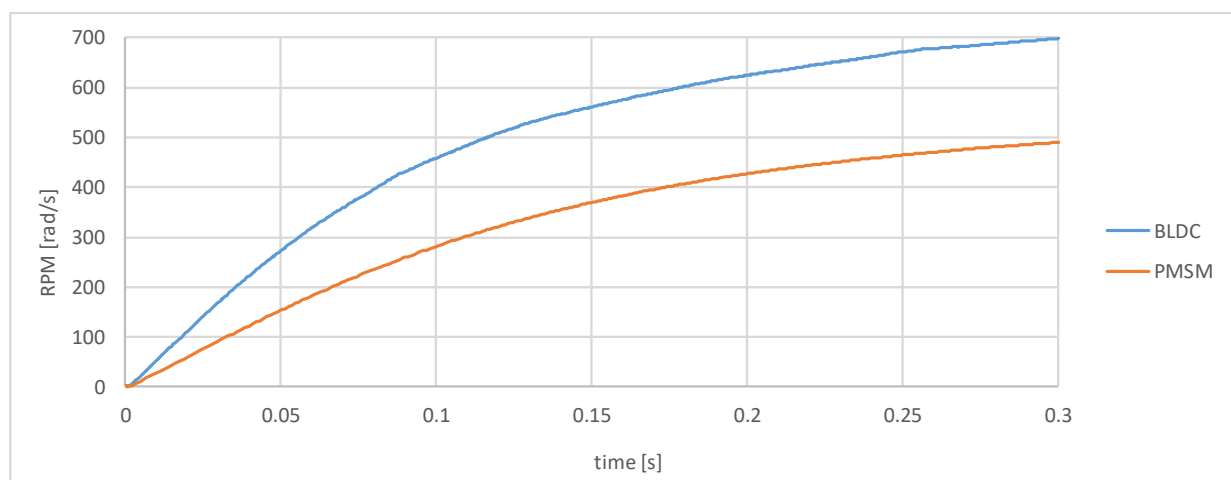


Figure 15. Simulated angular speed-time functions of PMSM and BLDC motors.

The Figure 15 shows that the BLDC motor spins up to a significantly higher speed in 0.3 s than the PMSM motor. Figure 16 shows the torque-time dependence of the motors.

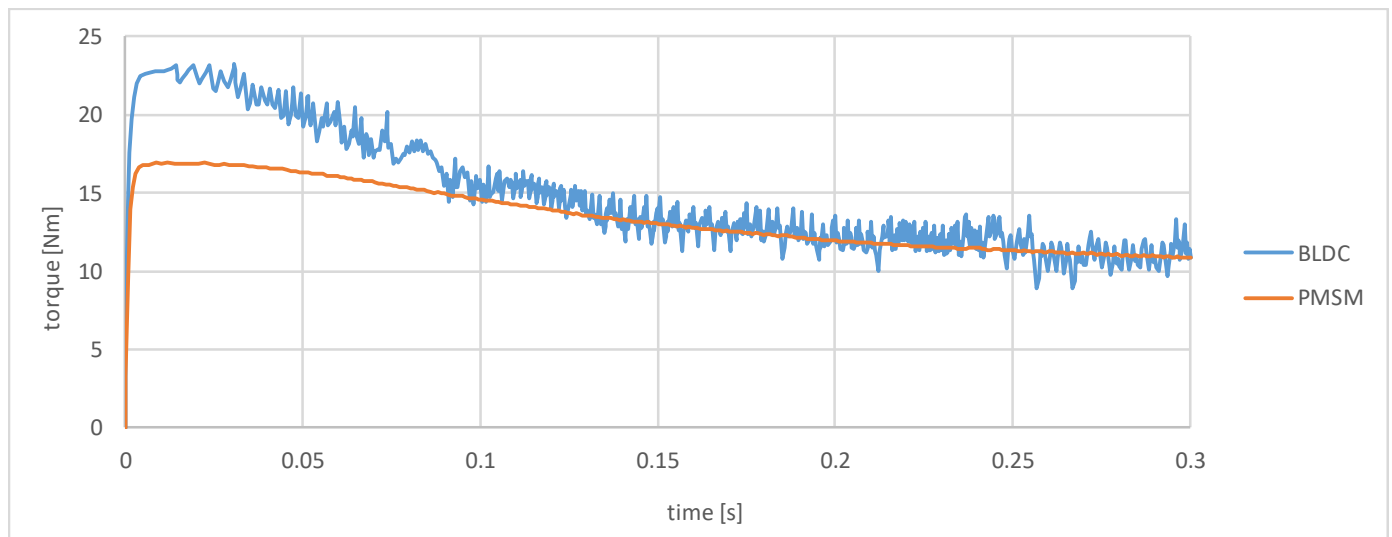


Figure 16. Simulated torque-time functions of PMSM and BLDC motors.

The maximum torque of the BLDC motor is substantially higher, after this first section, the torque of both motors approaches the 10 Nm value set for the load. It can also be seen that the function obtained with the PMSM motor is much smoother.

The differences between the simulated functions above are presumably caused by differences in the supply voltage and the Back EMF signal waveforms. Thus, based on the above, it can be said that for BLDC and PMSM motors of the same power, this power can be achieved with different motor characteristic parameters.

In Figure 17, in case of the voltage-time function of the PMSM motor, we compared the interpolation methods that can be set in the “look-up tables”. These interpolation methods are: Flat, Nearest, Linear point-slope, Linear lagrange, Cubic spline.

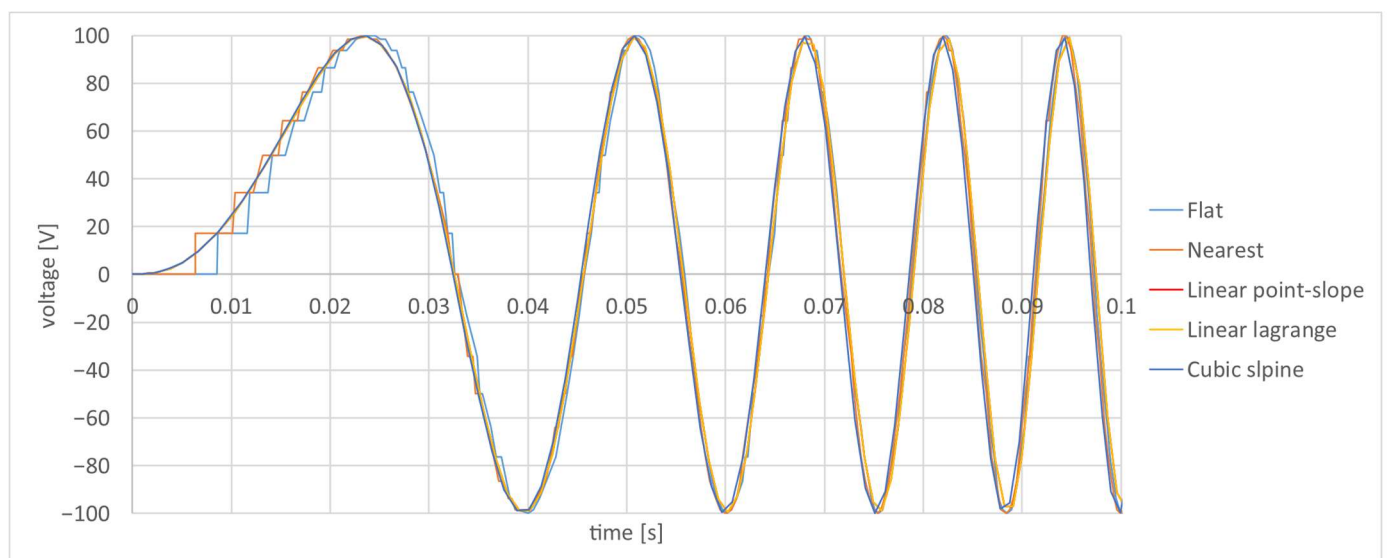


Figure 17. Comparison of interpolation methods.

The figure shows that the Flat and Nearest methods are less accurate, while the Linear point-slope, Linear lagrange, and Cubic spline methods give very similar results.

3.4. Determination of Motor Characteristics for Permanent Magnet Synchronous Motor (PMSM) Simulation

To run the simulation program, required the motor characteristics described in the previous sections. These, or part of them, are provided by the manufacturer in some cases, but the unknown data must be determined experimentally with the highest possible accuracy to ensure the most accurate simulation. In our previous research, we have dealt with the experimental investigation of different types of electric motors [15–18], so we use the experience gained from that research to describe the experiments designed to determine the different characteristics of the PMSM motor and the corresponding measurement setups.

To test electric motors, we have developed a complex measurement system (Figure 18) that is flexible enough to be used for different types of motors and experiments. A detailed description of the measurement system can be found in [22].

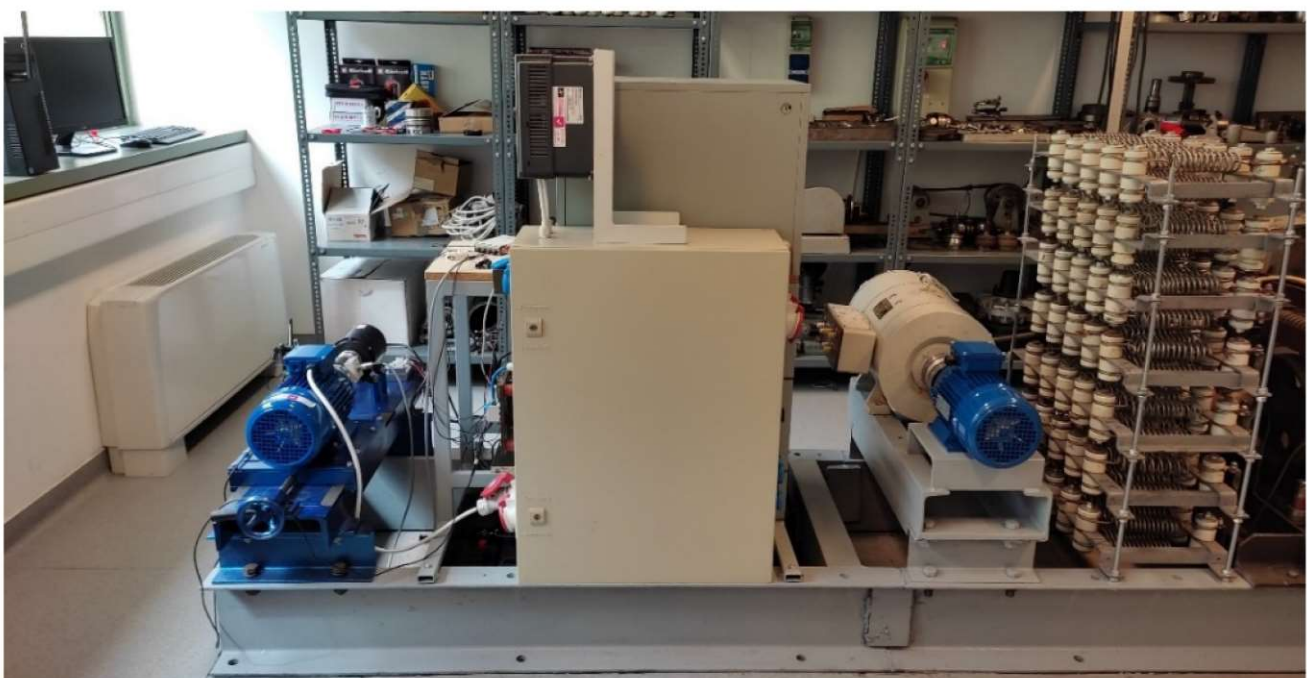


Figure 18. The measurement system developed for testing electric motors [22].

For the PMSM motor, the following characteristics are planned to be experimentally determined: Back EMF, electric resistance, self- and mutual inductance of the windings, and moment of inertia and friction torque of the rotor.

3.4.1. Experimental Determination of Back Electromotive Force (Back EMF)

We plan to experimentally determine the Back EMF in one phase using the measurement setup shown in Figure 19. In the experiment, the analyzed PMSM motor is connected via a clutch to a 3-phase asynchronous motor that drives the analyzed PMSM motor. The experiment can then be performed at different speeds, while measuring the speed and the voltage induced on a phase of the analyzed PMSM motor. The measured characteristics would then be given into the simulation program as a “look-up-table”. A detailed description of the sensors used for the measurement and the data acquisition system can be found in [22].

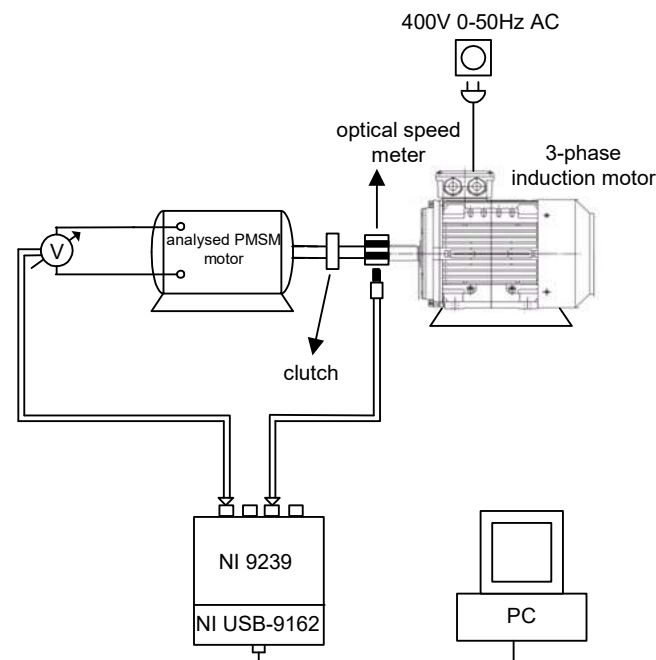


Figure 19. Outline of the measurement setup for the experimental determination of the Back EMF [22].

3.4.2. Experimental Determination of Electric Resistance of Windings

During the measurements, the motor rotor is fixed by a disc brake, thus eliminating the voltage induced by one winding in the other. The measurements require a strictly constant DC current, which can be provided by a car battery with a nominal voltage of 12 [V], for example. By varying the value of the load resistance (R_{load}), we can control the current flowing through the winding, so that measurements can be made at different current levels. The measurement of the current intensity is reduced to the measurement of the voltage across a shunt resistor. Thus, from the resulting current and voltage measured on a voltage divider, the electric resistance of the winding can be determined. The measuring arrangement is shown in Figure 20.

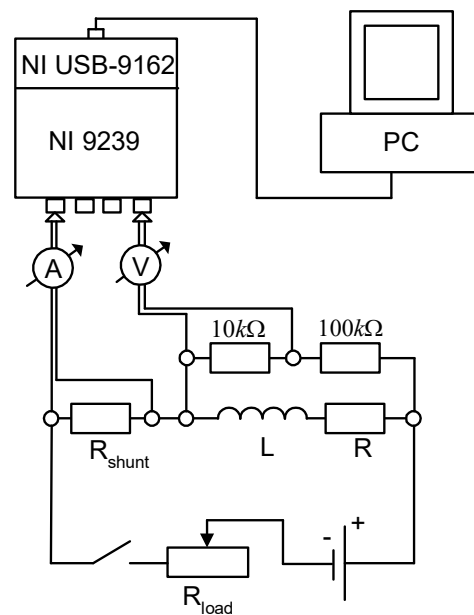


Figure 20. Outline of the measurement setup designed for the experimental determination of the electric resistance of windings [22].

3.4.3. Experimental Determination of Self- and Mutual Inductance of Windings

To determine the self- and mutual inductance of the windings, the measuring arrangement shown in Figure 21 can be used.

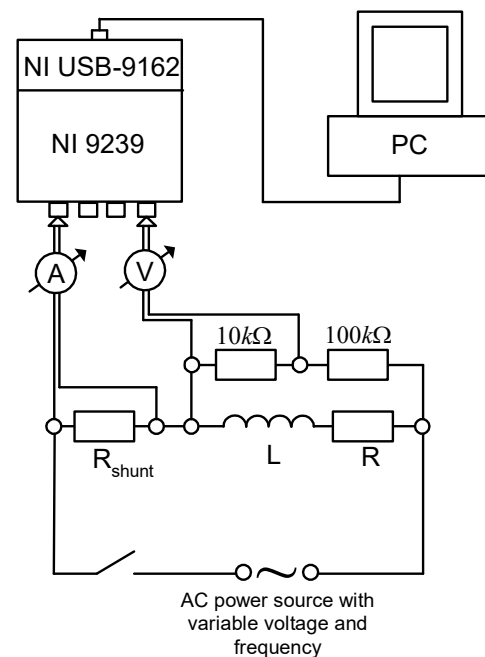


Figure 21. Outline of the measurement setup designed for the experimental determination of the self- and mutual inductance of windings [22].

To measure the self-inductance of the winding, the winding is excited with an AC voltage. The excitation can be performed at different frequencies (5, 10, 50 [Hz]) with a number of different peak AC voltages at each frequency. The intensity of the current flowing through the winding ($I(t)$) is measured as a function of time using a shunt resistor. The voltage across the windings is measured using a voltage divider.

From the voltage across the winding ($U(t)$) and the intensity of the current flowing through it ($I(t)$), the magnetic flux of the winding as a function of time can be calculated using the following equation:

$$(\Psi t) = \int_0^t (U(\tau) - I(\tau) \cdot R) d\tau + \Psi(0) \quad (29)$$

In the above equation, $U(\tau) - I(\tau) \cdot R$ is the self-induced voltage in the winding. Knowing the functions (t) and $I(t)$, the magnetic flux can be given as a function of the current (I). Then, by deriving this from the variable I , the dynamic self-inductance $L(I)$ is obtained as a function of the current.

To determine the mutual inductances, the above measurement setup and method can be used, with the difference that in this case one winding is excited while the current is measured in another winding.

3.4.4. Experimental Determination of the Moment of Inertia and the Resistance Torque of the Rotor

There are several methods for the experimental determination of rotor moments of inertia and its resistance torque, which are summarized in [17]. Among the methods presented, the most suitable is the method described in detail in [18], where the two quantities are determined simultaneously without disassembling the motor. The corresponding measurement setup is shown in Figure 22.

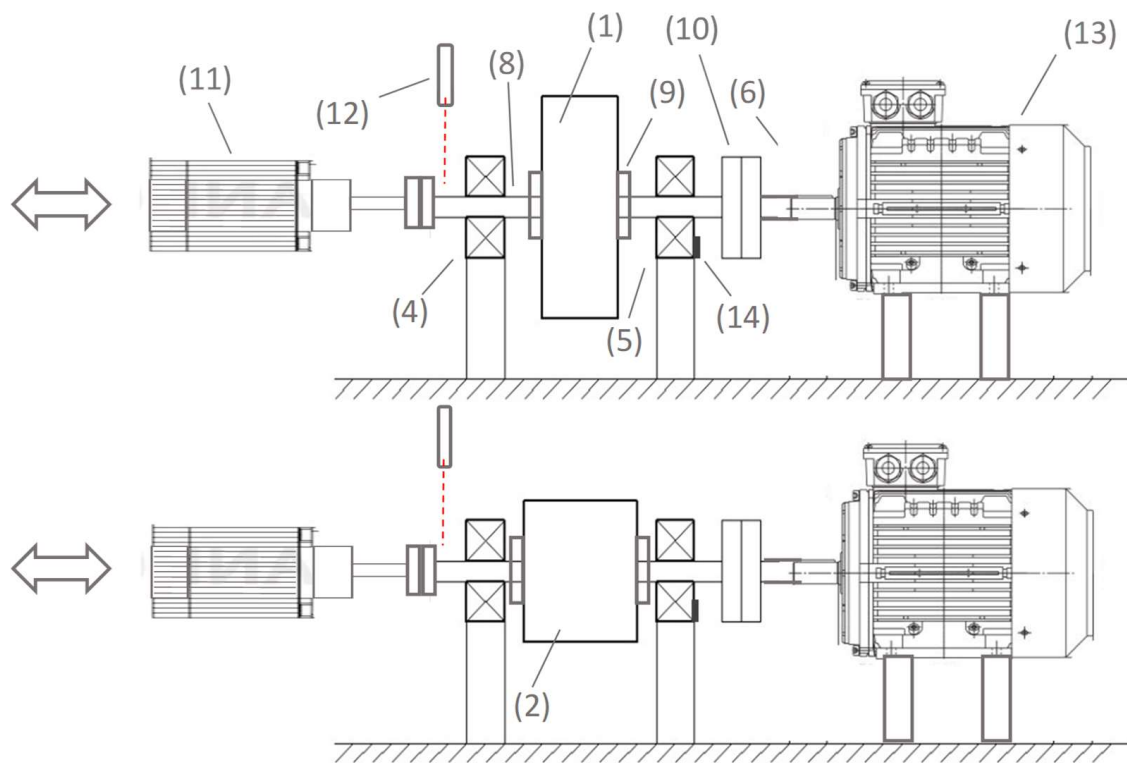


Figure 22. Outline of the measurement setup designed for experimental determination of rotor moments of inertia and its resistance torque [18].

The procedure is based on four independent measurements. For each of the four measurements, an external motor (11) is used to accelerate (spin up) the system from a stationary position, and then the acceleration motor is disengaged from the system after the maximum speed is reached.

For the first two measurements, the system is allowed to decelerate by removing the clutch (10) between the motor under test (13) and the load cylinders (1, 2), while for the other two measurements the clutch is maintained throughout, thus slowing down the motor under test and the load cylinders together until a standstill is reached.

For these two measurements, the moments of inertia of the load cylinders (1) and (2) are different, but their masses are the same. The identical masses ensure the same radial loading of the bearings (4, 5), and thus the same friction torques in the bearings for a given speed and temperature. In the experiments, the speed of the system is measured (12) as a function of time.

Four independent dynamic equations can be written for the run-out phase of the four independent experiments, and the resulting system of equations can be used to calculate the inertia and the friction torque of the rotor. It is important to note that the method can only achieve sufficient accuracy if the moments of inertia of the load cylinders are chosen appropriately for the motor under test. This is described in detail in [18].

4. Comparison of PMSM and BLDC Motor Simulation in a Prototype Race Car

The PMSM motor simulation module presented in Section 3 was integrated into the previous vehicle dynamics simulation program [4]. The simulation program was then run using the same vehicle and motor parameters (see Section 3) for both PMSM and BLDC motors. During the simulation, the vehicle accelerated for 15 s from a stationary start. The

speed-time, energy consumption-time and travelled distance-time functions obtained with the two motors are shown in Figures 23–25.

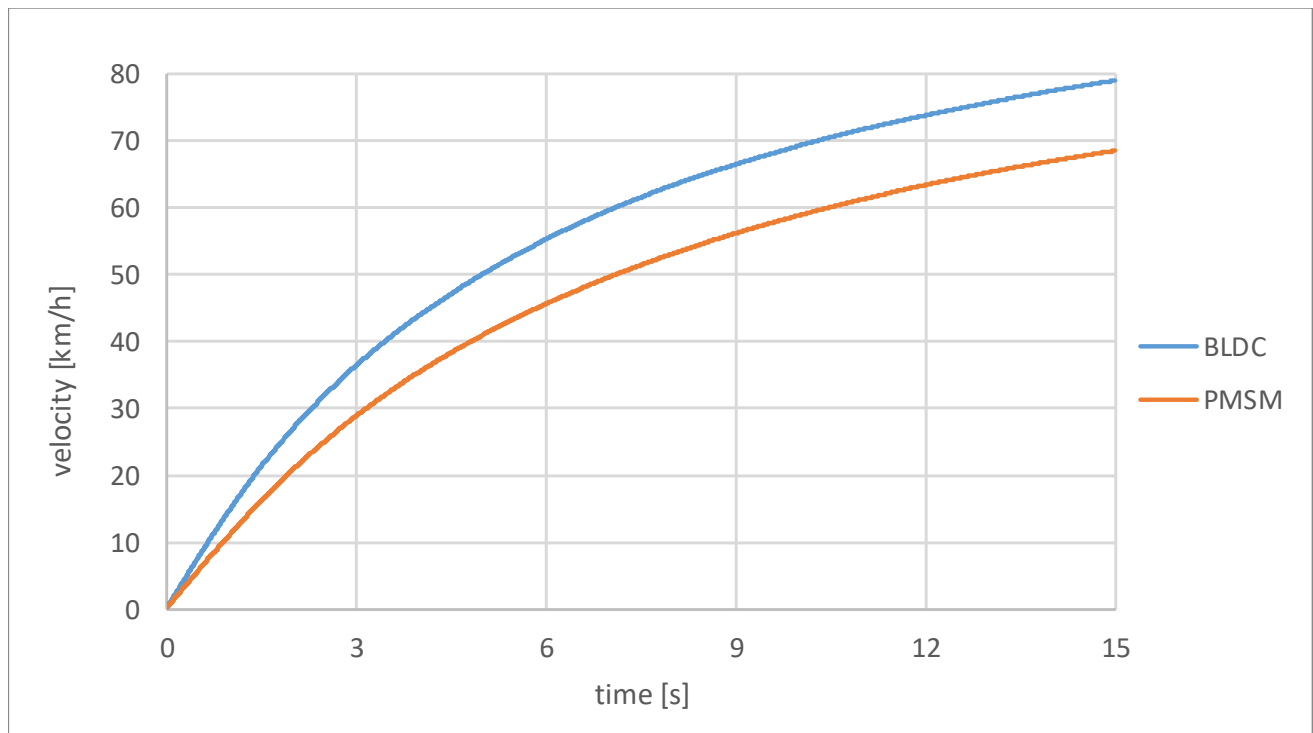


Figure 23. Speed-time function of a prototype race car with PMSM and BLDC motors.

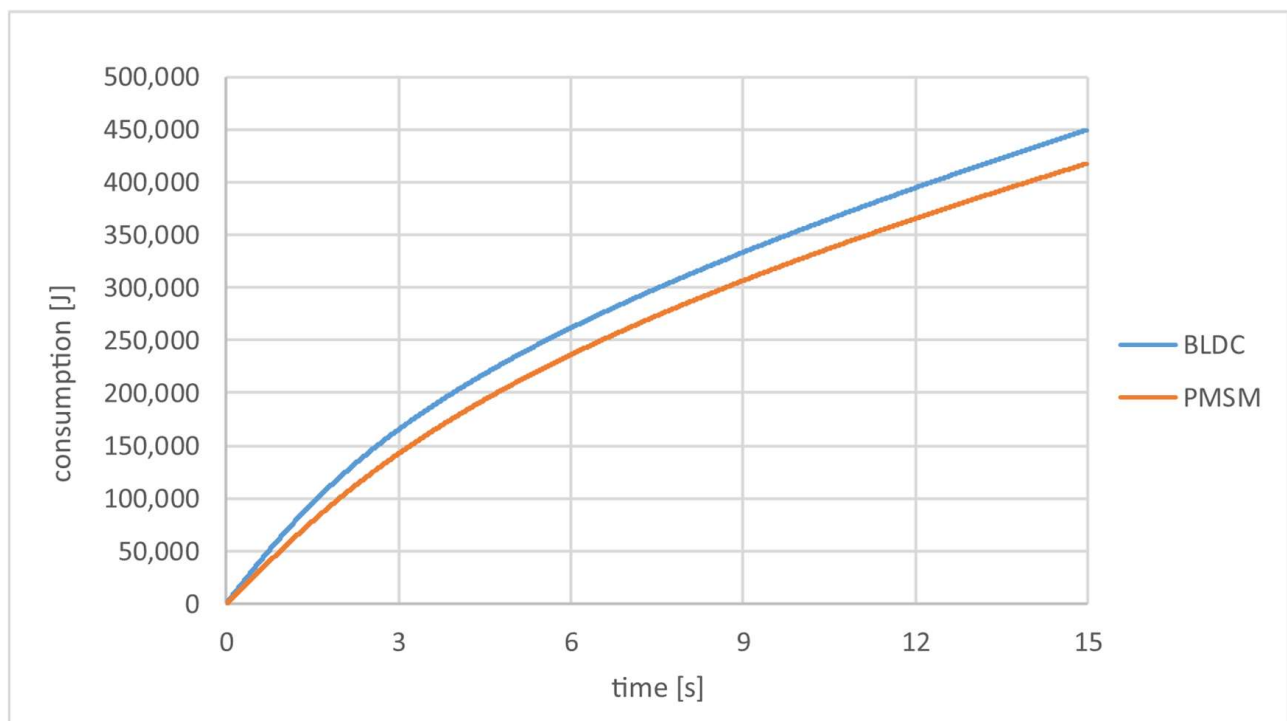


Figure 24. Energy consumption vs. time of a prototype race car with PMSM and BLDC motors.

The Figures 23 and 25 shows that between PMSM and BLDC motors simulated with the same motor parameters and peak voltage, the car with the BLDC motor accelerates faster in 15 s. In 15 s, the vehicle powered by a PMSM motor accelerates to 68.5 km/h

while traveling 192.78 m. A vehicle powered by a BLDC motor accelerates to 79 km/h in the same time, while traveling 229.7 m. The BLDC motor is the better choice in terms of performance, especially for competitive tasks that require higher power, such as a drag race. For example, if we look at a 150-m drag race, the PMSM motor-powered vehicle completes the distance in 12.69 s (at a speed of 64.74 km/h), while the BLDC motor-powered vehicle completes it in only 11.22 s (at a speed of 72.17 km/h), which is a significant time difference in a drag race.

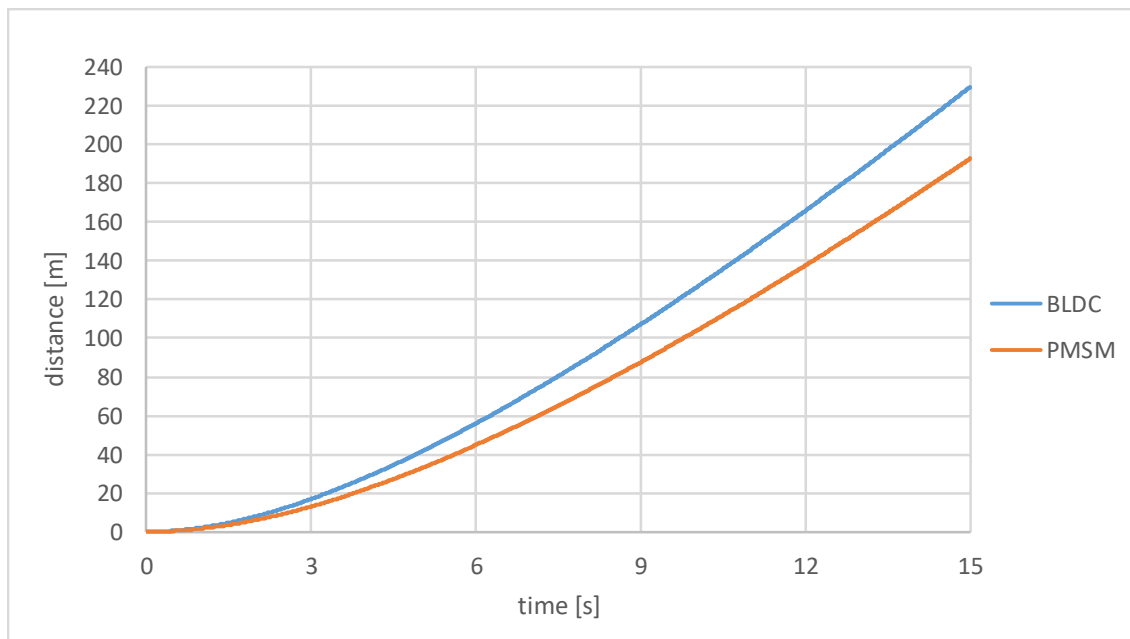


Figure 25. Travelled distance vs. time of a prototype race car with PMSM and BLDC motors.

However, Figure 24 also shows that the PMSM motor consumes less energy during the given time, making it the better choice for an energy consumption race (e.g., Shell ECO-Marathon race). However, if we consider the energy consumption over a given distance (e.g., 150 m), there is no big difference between the two motors (PMSM: 378,211.8 J, BLDC: 379,534.9 J).

It is important to note, however, that when designing a car for a specific competition task, it is advisable to simulate the specific motor (which may require experimental determination of various motor parameters) and then optimize the vehicle and motor specifications for the specific competition purpose. This type of optimization can be found in [31].

5. Conclusions

This paper addresses the modeling and simulation of a PMSM motor. Taking into account the modelling procedures mentioned in the literature, a novel custom model was developed and, based on it, a simulation module for the motor was created using MATLAB Simulink software to align with an existing vehicle dynamics simulation program. The above module is a universal simulation module for PMSM motors, which is also suitable for motor simulation on its own, and thus provides the opportunity to optimize various motor data. It can also be integrated into a vehicle dynamics simulation program, which can be used to perform driving dynamics analysis of electric prototype race cars, for example. Then, for the same motor parameters, the results obtained for the PMSM motor were compared with those from a previously prepared BLDC motor simulation.

Furthermore, the PMSM motor simulation module was integrated into the vehicle dynamics simulation program and compared the simulation results for the same model

parameters. Thus, the developed motor simulation module and the results obtained with it provide help in selecting the appropriate motor types when designing new electric vehicles for a specific task.

Since simulating a specific motor requires detailed motor specifications, which are sometimes not provided by the manufacturer, unique measurement procedures for experimentally determining these specifications have also been described. The outcomes build upon prior experience in this field.

Thus, in this publication, a comprehensive overview of the modelling and simulation of the PMSM motor and the experimental determination of the technical input data required for the simulation is presented.

Our future plans include experimentally determining motor characteristics and conducting test measurements. This way, we can determine the accuracy of our model, and we plan to examine how the neglect of various effects used in the model (magnetic saturation, magnetic flux nonlinearity, cogging torque, reluctance torque, and iron losses occur) affects the accuracy under both static and dynamic conditions.

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