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Performance analysis of electric motor for Formula Student race car

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Formula Student presents a unique engineering challenge for students offering them a platform to introduce innovative ideas related to control algorithms and electric drives. This article presents design of the electric motor made by PWR Racing Team and its expected performance characteristics derived from the simulation. Developed control algorithm of tractive system implemented in SpeedGoat – a control computer based on Simulink – is introduced as well as adaptation of this algorithm for research on a torque transducer. Results from measurements gathered through this system are presented and compared to theoretical expectations offering insights into the real-world performance of the electric motor made by Formula Student team.

Key words: *electric vehicle, permanent magnet synchronous motor (PMSM), torque characteristics, real-time control system*

1. Introduction: the influence of Formula 1 on automotive development

Formula 1 (F1) is not merely a spectacle of speed and precision; it is a crucible of innovation that has significantly influenced automotive technology. This high-stakes motorsport, with its relentless pursuit of performance and efficiency, has driven advancements that permeate the broader automotive industry. This essay delves into the scientific and technical aspects of how F1 has shaped automotive development, focusing on engine technology, materials science, aerodynamics, electronics, and safety systems.

One of the most significant contributions of F1 to automotive engineering is the development of hybrid power units. Introduced in 2014, F1's hybrid engines combine a traditional internal combustion engine (ICE) with an Energy Recovery System (ERS) that captures and reuses energy. This technology has directly influenced the hybrid systems used in modern road cars. The ERS in F1 recovers energy from both braking (via the MGU-K or Motor Generator Unit-Kinetic) and heat from the turbocharger (via the MGU-H or Motor Generator Unit-Heat). This recovered energy is stored in batteries and can be deployed to boost performance. In consumer vehicles, similar hybrid systems improve fuel efficiency and reduce emissions. The principles of energy recovery and hybridization seen in F1 are evident in the regenerative braking systems and electric motors of hybrid and electric cars. For example, Toyota's Prius, a leading hybrid vehicle, employs regenerative braking to enhance fuel efficiency, a concept that owes much to the advancements pioneered in F1.

F1's adoption of turbocharging to boost engine power without increasing engine size has had a profound impact on road car engines. Turbochargers compress the intake air, allowing more oxygen to enter the engine, thereby increasing power output from a smaller engine displacement. This principle of downsizing, where smaller engines deliver the power of larger ones, is now common in the automotive industry.

Modern cars, such as the Ford EcoBoost series, use turbocharged engines to achieve a balance between performance and fuel efficiency. The lessons learned in managing heat, pressure, and durability in F1 turbo engines have been directly applied to improve the reliability and efficiency of road-going turbocharged engines.

The use of carbon fiber reinforced polymer (CFRP) in F1 car construction has revolutionized automotive materials science. CFRP offers a remarkable strength-to-weight ratio, which is crucial for both performance and safety. F1 cars use carbon fiber extensively in their chassis and bodywork to reduce weight while maintaining structural integrity.

This technology has transitioned into high-performance road cars and even some mainstream vehicles. The BMW i3 and i8, for instance, utilize carbon fiber in their construction to improve efficiency and performance. The lightweight nature of carbon fiber reduces overall vehicle weight, enhancing fuel efficiency and handling characteristics.

F1 teams have also pioneered the use of advanced metal alloys to withstand extreme conditions. Titanium, for example, is used in F1 for its excellent strength-to-weight ratio and resistance to high temperatures. These materials are now used in critical components of road cars, such as engine valves, connecting rods, and exhaust systems. The aerospace-grade alloys used in F1 enhance durability and performance in consumer vehicles.

Aerodynamics is a critical factor in F1 performance, influencing speed, stability, and fuel efficiency. F1 teams utilize Computational Fluid Dynamics (CFD) to design and optimize aerodynamic components. CFD simulations allow engineers to predict how air flows over the car and identify areas for improvement.

These techniques have been adopted by automotive manufacturers to design more aerodynamically efficient road cars. Enhanced aerodynamics reduce drag, improving fuel efficiency and high-speed stability. The streamlined shapes and underbody designs of modern cars owe much to the aerodynamic research conducted in F1. For instance, the drag coefficient of production cars has significantly decreased over the years due to these advancements.

F1 has also been a testing ground for active aerodynamic systems, which adjust aerodynamic elements in real-time to optimize performance. The Drag Reduction System (DRS) in F1 is a notable example, reducing drag to increase straight-line speed.

Similar concepts are now seen in high-performance road cars, such as active rear spoilers and adjustable front splitters. These systems enhance performance by dynamically adjusting the car's aerodynamic profile based on driving conditions. The Porsche 911 Turbo S, for example, features an active rear spoiler that adjusts to improve downforce or reduce drag as needed.

The sophisticated electronic control systems developed for F1 cars have had a significant impact on road car technologies. F1 cars are equipped with telemetry systems that monitor and transmit vast amounts of data in real-time. These systems optimize engine performance, monitor tire conditions, and adjust suspension settings dynamically.

This technology has paved the way for Advanced Driver Assistance Systems (ADAS) in consumer vehicles. Features such as adaptive cruise control, lane-keeping assist, and automated emergency braking rely on advanced sensors and control systems. The real-time data processing and control algorithms developed in F1 have directly contributed to the development of these systems, enhancing safety and driving convenience.

F1's development of traction control and electronic stability systems has been instrumental in improving road car safety and performance. Traction control systems prevent wheel spin during acceleration, while stability control helps maintain vehicle stability during cornering.

These technologies have become standard in modern vehicles, enhancing safety by helping drivers maintain control in various driving conditions. The principles of electronic stability control (ESC) and anti-lock braking systems (ABS) in road cars are rooted in the control technologies refined in F1.

Safety is paramount in F1, and the sport has led to significant advancements in crash safety technologies. The carbon fiber monocoque chassis used in F1 provides a strong and lightweight survival cell that protects the driver. These monocoques are designed to withstand severe impacts and provide a safe environment for the driver.

The concept of a strong passenger cell has been adopted in road car design, leading to the development of rigid passenger compartments that protect occupants during a crash. Crumple zones, which absorb and dissipate impact energy, are another innovation inspired by F1. These zones deform in a controlled manner to reduce the forces transmitted to occupants, enhancing crash safety.

F1 has also pioneered advances in fire safety, crucial given the high-speed, high-risk nature of the sport. F1 cars use fire-resistant materials and advanced fire suppression systems to protect drivers in the event of a crash.

These innovations have influenced the design of road cars, particularly in the use of fire-resistant materials and improved fuel system safety. Modern vehicles incorporate advanced materials and safety systems to reduce the risk of fire and enhance occupant protection during a crash.

F1's focus on sustainability has led to innovations that benefit the broader automotive industry. The shift towards hybrid power units in F1 reflects a commitment to reducing environmental impact. The development of efficient hybrid systems and energy recovery technologies in F1 has accelerated the adoption of similar technologies in road cars.

Moreover, F1 is exploring the use of sustainable materials and biofuels, which could further influence automotive manufacturing. The emphasis on reducing carbon emissions and improving energy efficiency in F1 aligns with global efforts to combat climate change and promote sustainable transportation.

The intense competition and strict regulations in F1 drive teams to maximize efficiency in all aspects of car performance. This focus on efficiency has led to advancements in engine design, aerodynamics, and materials that contribute to more fuel-efficient road cars. The principles of reducing energy loss and optimizing performance are fundamental to both F1 and consumer vehicle design, driving continuous improvements in fuel economy and emissions reduction.

The suspension systems in F1 cars are designed for optimal performance and handling under extreme conditions. Innovations such as active suspension and advanced damper technology have been developed to enhance stability and control. These technologies have been adapted for road cars, leading to advanced suspension systems that improve ride comfort, handling, and safety. Active suspension systems, for example, adjust damping rates in real-time to provide the best possible handling and comfort based on driving conditions. High-performance vehicles, such as the Mercedes-Benz S-Class, use similar technology to offer a balanced blend of comfort and performance. F1 has also driven advancements in braking technology, with a focus on improving stopping power and reducing brake fade. The use of carbon-ceramic brake discs in F1 offers superior performance compared to traditional steel brakes. These high-performance braking systems provide consistent braking force and are resistant to high temperatures.

Carbon-ceramic brakes are now used in high-performance road cars, providing drivers with enhanced braking performance and durability. The principles of brake cooling and energy management developed in F1 have also influenced the design of modern braking systems, ensuring reliable and efficient braking under various conditions.

The influence of F1 extends beyond technology and safety to shape automotive culture and consumer expectations. The sleek, aerodynamic designs of F1 cars inspire the aesthetics of many road cars. Manufacturers incorporate motorsport-inspired elements, such as aggressive styling, aerodynamic features, and sporty interiors, to appeal to enthusiasts and convey a sense of performance and speed.

F1’s emphasis on performance and competition has shaped consumer expectations and marketing strategies in the automotive industry. Manufacturers leverage their involvement in F1 to promote their brand and showcase their technological prowess. Success in F1 is seen as a testament to a manufacturer's engineering excellence, and this success is often used in marketing campaigns to highlight the performance and reliability of their vehicles.

2. Formula Student

Formula Student is an engineering project that involves a team of students constructing a high-performance race car within a single year. Meeting the requirements of the competition rules adds an extra layer of complexity, demanding teams to navigate a delicate balance between innovation, adherence to safety standards, and the race against time to attain success in this highly competitive arena. Originating in an era dominated by internal combustion engine vehicles, Formula Student has undergone a significant transformation in response to prevailing trends in the automotive industry, characterized by a discernible shift towards the prominence of electric vehicles. This transformation is motivated by a heightened awareness of environmental issues [5], legal motivations [13], and the continuous advancements in electric vehicle effectiveness, for example, for urban operating conditions [10, 11].

For well-established teams like the PWR Racing Team, a scientific club associated with the Wroclaw University of Science and Technology, initially excelling in the era of combustion engines, the evolving requirements and escalating electrification within Formula Student present a significant challenge. In response to that shift, the team has constructed its own electric motor prototype due to their specific application requirements, choosing Interior Permanent Magnet Synchronous Motor (IPMSM) [1, 8, 17]. Additionally, an appropriate control algorithm had to be developed – given the restricted maximum power derived from the accumulator [2], the optimization of electric motor control emerges as a crucial area for competitive engagement.

The Maximum Torque Per Ampere (MTPA) control algorithm is frequently employed in the automotive industry, particularly within the context of electric vehicle powertrains, enhancing the overall efficiency and effectiveness of Interior Permanent Magnet (IMP) machines [9]. This algorithm prioritizes the optimization of the drive system's efficiency by aiming to achieve the maximum torque output while minimizing the electrical current (ampere) consumption [3]. By reducing the amount of current used, MTPA limits copper losses, mitigating the negative effects of temperature variation [12]. The Maximum Torque Per Ampere control method can be used in constant torque region [14, 16].

In order to effectively use the Maximum Torque Per Ampere method, employing a rotational rotor reference frame is highly advantageous. Using Clarke transform, three phase currents (U, V, W) are firstly converted into a two-axis stationary stator frame (α, β). Subsequently, Park transforms, considering the actual position of the rotor, changes it to a two-axis reference frame (d, q) that rotates synchronously with it. Here, the d-axis (direct) indicates the direction of the permanent magnet flux, while the q-axis (quadrature) is orthogonal to it [4, 7].

Using a d-q frame is extremely helpful in control because it provides an easy way to control the motor torque in terms of two separate components. The first one results from the interaction between magnetic flux and the stator current along the q-axis. Meanwhile, the second component is the reluctance torque, which is directly related to the difference between the q-axis and d-axis inductance of the stator [3, 15].

The Maximum Torque Per Ampere aims to maximize electro-magnetic torque given by eq. (1) choosing optimal values of I_d and I_q subject to (2) and (3) [6].

$$T_e = \frac{m}{2} \cdot \frac{p}{2} \left(\psi_d I_q - \psi_q I_d\right) \tag{1}$$

$$\omega_s \sqrt{(\psi_d^2 + \psi_q^2)} \le V_s \tag{2}$$

$$\sqrt{I_d^2 + I_q^2} \le I_{smax} \tag{3}$$

where m is a number of phases, p is a number of poles, $\psi_d \psi_q$ are d-q axis flux linkages, $I_d I_q$ are d-q axis peak current components, V_s and I_s are stator voltage and current.

In this article electric motor control algorithm for Formula Student race car is proposed. Then after introducing necessary modifications for controlling a motor on torque transducer its performance was measured and analyzed.

3. Tractive system and control algorithm

The Tractive System consists of two IPMSM positioned in the rear wheels, coupled with a planetary gearbox, two inverters, and the battery located in the vehicle behind the driver, similar to the main control computer.

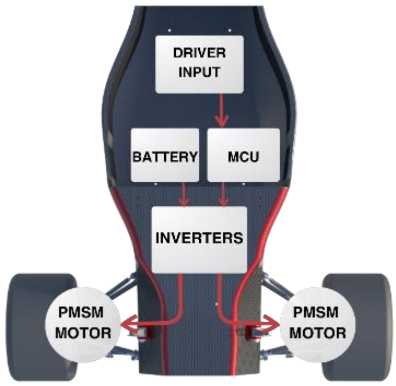

Fig. 1. Scheme of the Formula Student car's tractive system with rear wheel drive

The motor was designed by the team according to specific requirements and conditions to capitalize on its uniqueness. Initially, rule specifications and accumulator design were considered as constraints for voltage and power. Subsequently, utilizing vehicle dynamics simulation, the maximum torque of the motor was defined to optimize performance on Formula Student tracks. Once the maximum motor torque was established, the power base speed could be determined. Considering additional factors such as limited space in the rear wheels, available materials, and technical feasibility, the motor design underwent iterative refinement to meet the set design goals. The final motor performance simulated in MotorCAD software is illustrated in Fig. 2, and simulation results are gathered in Table 1.

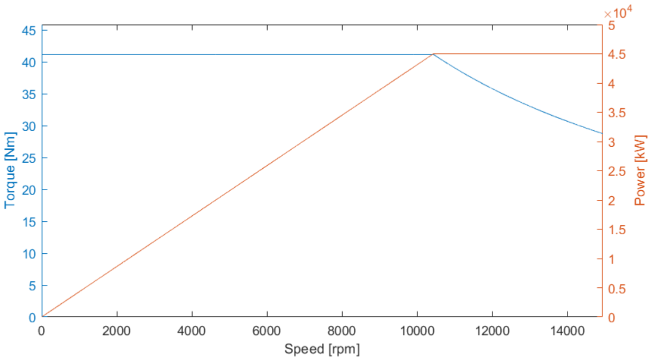

Fig. 2. Motor simulated torque-speed curve

The control system utilizes the Speedgoat computer, based on the Simulink platform, which serves as the main control unit mounted in the car. This system reads data from sensors, implements algorithms specified in the competition regulations, and manages the operation of the drivetrain.

Driver requests, transmitted through the Accelerator Pedal Position Sensor, are transformed into percent of maximum torque. Then, input value is processed by Torque Vectoring (TV) and Traction Control (TC) algorithms, considering the regulatory power limitations. Based on the motor speed read from the resolver and the desired torque, appropriate values of d-q axis current are selected from lookup tables. These values serve as a reference for the current regulator in the inverter, enabling precise control over the operation of the vehicle's motors. The control algorithm diagram for the vehicle's motors, executed by the Main Control Unit and inverter, is presented in Fig. 3.

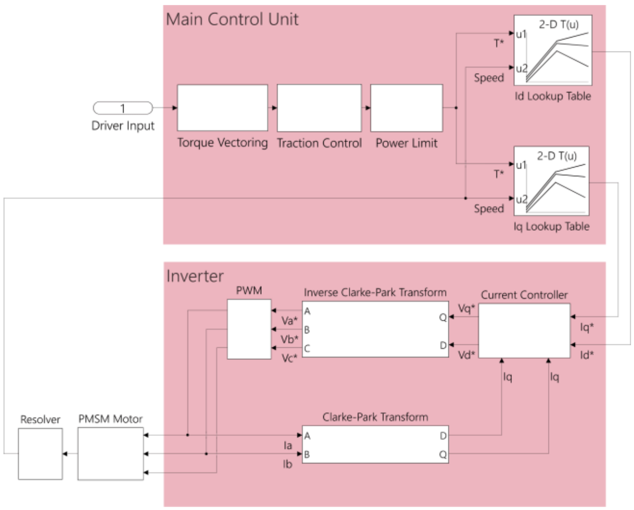

Fig. 3. Motor Control System executed by Main Control Unit and inverters, second pair of inverter and motor is controlled similarly

Reference values of currents were computed using MotorCAD software. Through electromagnetic simulation of the motor, current values for maximum torque were determined for 1650 operating points using eq. (1)–(3). Values for the whole range of motor speed are presented in Fig. 4 and 5, as well as the simulated output of torque given in Fig. 6.

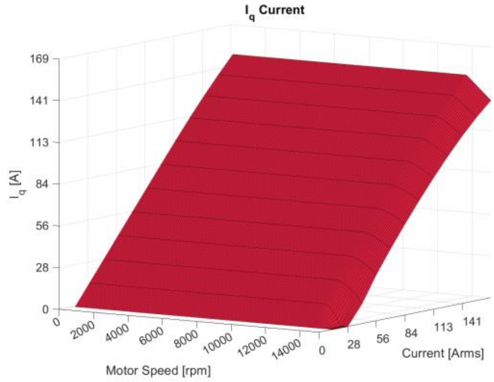

Fig. 4. Simulated values of q axis peak current

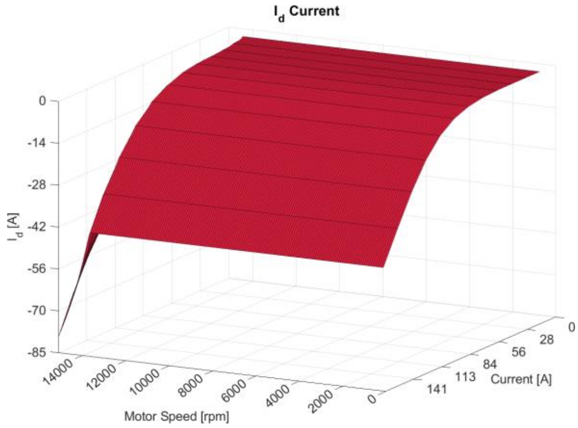

Fig. 5. Simulated values of d axis peak current

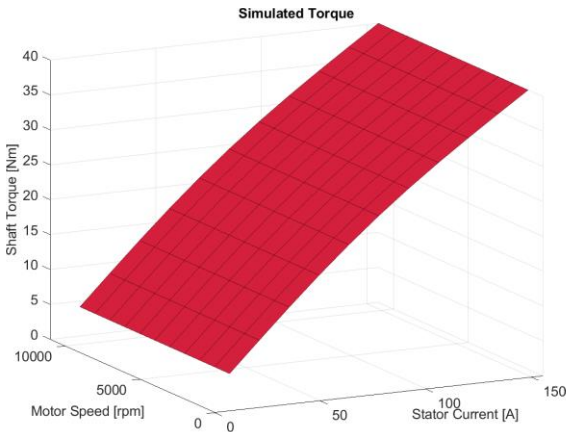

Fig. 6. Simulated output of torque for computed values of peak currents

4. Experimental setup

The parameters of tested motor are presented in Table 1.

Table 1. Theoretical parameters of measured motor

Motor type	IPMSM
DC Bus voltage	538 V
Maximum possible torque	41.4 Nm
Speed limit for constant torque	11467 rpm
Torque constant (k_T)	0.253596 Nm/A
Back EMF constant (k_e)	0.352145 V/rpm
Number of phases	3
Number of poles	8
Inductance of phase L_d/L_q [μL]	161/218
Flux linkage ψ_d/ψ_q [mWb]	43/32
Motor controller	Cascadia Motion PM100DZ
Gear ratio	9.8

The motor control algorithm was adjusted to conduct an experiment, separating the part responsible for Maximum Torque Per Ampere control from other algorithms such as Torque Vectoring and Traction Control. Additionally, power limitation was excluded from the research. The experiment involved iterating the stator current values. Using lookup tables implemented in MCU, appropriate peak currents in the d-q axis were sent to the inverter. This process was repeated for different speeds specified in the table, allowing for the measurement of real torque values correlated with the given currents.

The torque and speed measured by the torque transducer were recorded as analog signals using a power analyzer. Additionally, current and voltage probes were connected to the three phases and power supply cables, enabling the measurement of currents, voltages and power. The temperature of the motor was monitored at various points on its surface and through a sensor placed in the winding. Furthermore, the temperature of the planetary gearbox was read using an analog input in Speedgoat computer. During the tests, a thermal camera was also used to capture images, and the motor's operation was recorded. Setpoints were logged in Speedgoat and all signals from the inverter and motor were recorded in the datalogger. The measurement setup is presented in Fig. 7.

5. Results

Torque values produced for given d-q axis currents were measured in the constant torque region for this motor, and the outcomes are illustrated in Fig. 9. It is evident that the measured torque consistently falls below the simulated values, with the maximum achieved torque reaching 31.8 Nm. This represents a notable 23.2% discrepancy compared to the predicted values. Notably, the torque recorded at various speeds within the constant torque region remains nearly constant for identical currents.

A visual comparison with the simulated values is depicted in Fig. 10. Beyond the observed lower torque constant in the measured data, the relationship is not strictly linear. The proportionality factor decreases with higher currents. It could be caused by increasing temperature during measurements as well as saturation. In Figure 11 the difference between measured and expected torque is presented according to the formula:

$$\Delta = \frac{T_{\text{measured}}}{T_{\text{simulated}}}$$

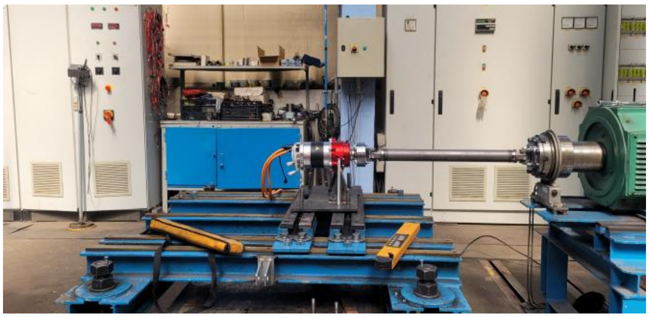

Fig. 8. The tested motor coupled with a planetary gearbox mounted on the torque transducer

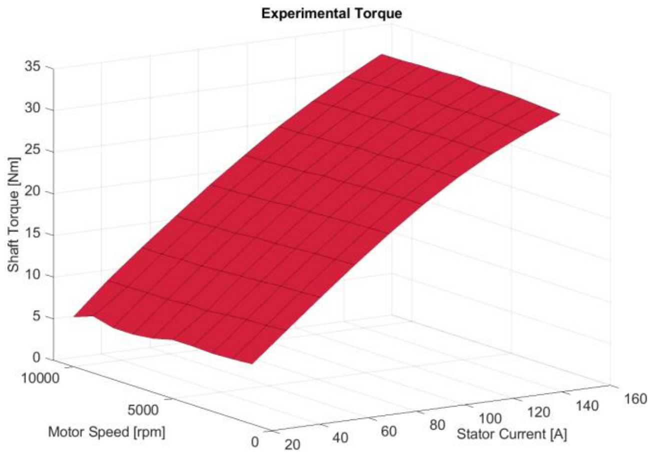

Fig. 9. Measured torque for computed values of peak currents

As shown, results are the most consistent for the middle range of measured currents with the maximum value of 81.3% for stator current I_s = 126.9 A and motor speed ω = = 3000 rpm. For low current values, the difference is significant, primarily due to lower efficiency in this operational range. Similarly, at high current values, the measured torque becomes more divergent, owning to the aforementioned impact of temperature and saturation.

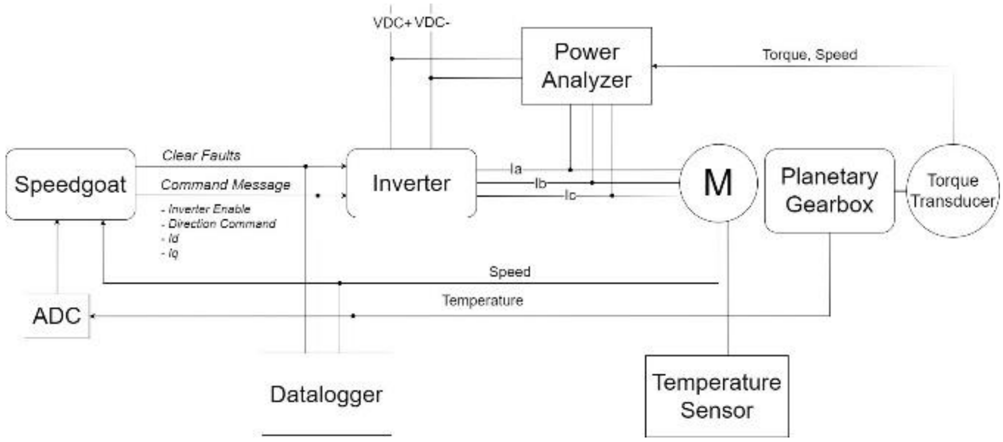

Fig. 7. The measurement setup

For obtained results from torque transducer, expanded uncertainty estimated with a level of confidence of 95% (k = 2) is respectively U(T) = 4.3 Nm and U(ω) = 3.7 rpm.

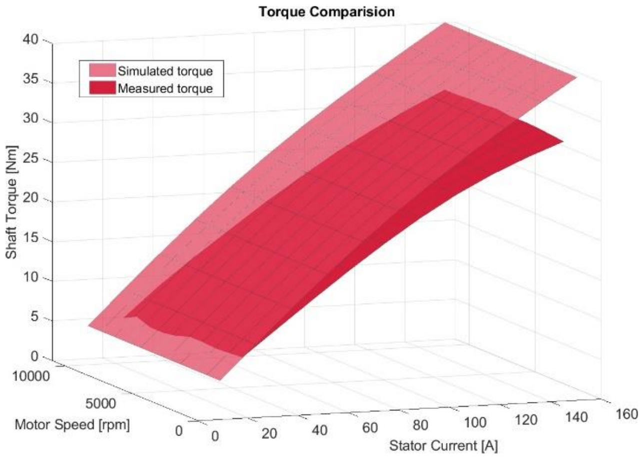

Fig. 10. Comparison between simulated and measured values of torque

Conclusions

The motor prototypes were thoroughly examined, and a comparison was made between the simulated and actual performance characteristics. The research revealed significant discrepancies between the simulated and measured torque due to prototype execution errors. The torque was proportionally lower due to reduced turn number. However, control using MTPA yielded higher values compared to control without it.

The proposed control algorithm is suitable for use in the race car because it employs lookup table values instead of recomputation for each change in torque, which is advantageous in this application given the rapid changes in desired torque. Use of SpeedGoat as the Main Control Unit is beneficial as it allows for easy integration with other algorithms on the vehicle, such as Torque Vectoring and Traction Control and facilitates frequent modifications during the testing phase.

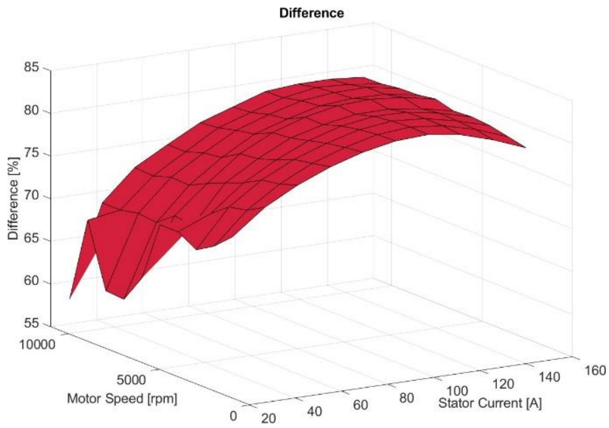

Fig. 11. Difference between simulated and measured values of torque

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