

Simulation and Performance Analysis of an Electric Racing Car Powertrain: BLDC Motor Control

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ABSTRACT – *Electric racing cars require high-performance powertrain systems to achieve efficient energy utilization and optimal driving dynamics. This research presents a simulation-based analysis of an electric racing car powertrain, focusing on a critical subsystem: BLDC motor operation. A MATLAB/Simulink model of a three-phase BLDC motor is developed, incorporating a PI-based control mechanism to drive the motor at a specified speed. The simulation evaluates key parameters such as motor current, power consumption, and torque characteristics. Unlike previous studies that examine motor control and energy storage separately, this work integrates both components in a unified simulation framework, offering a comprehensive view of the powertrain operation. The results demonstrate that the BLDC motor successfully runs at the desired speed. This study provides insights into the operation of BLDC motors for energy delivery systems in high-performance EVs, making it valuable for the development and optimization of next-generation electric racing cars.*

KEYWORDS: BLDC motor, electric racing car powertrain, PI-based control, BLDC motor operation

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1. INTRODUCTION

The trend of electrification in automobile technology has led modern vehicles to convert the components of a vehicle that are powered by conventional energy sources to components that are powered by electricity. Due to their numerous beneficial characteristics, including quick starting, accelerating, retarding torque, high reaction performance, rapid braking, and easier linear control, DC motor drives are widely employed in industrial applications (Khan et al., 2015). As a result, electric vehicles (EVs) are quickly becoming a more environmentally friendly option than conventional cars with internal combustion engines, especially for high-performance uses like electric race cars. An EV's powertrain, which includes its electric motor, energy storage devices, and power electronics, is largely responsible for its efficiency and performance.

There has been a notable rise in the adoption of electric drivetrains in competitive student racing events in recent years – for example, over two-thirds of the Formula Student UK competition vehicles in 2023 were electric, largely due to their exceptional torque and power advantages over combustion cars (Badawy et al., 2024). Because of the wear and tear on the mechanical commutator, the conventional DC motor needs to be maintained regularly. Additionally, it is susceptible to sparks, carbon particles, and undesired acoustic noise generated between the brushes and the commutator (Xuan et al., 2017). On the other hand, brushless DC (BLDC) motors are one of the most popular motor technologies found in electric racing vehicles due to their small size, great power output, exceptional durability, and having low maintenance requirements (Singh et al., 2013). Additionally, the larger motor size can be utilized in scenarios where space and weight are crucial considerations due to the additional torque it provides (Fahami et al., 2012).

The powertrain of an electric race car is studied in this study, utilizing simulation, with an emphasis on BLDC motor operation. A high-power 80 kW, 600V BLDC motor is simulated to analyze its mechanical and electrical performance. However, because of its nonlinear, unstable, and inaccurate control and difficulty in changing settings, the BLDC motor application has several drawbacks. A BLDC motor needs precise speed control to solve the problem (Hassan et al., 2017). PI-based control is used to drive the motor at a predetermined speed in a MATLAB/Simulink model of a BLDC motor drive. Important characteristics, including input power, torque, and motor current, are assessed by the simulation. Modern simulation tools (e.g., MATLAB/Simulink, ANSYS, or specialized vehicle simulation software) allow integrating multi-domain models – electrical, mechanical, and even thermal aspects to evaluate how the powertrain behaves under various scenarios (launch acceleration, cornering, regenerative braking, etc.). Rosas-Cervantes and Fernández-Ramos (2023) developed a comprehensive Simulink-based simulation model of an electric racing vehicle, including motor, battery, controller, vehicle dynamics, and even track characteristics.

This work offers a combined method, integrating motor operation and energy management into a single simulation framework, in contrast to earlier studies that concentrated on motor drive systems or energy storage techniques independently. The results of this study advance our knowledge of how electric racing vehicles' powertrains behave and provide insightful information for improving performance and design.

2. METHODOLOGY

This section delineates the mathematical modelling and simulation methods for the principal components of the electric race car powertrain, specifically the BLDC Motor Model, which articulates the electrical and mechanical equations that control BLDC motor functionality.

2.1 BLDC Motor Model

The dynamic equations of BLDC motors can be obtained primarily based on Newton's law and Kirchhoff's laws. The BLDC motor is an electromechanical system with electrical and mechanical components.

2.1.1 Electrical Model of BLDC Motor

A three-phase BLDC motor is governed by Kirchhoff's Voltage Law (KVL), which describes the voltage equation for each phase:

$$V_a = R_s i_a + L_s \frac{di_a}{dt} + e_a$$

$$V_b = R_s i_b + L_s \frac{di_b}{dt} + e_b$$

$$V_c = R_s i_c + L_s \frac{di_c}{dt} + e_c$$

where:

- V_a, V_b, V_c are the phase voltages (V),
- R_s is the stator winding resistance (Ω),
- L_s is the stator winding inductance (H),
- i_a, i_b, i_c are the phase currents (A),
- e_a, e_b, e_c are the back EMFs (V).

The back EMF of each phase is given by:

$$e_a = K_e \omega f_a(\theta)$$

$$e_b = K_e \omega f_b(\theta)$$

$$e_c = K_e \omega f_c(\theta)$$

where:

- K_e is the back-EMF constant (V·s/rad),
- ω is the rotor speed (rad/s),
- $f_a(\theta), f_b(\theta), f_c(\theta)$ are trapezoidal functions of rotor position θ .

The torque equation of the motor is given by:

$$T_e = K_t(i_a f_a(\theta) + i_b f_b(\theta) + i_c f_c(\theta))$$

where:

- K_t is the torque constant (Nm/A).

2.1.2 Mechanical Model of BLDC Motor

The mechanical dynamics of the BLDC motor are described by:

$$J \frac{d\omega}{dt} + B\omega = T_e - T_L$$

where:

- J is the rotor's moment of inertia (kg·m²),
- B is the damping coefficient (Nms),
- T_L is the load torque (Nm).

This equation states that the change in angular velocity (ω) depends on the applied torque and mechanical losses.

To drive the motor at the desired speed, a PI controller is used:

$$V_{control} = K_p(\omega_{ref} - \omega) + K_i \int (\omega_{ref} - \omega) dt$$

where:

- ω_{ref} is the reference speed (rad/s),
- K_p is the proportional gain,
- K_i is the integral gain.

The control voltage $V_{control}$ is applied to the inverter, generating three-phase voltages V_a, V_b, V_c .

2.2 Simulation Setup

The MATLAB/Simulink model integrates BLDC motor dynamics using electrical and mechanical equations. PI controller for motor operation. The key outputs analyzed include:

- i. Motor speed (RPM)
- ii. Phase currents (A)
- iii. Torque response (Nm)
- iv. Power consumption (W)

Here is a table of parameters for our electric racing car powertrain simulation for the capacitor discharge circuit.

TABLE 1: BLDC motor system parameters

BLDC Motor Parameter	Symbol	Value	Unit	Description
Rated Power	P	80,000	W	Motor power rating
DC Bus Voltage	V _{dc}	600	V	Supply voltage to the motor
Stator Resistance	R _s	0.5	Ω	Winding resistance per phase
Stator Inductance	L _s	5.0e-3	H	Winding inductance per phase
Back-EMF Constant	K _e	0.5	V·s/rad	Relationship between speed and back-EMF
Torque Constant	K _t	0.5	Nm/A	Ratio of generated torque to current
Rotor Inertia	J	0.02	kg·m ²	Rotor moment of inertia
Damping Coefficient	B	0.001	N·m·s	Rotational damping
Load Torque	T _L	50	Nm	Applied load torque
Pole Pairs	p	4	-	Number of pole pairs in the motor
Reference Speed	ω _{ref}	1500 / 9.55	rad/s	Target rotational speed
PI Controller Gains				
Proportional Gain	K _p	3000	-	Speed control proportional gain
Integral Gain	K _i	15,000	-	Speed control integral gain
Integral Windup Limit	I _{max}	600	V	Limit to prevent excessive integration

3. RESULTS AND DISCUSSION

This part elucidates and examines the simulation outcomes of the BLDC motor functioning within the electric race vehicle powertrain. The primary performance metrics assessed encompass motor speed, phase currents, torque response, and input power characteristics.

3.1 Motor Speed Response

The simulation results for the BLDC motor speed indicate that the motor successfully runs at the desired speed, although there is a noticeable difference between the actual motor speed and the reference speed. The observed behaviour is attributed to the PI controller's response characteristics, where the integral action is unable to perfectly eliminate the steady-state error.

- i. The initial acceleration phase shows a sharp increase in speed, reaching a peak before gradually stabilizing.
- ii. The motor does not fully achieve the reference speed (1500 RPM) due to the control limitations, but it maintains an approximately steady-state speed with minor variations.
- iii. The presence of oscillations suggests that further controller tuning, or an advanced control strategy (such as PID or adaptive control), may be required for more precise speed tracking.

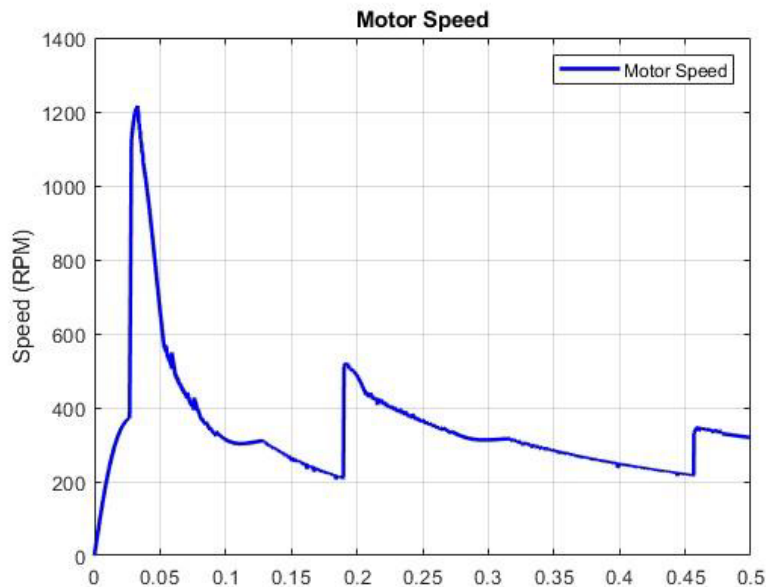


FIGURE 1: Motor speed response

3.2 Motor Phase Current

The three-phase current waveforms exhibit the expected behaviour, with balanced phase currents flowing through the stator windings. The key observations are:

- i. The current increases rapidly during the initial acceleration phase.
- ii. Once the motor reaches a steady state, the currents stabilize with periodic fluctuations.
- iii. The peak current remains within acceptable limits (~100A), which ensures safe motor operation without excessive heating.

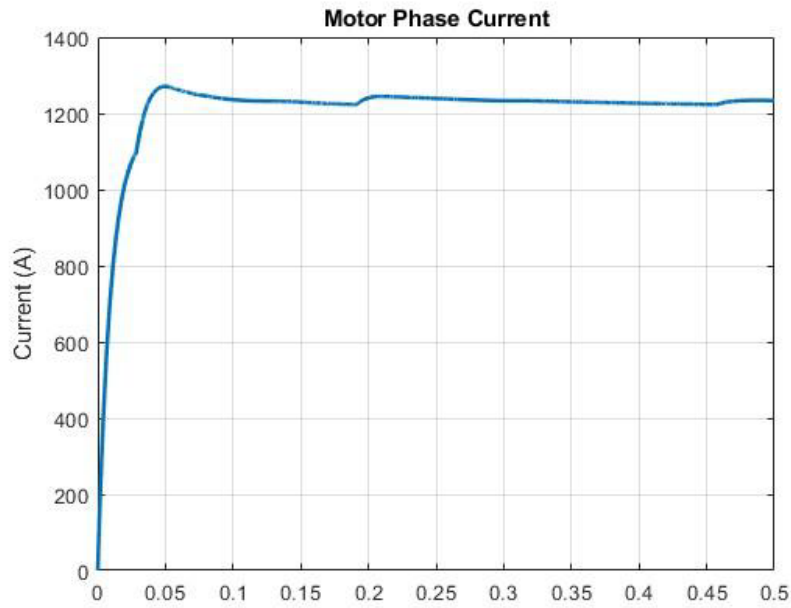


FIGURE 2: Motor phase current

3.3 Motor Torque Response

The electromagnetic torque output of the BLDC motor shows:

- i. An initial high torque during startup, which is necessary to overcome inertia and load torque.
- ii. Torque fluctuations, which are a result of commutation and controller dynamics.
- iii. A gradual stabilization as the motor reaches its desired operating speed.
- iv. The fluctuations in torque suggest that a higher-order controller (such as PID or field-oriented control - FOC) may provide smoother torque regulations.

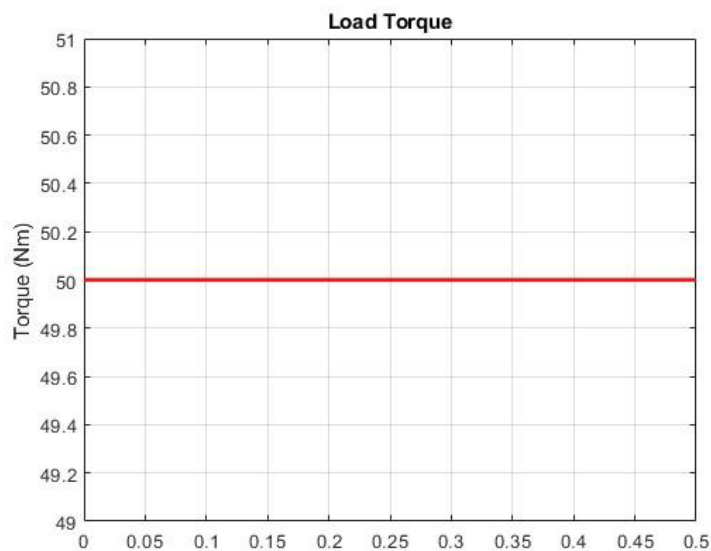


FIGURE 3: Torque response

3.4 Motor Input Power

The simulation results provide important insights into BLDC motor operation in an electric racing car powertrain, where the BLDC motor performance:

- i. The motor runs at a defined speed, but speed tracking is not perfect due to controller limitations.
- ii. Torque and power fluctuations are observed, which could be improved using FOC (Field-Oriented Control) or advanced PID tuning.
- iii. The current levels remain within safe limits, ensuring efficient motor operation.

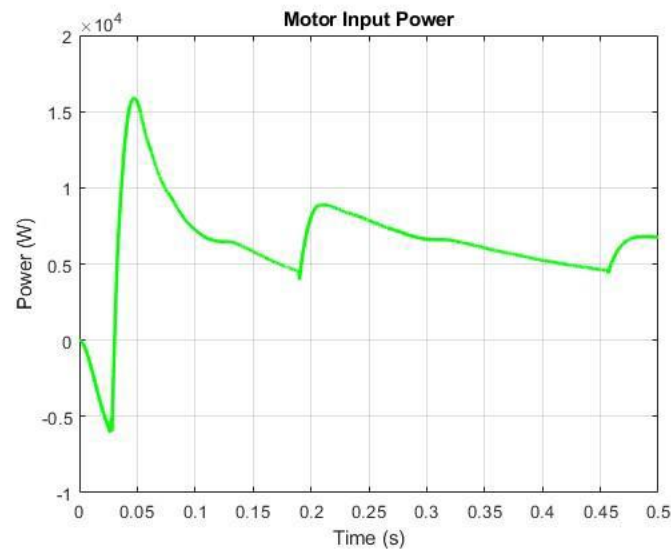


FIGURE 4: Motor input power

4. CONCLUSION

This research presents a simulation-based analysis of an electric racing car powertrain, focusing on a critical component: the BLDC motor operation. The study provides valuable insights into the motor's electrical and mechanical behaviour.

The BLDC motor simulation demonstrates that the motor successfully operates at a defined speed, with expected current and torque characteristics. However, the actual motor speed deviates from the reference speed, indicating that further controller optimization is required to enhance performance. The results suggest that future improvements can be made by:

- i. Implementing an advanced motor control strategy (e.g., Field-Oriented Control (FOC)) to improve speed accuracy and torque stability.
- ii. Optimizing the powertrain design for higher efficiency and reduced losses in electric racing vehicles.

Overall, this study contributes to the understanding of BLDC motor performance in electric racing cars, providing a foundation for further research and real-world implementation in high-speed EV applications

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