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Research paper

Study of Electric Vehicle Drivetrain with Different Drive Cycles

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Abstract

Electric vehicles (EVs) provide reduced emissions, consume less energy, and have become an eco-friendlier option than fuel-based transportation. In this study, MATLAB/Simulink is used to simulate an electric vehicle (EV) powertrain in different driving scenarios, such as city, highway, and off-road conditions. The performance of main components such as battery, inverter, and Permanent Magnet Synchronous Motor (PMSM) is evaluated by analyzing State of Charge (SoC), current, voltage, motor torque, vehicle speed, and brake torque. The simulation results show precise torque tracking and vehicle speed across all driving profiles, frequent use of regenerative braking in city, steady energy consumption on highway, and high energy demand of the vehicle in off-road conditions. Future work could focus on these results to design optimised EV control systems for improving efficiency and performance in extreme driving conditions.

Keywords: *MATLAB-Simulink, Driving Cycles, Simulation, EV Powertrain, Battery Electric Vehicle.*

1. Introduction

The growing demand for eco-friendly and energy-efficient transportation has boosted the popularity of electric vehicles (EVs) [1], [2]. With increasing environmental pollution and depletion of fossil fuels, EVs became more efficient than conventional internal combustion engine vehicles that depend on fossil fuels [3], [4]. Electric motors in EVs are driven by rechargeable batteries that reduce carbon emissions and energy consumption, and play a vital role in future mobility [5], [6].
This study deals with simulating an EV powertrain using MATLAB/Simulink. The model has main parts like a battery, an electric motor, and a transmission system [7], [8]. The objective of this study is to assess the performance of an EV that uses a PMSM motor with a Field-Oriented Control (FOC) controller in different driving road conditions – city, highway, and off-road cycles [9]. Simulations examine the behaviour of parameters such as the State of Charge (SoC) of the battery, load voltage, load current, motor torque, vehicle speed, and brake torque in different driving conditions of the powertrain model (Figure 1) The data obtained from this study contributes to further advancements in the development of electric vehicles related to sustainable development [10].

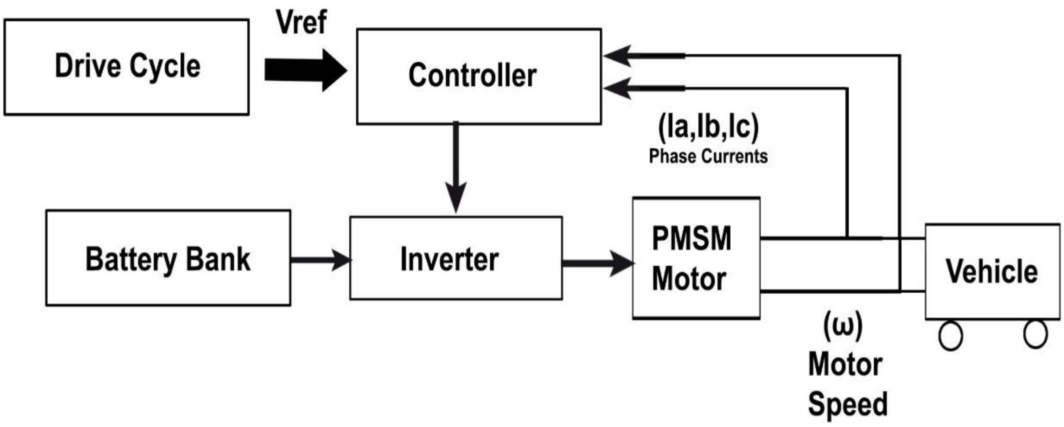


Fig. 1: Block diagram of powertrain model

2. Vehicle Components

2.1 Battery

A Battery Management System (BMS) preserves the performance and life of Li-ion batteries, ensuring safe operation. BMS checks voltage, current, and State of Charge [5], [6]. The State of Charge (SoC) means a percentage of energy left in the battery. It is given by [2]:

$$SoC = \frac{Q(t)}{Q(num)} \times 100 \tag{1}$$

Table 1: Battery specifications

Parameter	Value/Unit
Nominal Voltage (V_{nom})	300V
Initial State of Charge (SoC)	50 %
Rated Capacity	100 Ah
Internal Resistance	0.03Ω
Cut-off Voltage	225 V

2.2 Three-Phase Inverter

The inverter converts DC to 3-phase AC, where sinusoidal pulse width modulation generates gate signals to drive the PMSM motor [3], [4].

Table 2: Inverter specifications

Parameter	Value/Unit
Inverter Type	Voltage Source Inverter
Switching Device	IGBT/Diodes
Conduction Mode	180^0 Conduction
Snubber Resistance(Rs)	100 kΩ
On-state Resistance	1mΩ

The vehicle dynamics model is implemented in MATLAB/Simulink to calculate the total tractive effort required and to simulate vehicle motion in different road conditions in city, highway, and off-road [10], [11]. This model evaluates the combined impacts of physical parameters such as rolling resistance, aerodynamic drag, road gradient, and acceleration [9].
The vehicle powertrain model internally calculates these forces and uses them to simulate vehicle speed and brake torque. The parameters used in the simulation are listed in Table 3. The sum of physical forces, such as rolling resistance force, aerodynamic drag force, gravitational force, and acceleration force, gives the total tractive effort as given in Eq. (5) [12].

$$Fte=Frr + Fad +Fg \tag{2}$$

Table 3: Vehicle dynamics specifications

Parameter	Value/Unit
Vehicle mass (m)	1500 kg
Total Tractive Effort (F_{te})	3000 N
Rolling Resistance (F_{rr})	200 N
Aerodynamic Drag coefficient (C_d)	0.4
Rolling Resistance coefficient (μ_g)	0.015

2.3 Driver Model

The driver model consists of two parts, which are the longitudinal driver model and the FOC controller. The longitudinal driver model calculates the desired speed and acceleration, taking the inputs from the accelerator and brake pedal. This model sends speed commands to the FOC controller, which adjusts the motor torque to achieve the required speeds. The FOC controller sends the PWM signals as gate signals to the inverter, which, in turn, drives the motor to achieve smooth acceleration and deceleration [13], [14].

2.4 Permanent Magnet Synchronous Motor (PMSM)

The PMSM motor block is utilized for simulation, which is based on equations of voltage and flux linkage [3], [15], [16].
Voltage Equations:

$$\begin{Bmatrix} u_{sq} = R_s i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_r \Psi_{sd} \\ u_{sd} = R_s i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_r \Psi_{sq} \\ u_{s0} = R_s i_{s0} + \frac{d\Psi_{s0}}{dt} \\ 0 = r'_{kd} i'_{kd} + \frac{d\Psi'_{kd}}{dt} \\ 0 = r'_{kq} i'_{kq} + \frac{d\Psi'_{kq}}{dt} \end{Bmatrix} \tag{3}$$

Where u_{sq}, u_{sd}, u_{s0} q, d, and 0 axes stator voltages (V), i_{sq}, i_{sd}, i_{s0} q, d, and 0 axes stator currents (A), i'_{kq}, i'_{kd} q, d-axis stator damper winding currents. Flux Linkage equations are given as:

$$\left\{\begin{matrix} \Psi_{sq} = L_{sq} i_{sq} + L_{mq} i'_{kq} \\ \Psi_{sd} = L_{sd} i_{sd} + L_{md} i'_{kd} + L_{md} i'_{m} \\ \Psi_{s0} = L_{ls} i_{s0} \\ \Psi'_{kq} = L_{mq} i_{sq} + L'_{kq} i'_{kq} \\ \Psi'_{kd} = L_{md} i_{sd} + L'_{kd} i'_{kd} + L_{md} i'_{m} \end{matrix}\right\} \tag{4}$$

i'_m is a permanent magnet equivalent current(A).
$\Psi_{sq}, \Psi_{sd}, \Psi_{s0}$ q, d, and 0 stator flux linkages (Wb).
Ψ_{kq}, Ψ_{kd} q and d axis damper windings flux linkages referred to the stator (Wb), L_{ls} stator phase leakage inductances (H),
L_{sq}, L_{sd} q and d-axis stator inductances (H),
L_{mq}, L_{md} q and d axis magnetising inductances (H),
L'_{kq}, L'_{kd} damper winding inductances in q and d axes [3], [15].

Table 4: PMSM Motor specifications

Parameter	Value/Unit
No. of Phases	3
Back EMF Waveform	Sinusoidal
Rated Speed (RPM)	2500
Stator Phase Resistance	0.0485Ω
Armature Inductance	0.000395 H
Inertia (J)	0.027 kgm^2

Driving cycles are vehicle operation schedules that give speed and gear selection as a function of time during simulation [9]. Different driving cycles are considered in this study to simulate the behaviours of city, highway, and off-road conditions [2], [12]. IM240 cycle for city to simulate stop and go traffic, HWFET cycle for highway to simulate high speed and acceleration scenarios [9], RTS95 cycle for off-road to simulate rough terrains [12].

3. Methodology

MATLAB-Simulink is used to design components of the electric vehicle drive system. Battery, Inverter, PMSM, longitudinal vehicle model, FOC Controller, and vehicle dynamics model are simulated using Simulink, Simscape [5], [12]. The efficient torque production and speed control will be ensured by the FOC Controller [3], [5]. The Vehicle dynamics model calculates forces acting on a vehicle in various driving conditions. Various driving cycles: city, highway, and off-road, are used to evaluate the performance of a vehicle. The simulation helps in analysing the performance and response of the powertrain system, such as battery performance, inverter, motor torque with reference torque and error, brake torque, and speed of the vehicle in various real-world driving scenarios [2].

4. Simulation Results

DC power from the battery is fed to a three-phase inverter, converting the DC voltage to AC to drive the motor [12]. Motor is regulated by FOC to match the reference speed and reference torque from the driving cycle [3]. Motor speed (ω) and phase currents (Ia, Ib, Ic) are transformed to control torque and magnetic field using Clarke and Park transformations [3]. Iq is adjusted by the speed PI controller for better torque control, and the current PI controller regulates Id, Iq[5]. These signals are converted back to three-phase using the Inverse-Park transformation, with PWM generating the gate signals to the inverter. The torque sensor is used to compare the actual torque with the required torque to ensure better control. The motor torque is transmitted to the wheels via the transmission system. Environmental forces are important quantities that should be taken into account when simulating a model with real-life driving modes, so the physical quantities like rolling resistance, air drag coefficient, and hill climbing force will be simulated using a vehicle dynamics model [9].
The longitudinal driver model sends acceleration and braking commands to the FOC controller [16]. When there is an acceleration, the motor will be supplied with high power. During deceleration, the motor reduces the torque, and regenerative braking is applied [10]. During braking, the motor acts as a generator that converts kinetic energy back into electrical energy. This recovered electrical energy is sent back to the battery, increasing its SoC [6]. If there is a need for extra braking force, then the braking method shifts from regenerative to mechanical braking, generating brake to slow the vehicle.

4.1 City Simulation

IM240 driving cycle is used to evaluate the performance of the electric vehicle powertrain under city and urban stop-and-go traffic conditions, as shown in Fig. 2.

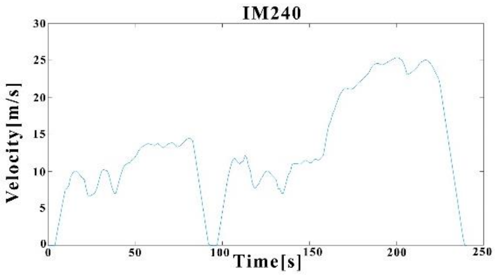


Fig. 2: IM240 Drive cycle plot.

Figure 3 shows a decrease in State of Charge (SoC) from 51.7% to 50.2% with fluctuations of battery current ranging from -300A to 300A, indicating huge energy demand in the IM240 city cycle. Battery voltage is stable, which is approximately 400 V.

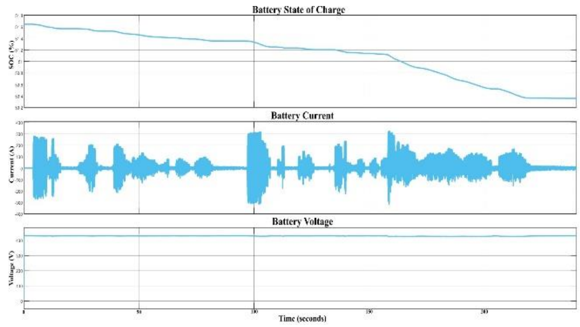


Fig. 3: Battery Performance a) SoC b) current c) Voltage

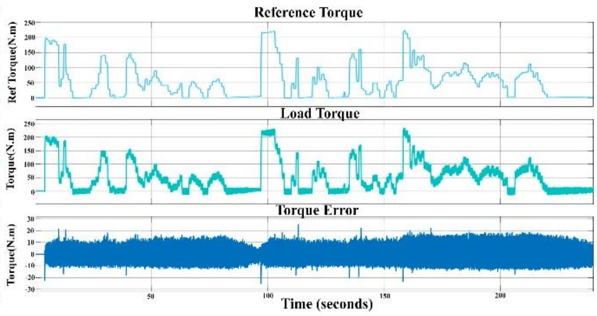


Fig. 4: a) Reference torque, b) Load torque, c) Torque error

Figure 4 shows the variations in torque from 0 Nm to 200 Nm, indicating dynamic load changes. From Figure 4b, the load torque actively follows the reference torque, achieving a peak of 200 Nm. Figure 4c illustrates the Torque error being minimal within an error of around -10 Nm to 10 Nm, which indicates the effective response of the motor in dynamic city driving conditions.

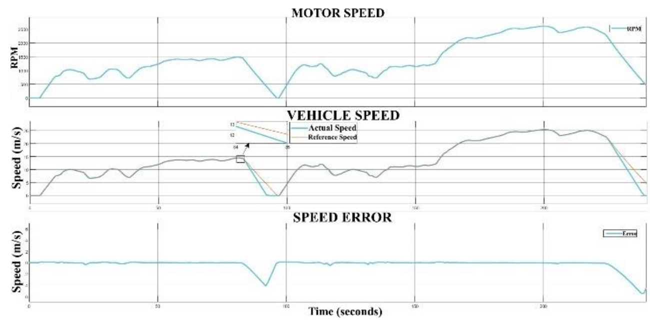


Fig. 5: a) Motor speed, b) Vehicle speed, c) Speed error

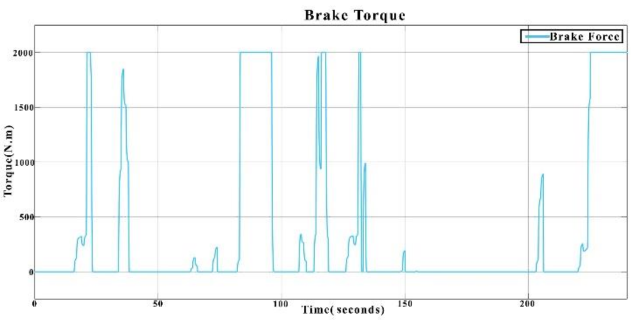


Fig. 6: Brake torque analysis

Figure 5a) shows motor speed variations during city driving. The highest speed achieved by the motor is around 2500 rpm, which matches the motor's rated speed (~2500 rpm). Vehicle speed in Figure 5b for the city is around 50-80 km/h and has a small error when braking, and after a few seconds, the vehicle attains the desired speed. In the time between the 80s and 100s, Figure 5c shows a small speed error (~-4), indicating that the actual speed is lower than the reference speed. This error is very small in the city due to frequent acceleration and stops, which do not significantly affect performance as the vehicle still closely follows the desired speed.

Figure 6 shows the brake torque variations during the city driving cycle, with torque spikes indicating active braking instances. The analysis of brake torque can be studied with load torque (Figure 4) and battery characteristics (Figure 3). The spikes in brake torque show the application of braking force, which is either mechanical or regenerative braking. The negative battery currents (Figure 3b) show the vehicle is in regenerative mode. An increase in braking force results in a decrease in motor torque, leading to vehicle deceleration. This analysis shows that the braking system of the vehicle adjusts the torque for the right amount of deceleration, which ensures recovery of energy and safety.

4.2 Highway Simulation

The Drive cycle used for the highway is HWFET (Highway fuel economy test) as shown in Figure 7, which consists of steady speeds and fewer stops due to higher speeds, acceleration, and cruising phases. The simulation is set to 300 seconds.

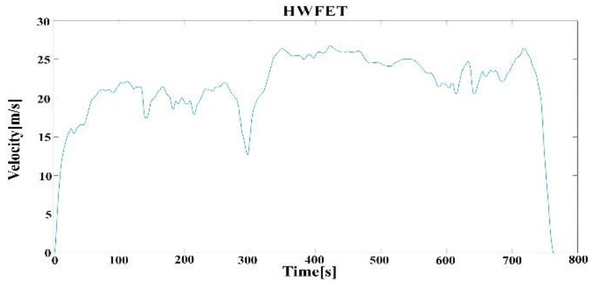


Fig. 7: Highway Drive cycle plot

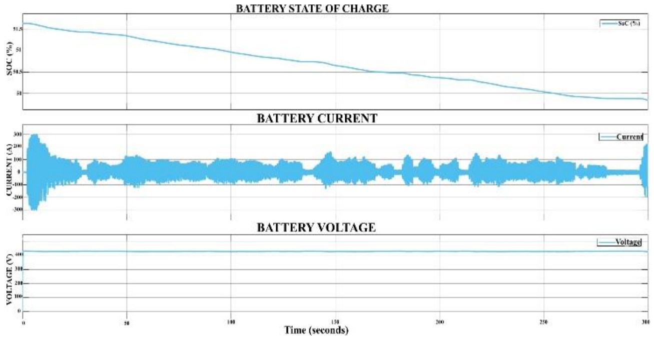


Fig. 8: a) State of Charge, b) Battery current, c) Battery Voltage

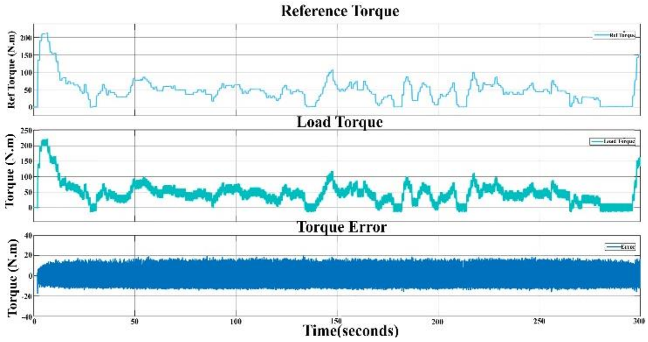


Fig. 9: a) Reference torque, b) Load torque, c) Torque error

Figure 8a shows a decrease in State of Charge (SoC) from 51.5% to 48% with fluctuations of Battery current (Figure 8b) ranging from -300A to 300A, indicating high energy demand in a 300-second highway Drive cycle. Figure 8c shows a stable battery voltage, which is approximately 400V.

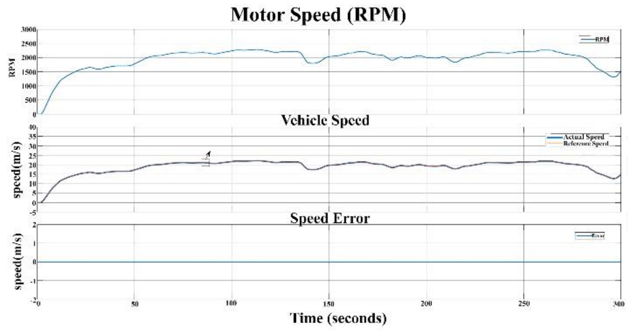


Fig. 10: a) Motor speed, b) Vehicle speed, c) Speed Error

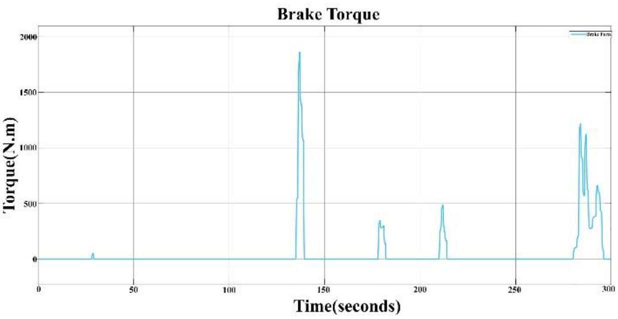


Fig. 11: Brake torque in highway driving mode

Figure 9 shows the variations in torque from 0 Nm to 250 Nm, indicating smooth changes in load when compared to city driving. From Figure 9b, the load torque actively follows the reference torque, achieving a peak of 250 Nm. Figure 9c shows a small Torque error within an error of around -10 Nm to 10 Nm, indicating an effective response of the motor on the highway.

Figure 10 represents the driving speed and motor speed of the vehicle in highway driving. From Figure 10a, the motor RPM is operated near its rated 2500 RPM. Figure 10b shows that the vehicle speed closely tracks the desired speed, having a speed of around 100-130 km/h with a minute error, indicating an accurate speed control. In highway mode, due to steady state operation, braking forces remain low, where regenerative braking is applied until 120s (Figure 11); then, for a full stop, friction braking is applied.

4.3 Off-road Simulation

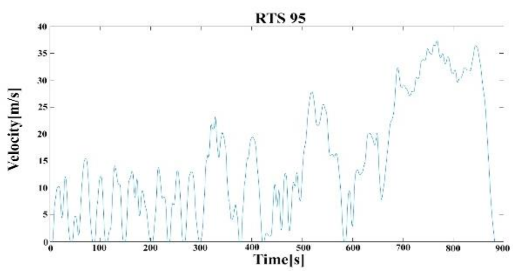


Fig. 12: Off-road Drive cycle plot

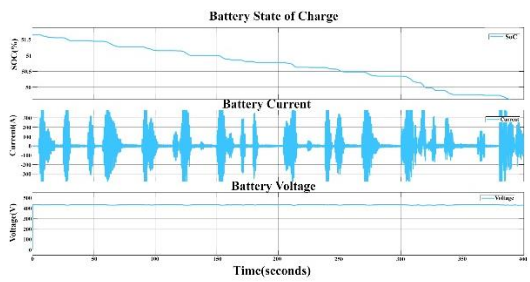
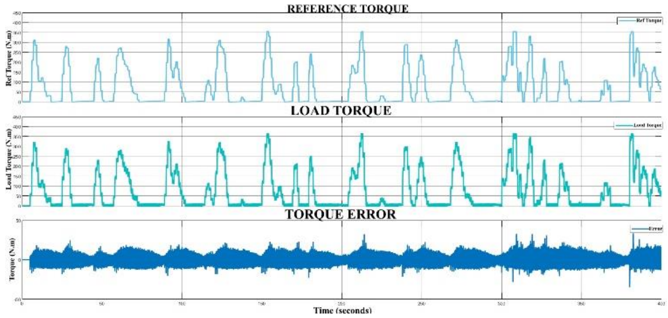


Fig. 13: a) State of Charge, b) Battery current, c) Battery Voltage

Figure 12 shows the RTS95 Drive cycle, simulating high torque demands in rough and uneven terrain for 400 seconds. Figure 13a shows a rapid decrease in State of Charge (SoC) from 51% to 15%, and Figure 13b shows Battery current ranging from -350A to 350A over the 400-second off-road Drive cycle, having high acceleration and frequent stops. Battery voltage is stable, which is approximately 400V as shown in Figure 13c. Due to the rough and uneven terrain between 300s and 350s, SoC shows a quick noticeable drop, while current shows a sharp spike, which indicates a high-power burst.



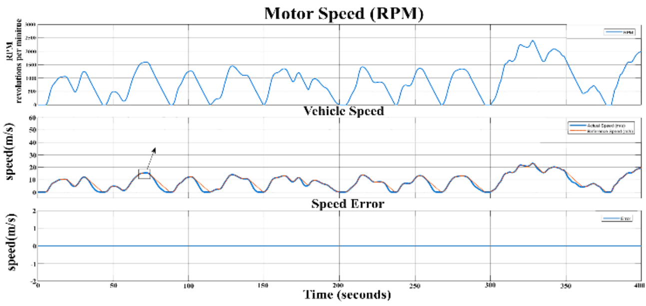


Fig. 14: a) Reference torque, b) Load torque, c) Torque error. **Fig. 15: a**) Motor Speed, b) Vehicle Speed, c) Speed Error

Figure 14 shows fluctuations in load torque, reaching a maximum torque of around 360 Nm, indicating high power demand due to rough and uneven terrain. Figure 14c shows the Torque error between approximately -20 Nm and 20 Nm, indicating the response of the motor to these extreme load variations, resulting in more energy consumption when compared to city and highway driving.
Figure 15 shows the speeds of the motor with the vehicle in rough terrain. The motor speeds are more than 2500 RPM, and the maximum speed is around 10-50 km/h, where the vehicle moves more slowly when compared to the city and highway. There are high-speed variations due to frequent acceleration and braking, as shown in Figure 15b above.

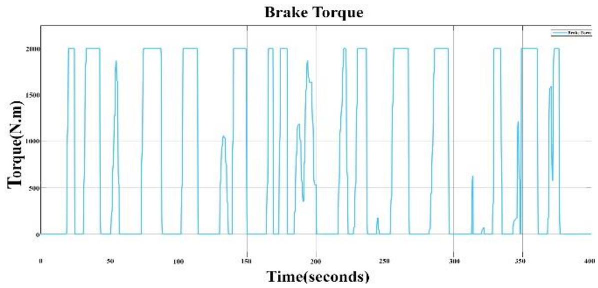


Fig. 16: Brake torque in off-road driving mode

Figure 16 shows high dynamic braking torque patterns, essential for vehicle stability in off-road driving mode. The sharp torque shifts in braking show the car is utilising friction braking mostly for quick stops on rough ground and steep inclines. This analysis shows that off-road driving offers better braking performance, which helps in maintaining good control of the vehicle even in rough and uneven terrain with high braking demands.

5. Conclusion

This study successfully modeled and analyzed the powertrain performance of an electric vehicle under different driving conditions, including urban (IM240), highway (HWFET), and off-road (RTS95) simulations using MATLAB Simulink. Unique powertrain behaviors and energy usage patterns are identified by analyzing motor speed, vehicle speed, braking torque, and battery State of Charge (SoC) for each driving cycle. The simulation results show that urban driving often relies on regenerative braking due to frequent starts and stops. Highway driving shows a steady decrease in the battery's State of Charge (SoC). In off-road driving, the vehicle has higher load torque variations due to rough terrains, which require more mechanical braking, leading to a rapid SoC drop.
Finally, this study provides a useful and clear understanding of how an electric vehicle powertrain behaves and performs in different driving conditions, providing a foundation for future advancements in energy management and performance optimisation of electric vehicles.

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