Chapter 17
DC Drive Electric Car Utilizing Series Motor and Four Quadrants Drive DC Chopper Parameter Determination from General Design Requirements

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Abstract The general requirement of a DC drive electric car (EC) is to carry a maximum load of 850–1300 kg. The expected maximum speed of the EC is about 110–120 km/h, and the acceleration is for 60 km/h in less than 10 s. This paper is to study how to determine specific requirements such as motor kilowatt power, gear ratio, maximum motor torque, battery voltage, maximum current, etc. The DC drive an electric car (EC) using a series motor and four quadrants DC chopper (FQDC) to meet the earlier mentioned general requirements. A vehicle dynamic mathematical equation has been used to assist in finding the parameters. A simulation model of this vehicle dynamics equation using MATLAB/Simulink software is developed to study, investigate, and obtain the specific requirements earlier mentioned. Once the specific parameters have been determining, it is tested with the complete electric vehicle model to test the conditions. It concluded that the design requirements parameters

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and the FQDC could represent using a vehicle dynamics mathematical model, and it can perform all requirements for the DC drive EC.

Keywords DC drive · FQDC · Design requirement · EV · Mathematical model chopper · NEDC · Series motor · Four quadrants chopper

17.1 Introduction

Using electric vehicles is one of the solutions to reduce global hydrocarbon emissions. Unfortunately, the price of EVs is expensive and unattainable to many people, especially those living in developing countries. This fact has led to the study on the possibility for DC drive EV, which is known to be economical.

17.2 Review Stage

Oak Research National Laboratory (ORNL) (2009), United States in 2009, had succeeded in designing a DC brushed motor with high power output (55 kW), high efficiency (92%) that can operate at low operating voltages (13 V), and this has started the interest to embark research in DC drive EC. A new series motor four quadrants DC chopper such as shown in Fig. 17.1, was designed, and the proposed chopper has multiple operations (Arof et al. 2014). Several other studies related to DC drive EV led to research on EC battery chargers (Arof et al. 2019a) and different types of DC drive motors such as separately excited (Arof et al. 2019b). Detailed investigations on the chopper operation modes led to the establishment of a simulation model to test the chopper operations for the application of electric car and light rail transit (LRT) been done (Arof et al. 2017a). This led to further investigations on each of the chopper operations in detail on the specific pattern of voltage, current, torque, speed, of the FQDC running DC series motor been carried out (Arof et al. 2017b). For the DC series motor traction EC application, the speed, and torque control has been successfully done and implemented with direct current control (Arof et al. 2016). For power regeneration, the FQDC offers the generator mode, and several techniques of regenerating the power are studied and discussed in (Arof et al. 2019c). In order for the FQDC has to be applied in the real world, it needs controllers running control algorithms in the embedded system. The controller and its control algorithm are studied and tested using a processor in the loop technique (Arof et al. 2019d). The new FQDC can improve the performance of optimization tool such as artificial intelligence (AI). It is introduced to control all the chopper operations of the proposed FQDC chopper (Arof et al. 2015a, b, 2019e). Each operation of FQDC modes performance can be improved using an AI optimization tool such as the genetics algorithm to set up a specific look-up table (Arof et al. 2019f). The pole placement (Arof et al. 2020a) method is used to tune the close loop PID controller to improve controller

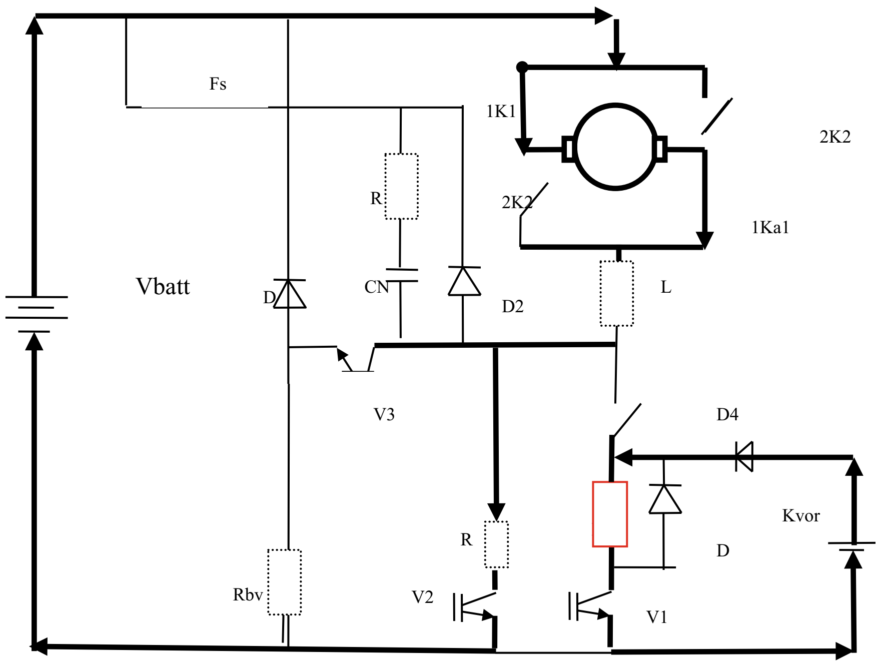


Fig. 17.1 Proposed four quadrants DC chopper (FQDC)

performance while the fuzzy logic controller is used to control the motor current (Arof et al. 2020b) and applied to improve the control performance and system stability. For fault diagnosis and online system tuning and optimization, a numerical representation using Taylor's series (Arof et al. 2020c) has been studied and tried for the driving mode. This method has improved performance using PID cascade and algorithm fluctuations. After improvization made and associated with steering (Arof et al. 2020d) and vehicle movement control (Arof et al. 2020e) was used for autonomous EV automatic reverse parking. As the conducted research studies and investigations are expected to realize in a real prototype of an electric vehicle (EV), all design requirements are needed to fulfill the actual need of the electric vehicle (Gao and Ehsani 2010).

17.2.1 General Requirements of Low Cost, Fuel Economics EV Design

The requirements of the DC drive EV powered by FQDC as in Fig. 17.1, are based on the 35–50 kW of DC series motor and a maximum weight with a load of 800–1300 kg (Westbrook 2001). The maximum speed is expected to be 100–120 km/h (Husain 2003; Bansal 2005). In this paper, the design requirements of a DC drive

EV using a series motor and FQDC are presented. This paper is to study how to determine specific requirements of series motor FQDC DC DRIVE EV such as the motor kilowatt power, gear ratio, maximum motor torque, battery voltage, maximum current, etc. The design requirements and the expected parameters to be determined are needed to allow the DC drive EV using a series motor and FQDC that have been designing to pass the New European Driving Cycle (NEDC) test.

17.2.2 Vehicle Dynamics

The propulsion unit of the vehicle needs a tractive force F_{TR} to propel the vehicle. The tractive force must fulfill the requirements of vehicle dynamics to overcome forces such as the rolling resistance, gravitational, and aerodynamically which are summed together as the road load force F_{RL} as shown in Fig. 17.2 (Arof et al. 2020a, b, c, d).

17.2.2.1 Grading Resistance—Gravitational Force

The gravitational force F_{g} depends on the slope of the roadway, as shown in Eq. (17.1). It is positive when climbing and negative when descending a downgrade roadway.

$$F_{\mathrm{g}} = \mathrm{mg}\sin\alpha \tag{17.1}$$

α is the grade angle, m is the total mass of the vehicle, g is the gravity constant.

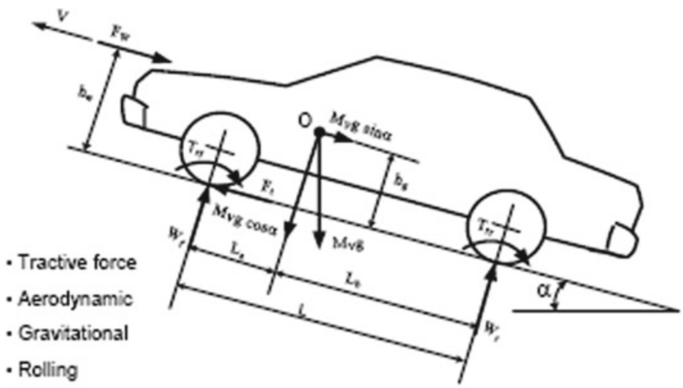


Fig. 17.2 Vehicle dynamic of a car

17.2.2.2 Rolling Resistance

The hysteresis of the tire material causes it at the contact surfaces with the roadway. The centroid of the vertical forces on the wheel moves forward when the tire rolls. Therefore, from beneath the axle toward the direction of motion by the vehicle, as shown in Fig. 17.3.

Tractive Force

The tractive force was used to overcome the F_{roll} force along with the gravity force and the aerodynamic drag force. The rolling resistance has been minimized by keeping the tires as inflated as possible by reducing the hysteresis. The ratio of retarding forces due to rolling resistance and the vertical load on the wheel known as the coefficient of rolling resistance C_0. The rolling resistance force is given by

$$E_{\text{roll}} = \left\{ \begin{array}{lll} \text{sgn}[v_{xt}]\text{mg}(C_0 + C_1 v_{xT}^2) & \text{if} & v_{xt} \neq 0 \\ F_{\text{TR}} - F_{gxT} & \text{if } V_{xt} = 0 \text{ and} & \left| F_{\text{TR}} - F_{gxT} \right| \leq C_0\text{mg} \\ \text{sgn}(F_{\text{TR}} - F_{gxT})(C_0\text{mg}) & \text{if } V_{xt} = 0 \text{ and} & \left| F_{\text{TR}} - F_{gxT} \right| > C_0\text{mg} \end{array} \right\} \tag{17.2}$$

where V_{xt} is the vehicle speed, F_{TR} is the total tractive force, C_0 and C_1 are rolling coefficients Table 17.1.

Typical rolling coefficients are $0.004 < C_0 < 0.02$ (unit less) and $C_1 \ll C_0$ (S^2/m^2), C_0mg is the maximum rolling resistance at standstill. The

$$\text{sgn}[V_{xt}] = \left\{ \begin{array}{ll} 1 & v_{xT} > 0 \\ -1 & v_{xT} < 0 \end{array} \right\}, \text{Approximation}, C_0 = 0.01,$$

Fig. 17.3 Rolling resistance

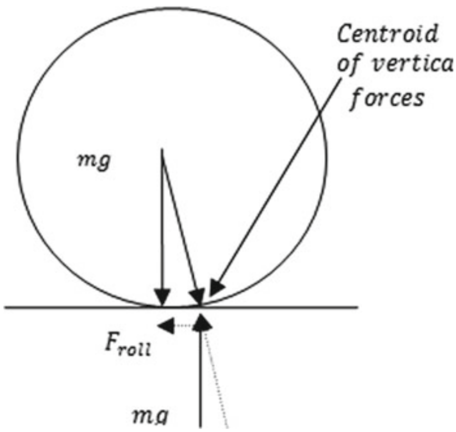


Table 17.1 The parameter of road condition

Road condition	Rolling coefficient C_0
Car tire on concrete or asphalt	0.013
Rolled gravel	0.02
Unpaved road	0.05
Field	0.1–0.35
Truck Tires on concrete or asphalt	0.006–0.01
Wheels on rails	0.001–0.002

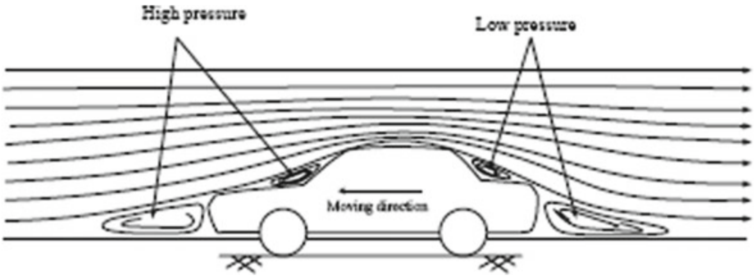


Fig. 17.4 Aerodynamic drag fore

$$C_1 = C_0 \frac{V_{xt}}{100} \tag{17.3}$$

Aerodynamics Force

The aerodynamic drag force is the result of the viscous resistance of the air against the motion, as shown in Fig. 17.4. The aerodynamic drag force $\boldsymbol{F}_{\mathbf{AD}}$ is

$$F_{\mathrm{AD}} = \mathrm{sgn}[V_{xT}]\left\{0.5\rho C_{\mathrm{D}} A_{\mathrm{F}} (V_{xT} + V\omega)^2\right\} \tag{17.4}$$

where ρ is the air density, C_{D} is an aerodynamic drag coefficient, A_{F} is an equivalent frontal area of the vehicle V_{ω} is the head-wind velocity.

17.2.2.3 Propulsion Power

The desired power rating for the electric motor has calculated based on the system constraints of starting acceleration, vehicle rated, and maximum velocity, and vehicle gradability. The torque at the vehicle wheels obtained from the power relation.

$$P = T_{\mathrm{TR}}\omega_{\mathrm{wh}} = F_{\mathrm{TR}}.v_{xT}\,\mathrm{watts} \tag{17.5}$$

where T_{TR} is the tractive torque in Nm, ω_{wh} is the wheel angular velocity in rads/sec, F_{TR} is in N, and v_{xT} is in m/s., assuming no slip, the angular velocity, and the vehicle speed are related by

$$v_{xT} = \omega_{wh} r_{wh} \tag{17.6}$$

where r_{wh} is the radius of the wheel in a meter.

Tractive force versus steady-state velocity characteristics obtained from the equation of motion. When the steady-state velocity is reached dv/dt = 0; and $\sum F = 0$.

Therefore

$$\begin{aligned} F_{TR} - F_{AD} - F_{ROLL} - F_{gxT} = 0 \\ \Rightarrow F_{TR} = \text{mg}\left[\sin\beta + C_0 \text{sgn}(V)\right] \\ + \text{sgn}(V)\left[\text{mg}C_1 + \frac{\rho}{2} C_D A_F\right] V^2 \end{aligned} \tag{17.7}$$

17.2.2.4 Maximum Gradeability

The vehicle has expected to move forward very slowly when climbing a steep slope. Hence, the following assumptions for maximum gradeability made according to the vehicle move very slowly v is 0, $F_{AD} F_r$ are negligible. The vehicle is not accelerating, dv/dt is 0, and F_{TR} is the maximum tractive force delivered by the motor at or near zero speed.

With the assumptions, at near stall conditions,

$$\sum F = 0 \rightarrow F_{TR} - F_{gxT} = 0 \rightarrow F_{TR} = \text{mg}\sin\beta \tag{17.8}$$

If required mass (m) = 1300 kg, (full load)

$$F_{TR} = 1300 \times 9.81 \sin 18 = 3940\,\text{N}$$

the maximum percent grade is max % grade = 100 tan β,

$$\text{max\% grade} = \frac{100 F_{TR}}{\sqrt{(\text{mg})^2 - F_{TR^2}}} = \frac{100 \times 3940}{\sqrt{(1300 \times 9.81)^2 - (3940)^2}} = 32.48\%$$

17.2.3 Ideal Gearbox: Steady-State Model

The EV transmission equation has established by assuming an ideal gearbox as shown in Fig. 17.5 with P_{losses} is 0, and the efficiency is 100%, perfectly rigid gears, and no gear backlash.

17.2.3.1 Gear Ratio

For a tire wheel with radius r, the tangential and the angular velocity are related by:

$$\omega r = v, \omega = \frac{v}{r} \tag{17.9}$$

The tangential velocity at the gear teeth contact point is the same for the two gears with different radius.

$$r_{\text{in}}\omega_{\text{in}} = v = r_{\text{out}}\omega_{\text{out}} \tag{17.10}$$

The gear ratio has defined in terms of speed transformation between the input shaft and the output shaft.

$$\text{GR} = \frac{\omega_{\text{in}}}{\omega_{\text{out}}} = \frac{r_{\text{out}}}{r_{\text{in}}} \tag{17.11}$$

Assuming 100% efficiency of the gear train:

$$P_{\text{out}} = P_{\text{in}}, \Rightarrow T_{\text{out}}\omega_{\text{out}} = T_{\text{in}}\omega_{\text{in}} \tag{17.12}$$

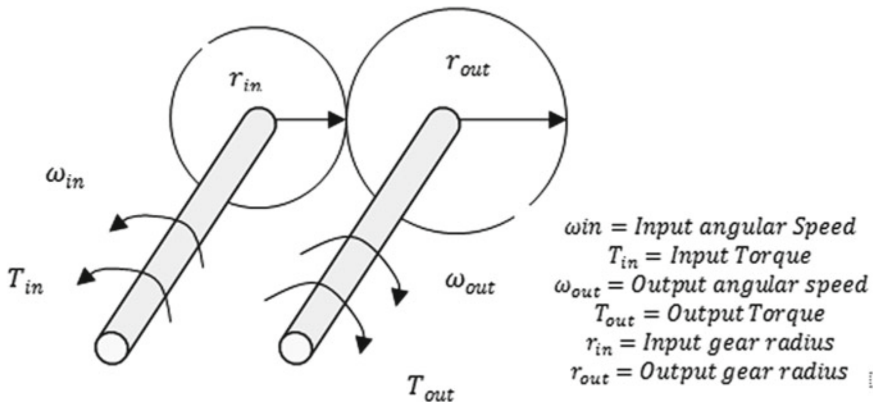


Fig. 17.5 Ideal gearbox: steady-state model

The gear ratio in terms of the torque at the two shafts is

$$GR = \frac{\omega_{\text{in}}}{\omega_{\text{out}}} = \frac{T_{\text{out}}}{T_{\text{in}}} \tag{17.13}$$

At the point of gear mesh, the supplied and delivered forces are the same. The torque at the shaft is the force at the mesh divided by the radius of the disk. In the two-gear combination, the torque ratio between the two gears is proportional to the ratio of gear disk radius. The torque of the inner disk in terms of its radius and force at the gear mesh is

$$T_{\text{in}} = F r_{\text{in}} \Rightarrow F = \frac{T_{\text{in}}}{r_{\text{in}}} \tag{17.14}$$

Similarly, for the other disk with radius r_{out}, the force at the gear mesh is

$$F_{\text{wheel}} = \frac{T_{\text{out}}}{r_{\text{out}}}, T_{\text{out}} = F_{\text{wheel}} \times r_{\text{out}} \tag{17.15}$$

Therefore, the gear ratio is

$$\text{GR} = \frac{T_{\text{out}}}{T_{\text{in}}} = \frac{r_{\text{in}}}{r_{\text{out}}} \tag{17.16}$$

17.2.4 Initial Acceleration

The initial acceleration is specified as 0 to v_f in t_fs. v_f is the vehicle rated speed obtained $v_f = \omega_{f\text{wh}}.r_{\text{wh}}$. The acceleration of the vehicle in terms of these variables has given by Eq. (17.17):

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{F_{\text{TR}} - F_{\text{RL}}}{m} \tag{17.17}$$

17.3 Methodology

MATLAB/Simulink is the medium to simulate the DC drive EV for vehicle design. The previous vehicle dynamics mathematical equations are grouped to form a physical-based model, as shown in Fig. 17.6 (Arof et al. 2017a). The model is used to determine specific requirements parameters of DC drive EC. Some general parameters of the model are preset as follows:

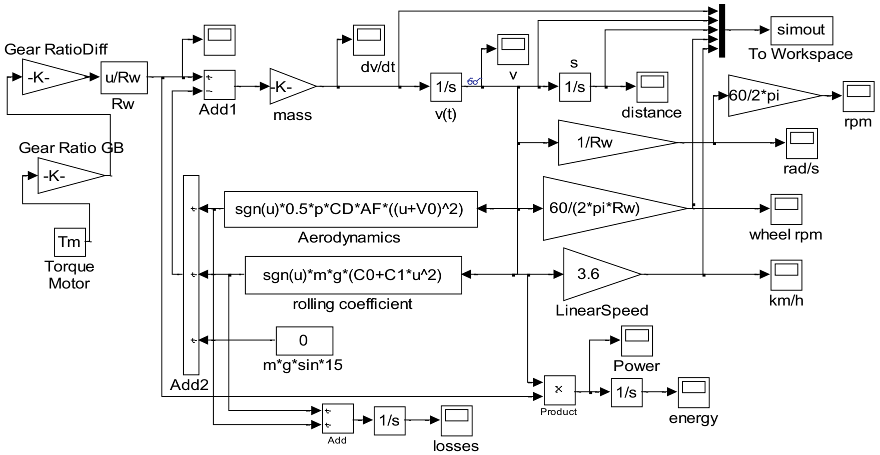


Fig. 17.6 Simulation of the vehicle

$m = 1350$ kg, (full load) $C_D = 0.2$, $A_F = 2\text{m}^2$, $C_O = 0.009$, $C_1 = 0$, $\rho = 1.1614\ \text{kg/m}^3$, and $g = 9.81\ \text{m/s}^2$, r_{wh} = radius of wheel 0.28 m = 11 in, gear ratio = 4.2

A complete simulation model of the series motor FQDC DC drive EV using the MATLAB/Simulink software that includes the vehicle dynamics model, four quadrants DC chopper, DC series motor and controllers is as shown in Fig. 17.7. The model is used to determine the EV acceleration from a standstill. It required torque for the acceleration, motor traction power, the EV maximum speed and maximum EV speed when climbing a steep hill from a standstill. The suitable EV battery voltage supply and the equivalent expected maximum battery current associated with it.

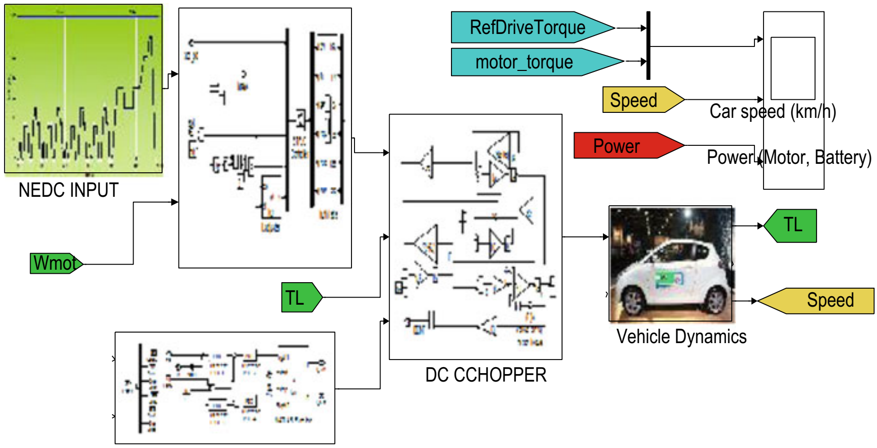


Fig. 17.7 Mathematical model of FQDC for EV

17.4 Result and Discussion

The first requirement is tested for acceleration from standstill to 60 km/h in 10 s, as shown in Fig. 17.8. From the figure, the constant acceleration has been obtained from 0 to 10 s. The speed of 100 km/h is also shown in the figure at 30 s and the maximum speed has expected to be slightly higher than 100 km/h.

The previous acceleration and speed have been tested. The required torque to achieve the acceleration and speed determined using the complete DC EC simulation model is 240 Nm. The required 240 Nm torque is as shown in Fig. 17.9. In this figure, the constant acceleration earlier mentioned, is obtained during the constant torque from 0 to 10 s.

From the torque, we determined the required motor traction power. To produce the required acceleration and torque the series motor and FQDC EC is requiring 41 kW/ motor power, as shown in Fig. 17.10.

The required current to produce 40 kW of series motor traction power is shown in Fig. 17.11. In the figure, there are several options of required voltage and battery current that can be selected. For instance, if the 150 V of battery voltage has set, therefore the expected maximum battery current to maintain the 40 kW of motor

Fig. 17.8 Acceleration test

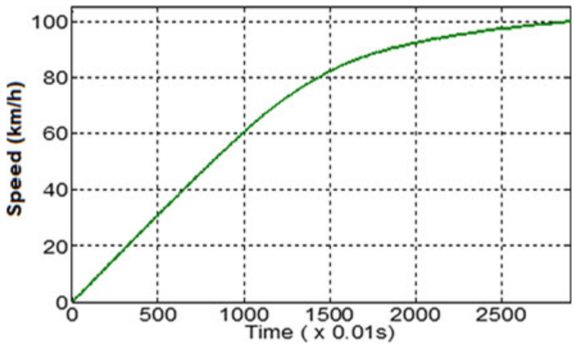
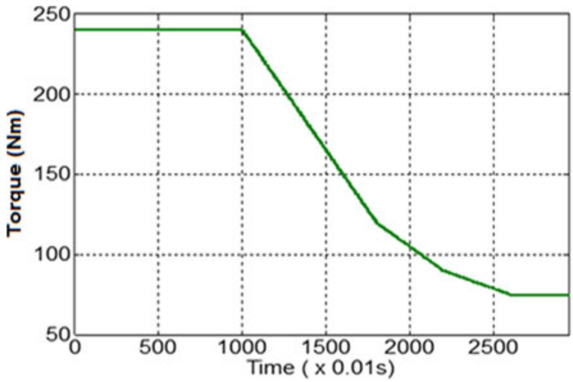


Fig. 17.9 Torque



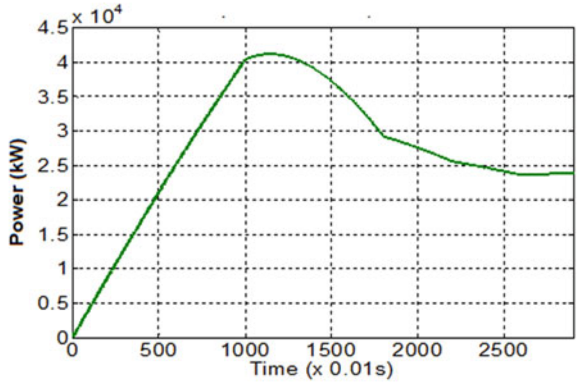


Fig. 17.10 Motor traction power

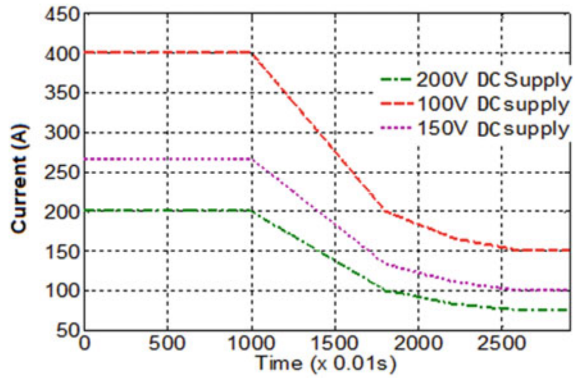


Fig. 17.11 The required current

power is required to be 275 A. While for 100 V of the battery voltage, the expected battery of maximum needed current is 400 A, and for 200 V of the battery voltage, 200 A of battery currents required.

The vehicle has been tested to climb a steep hill at a 21° angle from standstill carrying a maximum load of 1300 kg. The vehicle speed is as shown in Fig. 17.12. The speed is about 1.03 km/h, which is very slow but enough to meet the design requirements.

17.5 Conclusions

The vehicle dynamics mathematical model can determine the requirements of the specific parameter of DC drive EC such as the traction motor. The complete simulation model of EC, which consists of the vehicle dynamics model, FQDC, controllers and series motor can be used to find, test, and verify the design requirement parameters for EC application. These parameters have been used for testing with the New

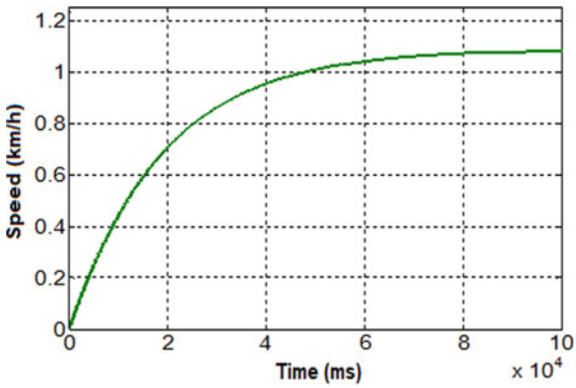


Fig. 17.12 Vehicle speed

European Driving Cycle (NEDC) Test. The proposed four quadrants DC chopper for DC drive series motor has a high potential to be utilized in EV. It is due to a simple design, low cost and excellent controllability.

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