Chapter 13
Series Motor Four-Quadrant DC Chopper: Reverse Mode, Direct Current Control, Triple Cascade PIDs, and Ascend-Descend Algorithm with Feedback Optimization for Automatic Reverse Parking

Saharul Arof, M. S. Said, N. H. N. Diyanah, N. M. Noor, J. A. Jalil, Philip Mawby, H. Arof, and Emilia Noorsal

Abstract This paper focuses on the reverse mode of a proposed series motor four-quadrant direct current chopper (FQDC). The paper proposes a control technique in controlling the acceleration and deceleration of an electric vehicle (EV) using triple cascade proportional-integral-derivative (PID) controllers with an ascend-descend algorithm for controlling speed, torque, and position. The aim is to control the electric propulsion motor powered by the FQDC for the application of automatic reverse parking of an autonomous DC drive electric car. The control technique was simulated

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S. Arof (✉) · M. S. Said · N. H. N. Diyanah · N. M. Noor · J. A. Jalil
Universiti Kuala Lumpur, Malaysian Spanish Institute, Kulim Hi-Tech Park, 09000 Kulim, Kedah, Malaysia
e-mail: saharul@unikl.edu.my

M. S. Said
e-mail: msazali@unikl.edu.my

N. H. N. Diyanah
e-mail: diyanahhisham94@gmail.com

N. M. Noor
e-mail: noramlee@unikl.edu.my

S. Arof · P. Mawby
University of Warwick School of Engineering, Coventry CV47AL, UK
e-mail: p.a.mawby@warwick.ac.uk

H. Arof
Engineering Department, Universiti Malaya, Jalan Universiti, 50603 Kuala Lumpur, Malaysia
e-mail: ahamzah@um.edu.my

E. Noorsal
Faculty of Electrical Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Malaysia
e-mail: emilia.noorsal@uitm.edu.my

M. H. Abu Bakar et al. (eds.), *Progress in Engineering Technology II*,
Advanced Structured Materials 131,
https://doi.org/10.1007/978-3-030-46036-5_13

using MATLAB/Simulink, and the results showed that the technique has successfully met the objective of torque, current, speed, and position control for reverse and auto-reverse parking. In addition, the technique is suitable to be implemented in a DC drive electric car.

Keywords DC drive · Reverse parking · Four-quadrant DC chopper · Series motor · Torque · Position and speed · Torque control · EV

13.1 Introduction

One of the primary reasons for the introduction of electric cars into the market is the concern over greenhouse gas emissions and their contribution to global warming. The purpose of creating electric cars that reduce or eliminate exhaust emissions is to overcome this issue. Unfortunately, the price of electric vehicles (EVs) and hybrid electric vehicles (HEVs) is expensive, thus making the vehicles unattainable to many people, especially those living in poor countries. Therefore, this has led to the study on the possibility for a direct current (DC) drive EV [1] which is known to be economical.

13.1.1 Literature Review

The study on DC drive EVs includes the design of new DC motors, battery charger, and four-quadrant choppers to improve the performance and extend the capability of EVs, such as adding the mode of chopper operations [1–4]. Further investigations of four-quadrant direct current chopper (FQDC) hardware and simulation model include a feedback control using DC control and optimization using artificial intelligence to optimize all operations to produce a complete EV while running in different earth profiles [5–13]. This paper further extends on the study and investigation of one of the modes of the proposed chopper operations, which is the reverse mode. The vehicle reverse mode is shown in Fig. 13.1. After releasing the pulses, a load current that corresponds to the preset control factor α (related to duty ratio) flows through the chopper. In this mode, the back electromagnetic force (EMF), armature voltage, and torque are negative. The paths of currents for reverse operation are shown in Fig. 13.1. The switching of the main IGBT V1 is determined by the control factor α.

The mathematical representations of the four-quadrant chopper in reverse mode are presented in the following equations:

$$I_{\mathrm{a}} = \frac{V_{\mathrm{batt}} - I_{\mathrm{a}}(R_{\mathrm{a}} + R_{\mathrm{f}}) - B_{\mathrm{emf}}}{L_{\mathrm{a}} + L_{\mathrm{f}}} \tag{13.1}$$

$$B_{\mathrm{emf}} = K_{\mathrm{v}} I_{\mathrm{f}} \omega \tag{13.2}$$

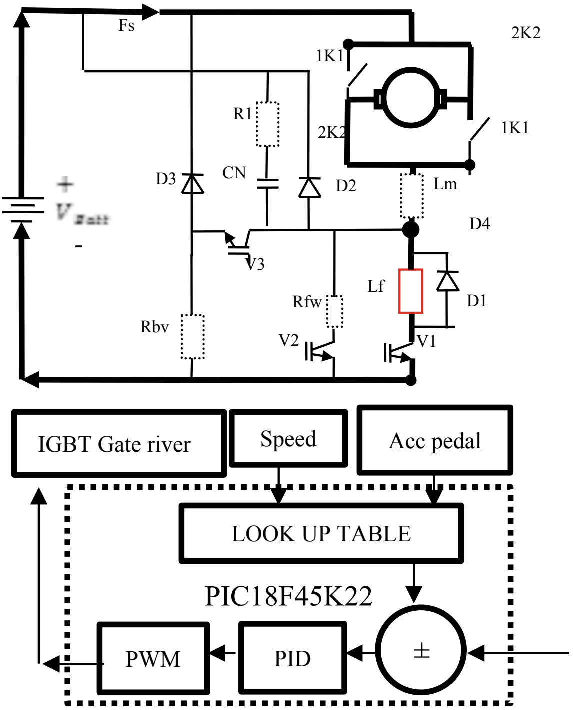


Fig. 13.1 Current paths in reverse mode

$$T_d = K_t I_f I_a \tag{13.3}$$

$$T_d = J\frac{d\omega}{dt} + B_w + T_L \tag{13.4}$$

13.1.2 Review of Automatic Parking

Automatic parking is important when a vehicle driver is dealing with a constrained environment where much attention and skills are required. Performing automatic parking requires coordinated control of the steering angle and the surrounding to avoid collision [14]. Parking assistance systems have been developed using image assistance by Mercedes, Volvo, and BMW. Automatic parking consists of parking trajectory, vehicle location detection, parking space detection, turning, and reverse position control [15]. Parking space detection is used to check the availability of a parking space, where the details are not covered in this paper.

13.2 Methodology

13.2.1 Control Strategy During Reverse Mode

The two required movements in automatic parking are the vehicle movement (in reverse mode) and the steering angle [16]. The latter is controlled using an electric power steering as illustrated in Fig. 13.2.

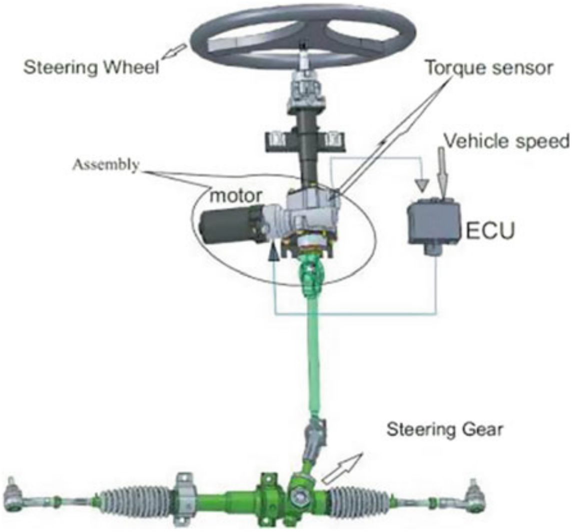


Fig. 13.2 Electric power steering

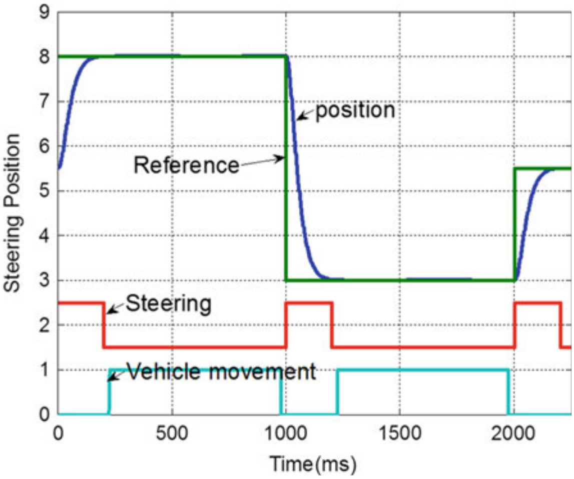


Fig. 13.3 Steering and vehicle movement

Fig. 13.4 Electrohydraulic brake system

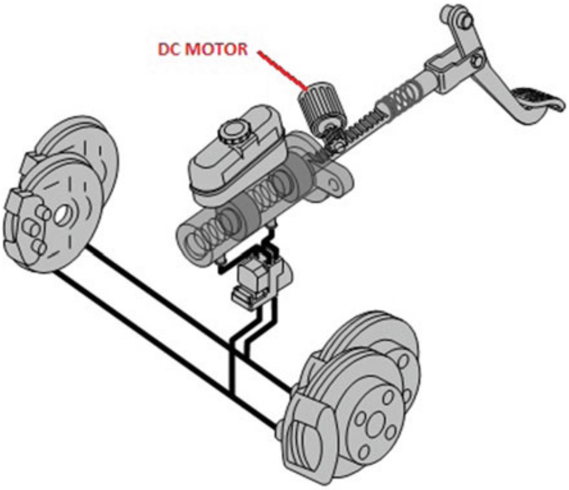
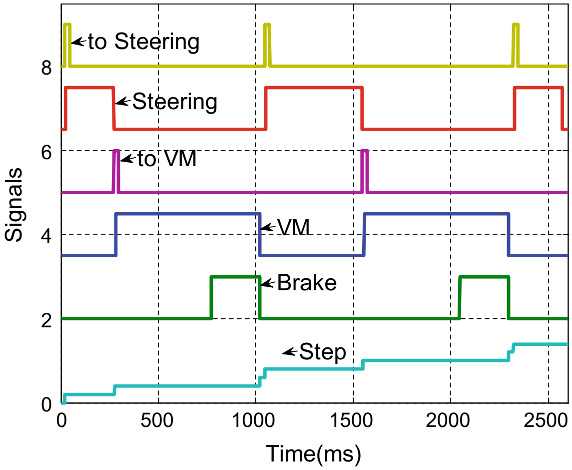


Figure 13.3 exhibits the steering and vehicle movement sequence. The *x*-axis represents time, in milliseconds, while the *y*-axis is normalized. Reference represents the desired position of the steering angle, while position is the actual steering angle movement. An FQDC operating in reverse mode provides the vehicle movement whereby the propulsion motor via FQDC provides motor torque to move an EV.

In the figure, the sequence of operation started with steering and followed by the vehicle movement. Brake control as shown in Fig. 13.4 is also important and the control is needed to create the deceleration effect and to the final stop of the EV [17]. Details regarding the brake and steering control are not covered in this paper.

Figure 13.5 shows the sequence of steering, vehicle movement, and brake. It should be noticed that brake is applied at the end session of the vehicle movement

Fig. 13.5 Steering, vehicle movement, and brake



to create the deceleration effect [18]. The overall function of an automatic reverse parking controller is to ensure that the position, acceleration, and speed are controlled according to the desired pattern for the application of automatic parking. To perform these actions, DC control, ascend-descend algorithm, and triple cascade PIDs are implemented. This is to ensure no tire slip, linear acceleration and deceleration of EV, and the final stop position are achieved.

13.2.2 Direct Current Control in Driving and Reverse Mode

DC control (DCC) is an economical way to be implemented and the approach can be used to limit excessive motor torque that causes tire slip, and consequently the EV will not be parked at the desired position [7] (Fig. 13.6).

In DCC, the motor current is set according to the speed of the motor. DCC uses the look-up table as shown in Table 13.1 and Fig. 13.7. The table represents the required

Fig. 13.6 DCC method

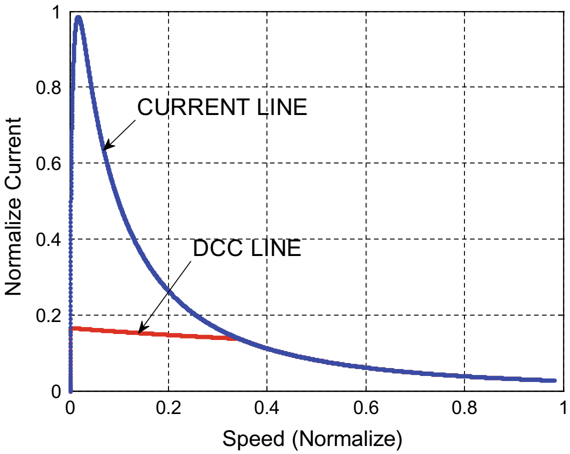


Table 13.1 Look-up table

Speed (rpm)	Current
0.00–0.34 * max speed	0.18 * max current
0.34–0.40 * max speed	0.16 * max current
0.40–0.50 * max speed	0.14 * max current
0.50–0.60 * max speed	0.12 * max current
0.60–0.70 * max speed	0.10 * max current
0.70–0.80 * max speed	0.08 * max current
0.80–0.90 * max speed	0.06 * max current
0.90–1.00 * max speed	0.06 * max current

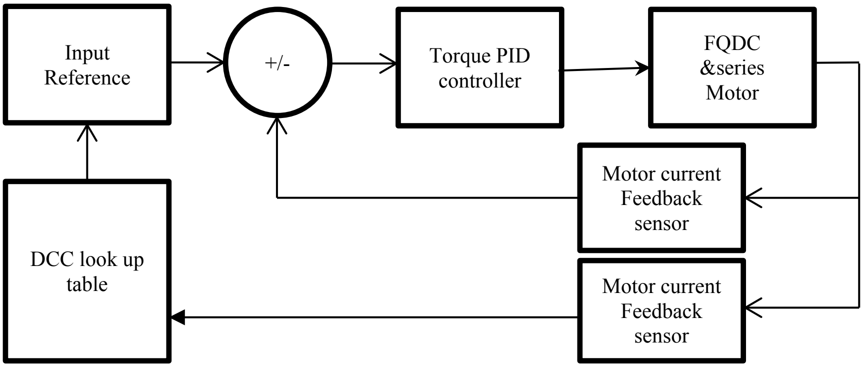


Fig. 13.7 DCC method flow

or expected current according to the motor speed. Interpolations can be made for values that are not available in the table.

13.2.3 Vehicle Movement Control with Cascade PIDs

Cascade PIDs allow several controls to be carried out in a single system. In this research, cascade PIDs were used to control the position, speed, and torque of a single propulsion motor. In a cascade PID, the output of one PID controller will be the input of the other PID controller. The most important aspect to control in this study is the position, which will be placed at the front/beginning, and followed by the least important aspects, which are speed and lastly torque. Figure 13.8 shows the PID controllers connected in cascade. The purpose of cascade PIDs is to control the system performance, such as speed and torque of the propulsion motor. The feedback

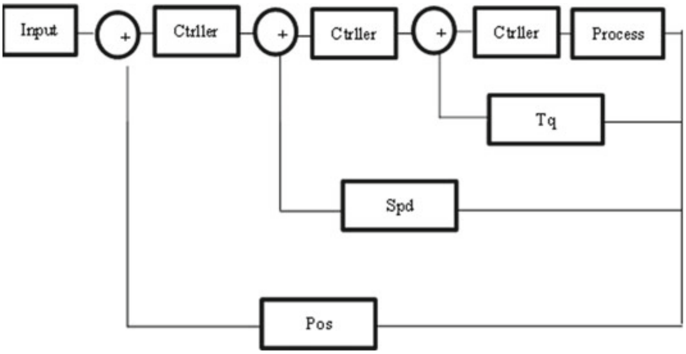


Fig. 13.8 Triple cascade PIDs

control is used to adjust the speed and torque based on the feedback gain. The DCC is controlled using current feedback gain in the cascade PIDs.

13.2.4 Ascend-Descend Algorithm

The ascend-descend algorithm is modified from the gradient descend algorithm. However, unlike the latter that is shown in Fig. 13.9, the former has no target and an error is included in the algorithm. Without error and target, the output will increase or decrease linearly.

The expected gradient effect of speed is presented in Fig. 13.10. In the figure, the speed (in rpm) increases linearly, becomes constant, and then decelerates linearly. This condition can be achieved by using the ascend-descend algorithm and applying the control algorithm output to the feedback sensor by controlling the gain of speed of the PID controller that is connected in cascade. Figure 13.11 shows the block diagram of the operation.

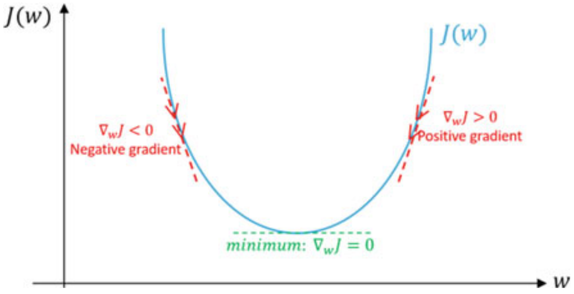


Fig. 13.9 Conventional gradient descend

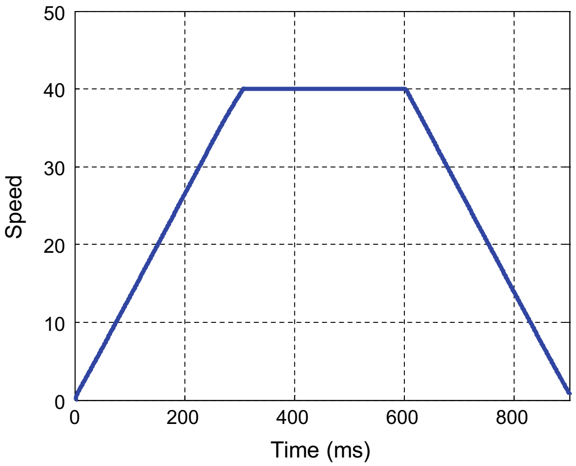


Fig. 13.10 Expected output signal of ascend-descend algorithm

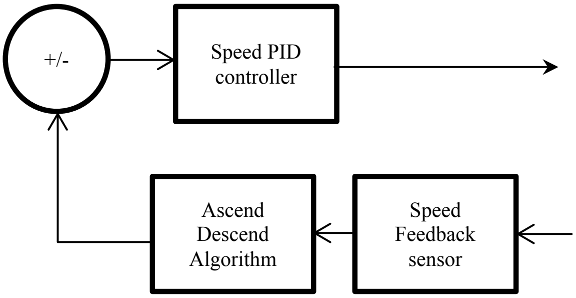


Fig. 13.11 Block diagram of ascend-descend operation

Details about DCC, cascade PIDs, and ascend-descend algorithm will be discussed in other studies.

13.2.5 *Simulation Model with MATLAB/Simulink*

A simulation model was developed to test the control technique. For monitoring the car trajectory, a path tacking simulation model using mathematical equations as shown in Fig. 13.12 was established.

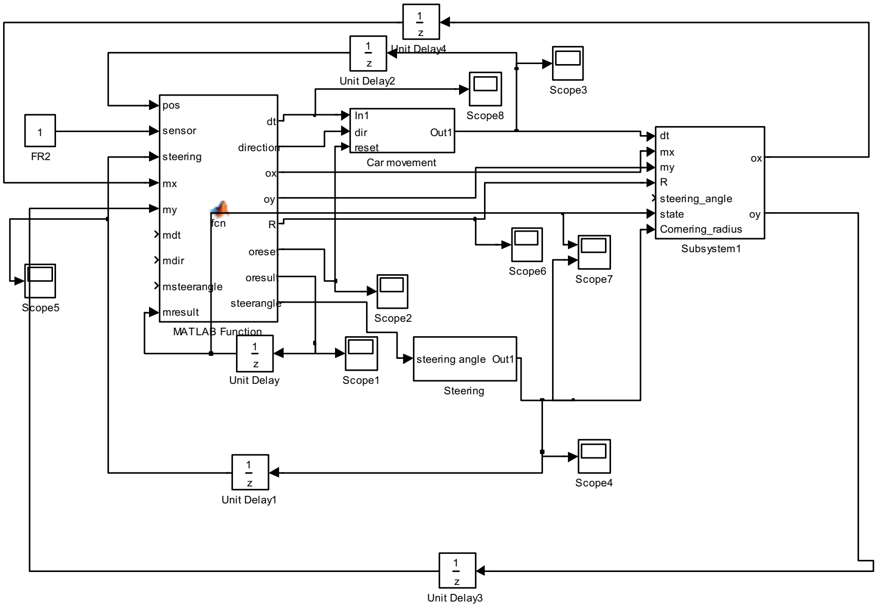


Fig. 13.12 Path trajectory simulation model

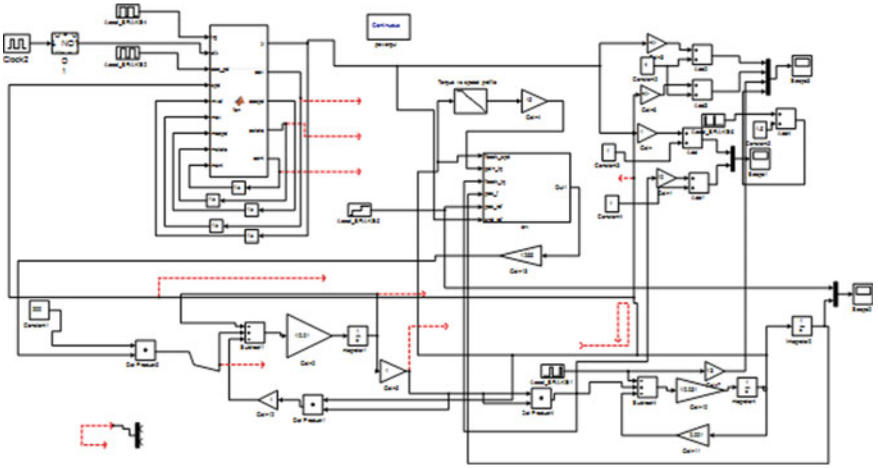


Fig. 13.13 Simulation model of vehicle movement

A simulation model of the vehicle movement for auto-parking was established as presented in Fig. 13.13. This model includes the ascend-descend algorithm controller.

Equations (13.1) to (13.4) can be grouped to form a physical-based model that represents speed. The vehicle position can be determined by adding an integrator and speed output. The MATLAB/Simulink linearize tool can be used to linearize the differential equation and finally tune the PID. MATLAB/Simulink PID drag-and-drop icon has a menu that can be clicked to tune the PID automatically. For the tuning of MATLAB/Simulink using the SISO tool, the physical-based model has to be transformed to the transfer function model using the MATLAB/Simulink system identification. The tool is used to find the system order. Finally, by using the SISO tool, the transfer function for the steering position system can be determined and the PID controller gain can be obtained. The SISO tool is also used to test system stability using root locus or Bode plot. The PID controller gain can be obtained using the PID auto-tune function.

The position, speed, and acceleration control for triple cascade PIDs are shown in Fig. 13.14.

13.3 Results and Discussion

The sequence of operations for automatic reverse parking is shown in Fig. 13.3. In the sequence, first, the steering angle makes the first movement and followed by vehicle movement. Once the vehicle movement has been completed, the steering then moves again for different steering angles and followed by vehicle movement. During steering movement, the vehicle is completely stopped.

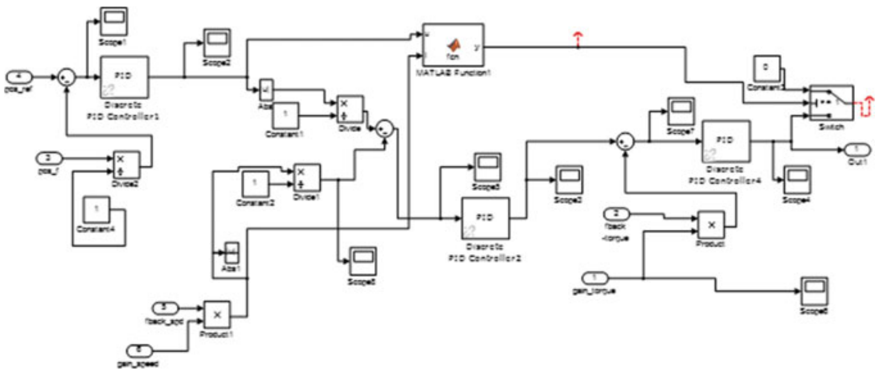


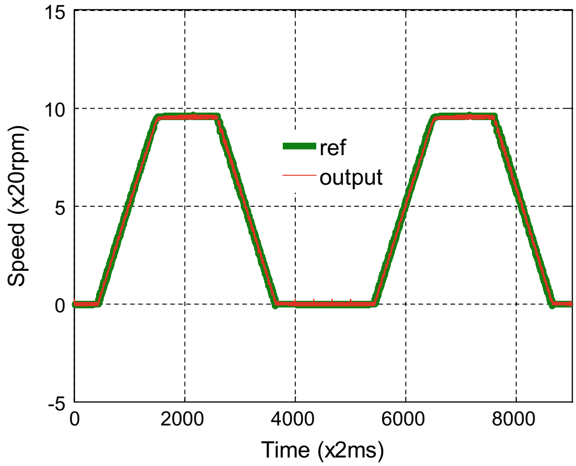
Fig. 13.14 Triple cascade PID simulation model

Figure 13.15 shows how the speed reference is applied. The speed reference is made from a small linear incremental speed value until the required speed is achieved. Once the expected speed is met, the reference speed is made constant. In the figure, the actual speed is lagging a bit from the reference speed during acceleration but once the speed is fixed, the actual speed is similar to the reference speed.

Figure 13.16 shows the vehicle movement speed and torque controlled using the cascade PIDs. The torque is constant and high at the beginning during acceleration before it decreased and increased again during acceleration. For reverse parking, the vehicle makes two movements and resulted in two similar graphs plotted. When the vehicle accelerates, the torque is maintained according to the DCC. The gap time at the beginning and between two graphs represents steering operation.

The vehicle movement position is shown in Fig. 13.17. The standstill at the beginning and middle indicates the steering turning operations.

Fig. 13.15 Speed reference with ascend-descend algorithm



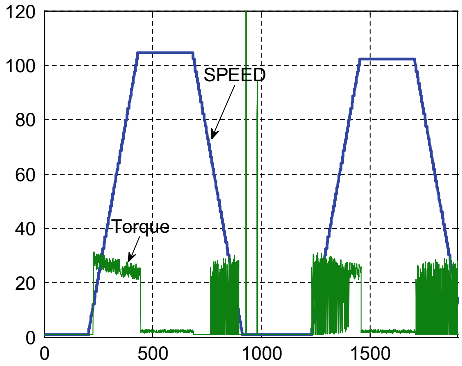


Fig. 13.16 Direct current control and vehicle speed

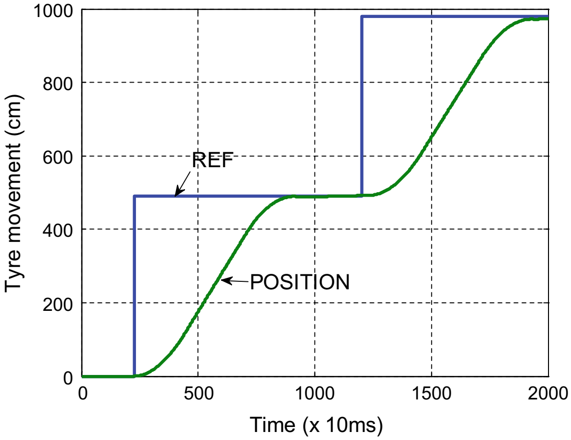


Fig. 13.17 Vehicle movement position

Figure 13.18 shows the vehicle trajectory resulted from the combination of vehicle movement and steering movement for automatic parallel parking. The X- and Y-axes represent the X, Y coordinates which are normalized to ease plotting.

Figure 13.19 shows the vehicle trajectory resulted from the combination of vehicle movement and steering movement for automatic reverse parking. The X- and Y-axes represent the X, Y coordinates which are normalized to ease plotting.

13.4 Conclusions

The control technique proposed for automatic parallel and reverse parking has been successfully performed and simulated. The speed, torque, steering position, and vehicle movement have been successfully controlled for the application of automatic reverse and parallel parking. Therefore, a DC drive electric car powered by FQDC

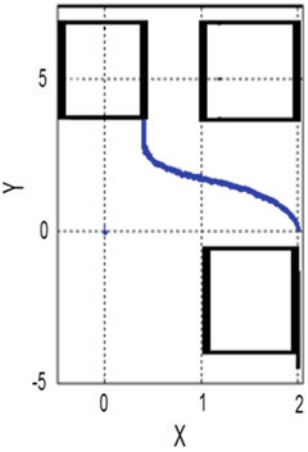


Fig. 13.18 Parallel parking measured from the rear right tire

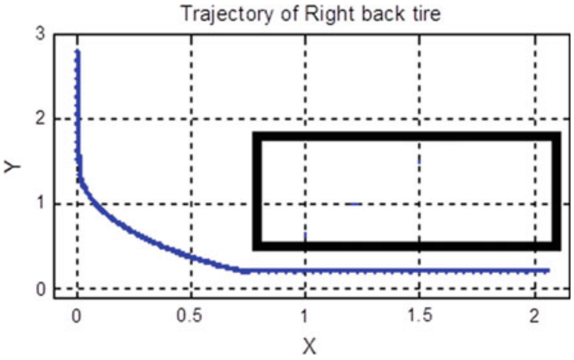


Fig. 13.19 Trajectory of the rear right tire for reverse parking

for series motor is suitable for the application of a DC drive electric car and will have automatic car parking as an extra feature.

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