New Series Motor Four Quadrants Drive DC Chopper for Economical EV Part5: Parallel mode

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Abstract. This is part five of an eight-part series of a new Four Quadrant DC Chopper. The paper describes the parallel mode of the proposed Four Quadrants DC Chopper (FQDC) for a series motor. The mode is designed to overcome a disadvantage of dc series motors which is the speed reduction under load. First, it is studied via simulation using Matlab/Simulink model. Then the FQDC is experimentally tested on a 0.65kW series motor in a lab setup. Finally, a MATLAB/Simulink model is developed to apply the FQDC to a 35kW series motor that propels an electric car (EV). The results indicate that the proposed technique manages to prevent the speed drop of a dc series motor when loaded. This is evident when the EV is subjected to a hill climb.

1. Introduction

Electric vehicles (EV) are hailed as a means of transportation that is economical and friendly to the environment. However, EVs are still expensive, making them unaffordable to many people. This concern has led to the studies on EVs driven by DC motors that are supposed to be cheaper [1, 2].

1.1. Literature

Producing efficient EVs powered by DC motors is challenging as it requires research and development in mechanical and electrical fields. In the electrical field, efforts have been made in the design of efficient dc motors [2], Four Quadrant DC drive [1, 3], closed-loop control of the DC motor using direct current [4], and closed-loop control of the battery charging and discharging [5]. Some related simulation works that have been reported include testing and implementing the FQDC and EV controllers [6, 7], incorporating a battery charger to the FQDC [8] and testing the FQDC on separately excited dc motor [9]. The FQDC operation controller can also be optimized using Artificial Intelligence to suit different
earth profiles [10-12]. The AI method can also help to improve the performance of the specific chopper operation [13]. This paper describes the operation of the proposed FQDC in parallel mode. This mode is needed to overcome the issue of speed reduction in series DC motors under load. The overall operation of the FQDC in the parallel mode is shown in Figure 1.

The following six equations dictate the voltage and current of the FQDC for all modes.

\[
I_a = \frac{V_{batt} - B_{emf}}{R_a + R_f} \quad (1)
\]

\[
B_{emf} = K_v I_f \omega \quad (2)
\]

\[
T_d = K_t I_f I_a \quad (3)
\]

\[
T_d = J \frac{d\omega}{dt} + B \omega + T_L \quad (4)
\]

where \(B_{emf}\) is the back emf of the motor, \(V_a\) and \(V_f\) are the armature and field voltages, \(K_v\) is the back emf constant, \(K_t\) is the torque motor constant, \(I_i\) is the field current, \(R_a\) and \(R_f\) are the motor coil resistances, \(I_a\) is the armature current, \(\omega\) is the angular speed, and \(T_d\) is the motor torque.

**Figure 1.** Four quadrants chopper in Parallel mode

The values of the armature and field currents when IGBT V1 and V2 turn ON are

\[
\frac{d}{dt} [I_f] = \left[ - \frac{R_f}{L_f} \right] [I_f] \left[ \frac{1}{L_f} \right] [V_{ext} \ K_{drv}] \quad (5)
\]

\[
\frac{d}{dt} [I_a] = \left[ - \frac{R_a}{L_a} \right] [I_a] \left[ \frac{1}{L_a} - \frac{1}{L_a} \right] [V_{ext} \ K_{drv}] \quad (6)
\]
2. Methodologies

2.1. DC series motor in Parallel Mode

The main advantage of a DC series motor is its high starting torque. However, its speed drop drastically when loaded. It is common for an electrical motor to have a slight decrease in speed when loaded but the speed drop shown by a series motor is significant.

To solve the problem, we propose an FQDC which allows the series motor to operate in parallel. In series, the armature and field windings are as shown in simplified Figure 2.

![Figure 2. Simplified circuit in series](image)

In series, the armature and field currents are both controlled by varying the PWM value of IGBTv1. But in parallel mode, the field current is separately controlled from the armature current as depicted in Figure 3. While the armature current is controlled by varying the PWM value of IGBT v2, the field current is controlled by varying the PWM value of IGBTv1. Thus, the field current can be changed or maintained independently.

![Figure 3. Simplified circuit in Parallel mode](image)

When a dc series motor running in series is loaded, its speed decreases which in turn reduces the Bemf voltage. According to Eq. 2. The decrease in Bemf voltage will increase the armature current as stated in Eq. 1. Since the armature and field windings are in series, the field current will also increase. This will increase the Bemf back and offset the earlier decrease caused by the speed drop. However, the Bemf of the motor in parallel connection drops a bit since the field current is separated from the
armature current and the field current can be controlled to stay constant. Figure 4 compares the scenarios when the DC motor in series and in parallel when loaded.

As we know the decrease in Bemf voltage will increase the armature current. For the DC motor in series connection, the field current will also increase by the same amount. This increases the Bemf again and reduces the armature current until they settle at new equilibrium values. Thus, the final increase in the armature and field current is not too obvious. However, for the parallel connection, the field current can be maintained separately. Thus, the increase in the armature current is more noticeable as illustrated in Figure 5. Figure 6 shows a slight increase in the field current of the series connection when the load is introduced. On the contrary, the Field current of the parallel connection is maintained. Since the field current of the parallel connection is separately controlled, it can be lowered, raised or maintained.
Figure 6. Field current when motor loaded

Since the increase in the armature current is more significant in the parallel connection, torque will also increase following Eq. (3). Figure 7 shows changes in the torque when a load is introduced for the series and parallel connections. For series connection, even though torque increases slightly, the load torque applied is much greater than the generated torque. As a result, the speed drops.

Figure 7. Torque motor when loaded

More specifically, for series connection, due to the applied load, the values of back emf, armature current, field current and torque will increase slightly. But since the counter torque of the load is greater than the slight torque gained, the speed drops. Thus Bemf will continue to drop so that the armature current, field current and torque will increase until the torque is equal to the load torque applied. At this point the speed of the motor will stop decreasing.

For parallel connection, the field current can be controlled separately thus the amount of torque produced can be adjusted to offset the applied torque. When the speed drops due to the load, the Bemf decreases. This increases the armature current while field current is kept constant. Therefore, the torque will increase. This new torque will offset the loading effect and maintain the speed. Figure 8 shows the speed of the motor in series and parallel connections when loaded. Using this approach, a DC EV driven by a series motor can overcome speed drop while climbing a steep hill.
2.2. Control strategy in Parallel mode

In order to get a high torque, the armature current is set to the maximum. This can be achieved by setting the PWM value of IGBT V2 to the maximum. The field current is adjusted by referring to a Look Up Table so that the Bemf is minimized while the torque is maximized [4, 13]. The field current cannot be too low because it is important in creating magnetic field and flux. These two entities are crucial in producing torque [13].

2.2.1. Control Strategy during parallel mode

The process of operating in parallel mode is briefly described in the flowchart of Figure 9. First, a change to the field current path is initiated so that the field current is separated and fed from a different power supply. Next, the armature current is set to the maximum, by firing IGBT V2 at the maximum PWM value. The field current value is loaded from a look up table and sent to a PID controller.

The Look Up table contains the best field current values with respect to the speed of the motor. The PID controller will determine the PWM signal for IGBT V1. This PWM value is fed to the IGBT in the FQDC. Fig 10 describes the whole process in a block diagram.

2.3. Experimental and Simulation Result in Parallel mode

Simulated mathematical modeling and laboratory experiment are employed to test the effectiveness of the parallel mode on a 0.65 KW series motor. The MATLAB/Simulink mathematical model used for studying the parallel mode operation is shown in Figure 11 while the hardware experimental setup is shown in Figure 12.

Figure 13 shows the DC EV simulation model developed using a 35kW motor operating at the limited maximum power of 22kW to drive its total weight of 1325kg. It is tested to climb an inclination as shown in Figure 14.
Figure 9. Flow Chart

Figure 10. Operation Block diagram
Figure 11. MATLAB/Simulink mathematical model

Figure 12. Experimental setup

Figure 13. EV simulation model with FQDC and Parallel mode.

Figure 14. DC EV Inclination TEST
3. Results and Discussion
The simulated mathematical modeling and hardware experimental results are shown in Fig. 16. It is observed that when the climbing signal is initiated the speed of the motor decreases. The increase in armature and field current is insignificant. But when the parallel mode is activated, the field current drops while the armature current increases. These result in a higher torque, so the motor speed rises.

![Graph showing speed and current implications](image1.png)

**Figure 15.** Simulation and experimental results

Fig. 15 simulation (dotted line) and experimental results (straight lines) of the current and speed of 0.65 KWatt for dc series motor in parallel mode of chopper operation is plotted. The MATLAB/simulink results of the DC EV driven by the novel chopper in Parallel mode is shown in Figure 16. At the beginning, the vehicle speed drops due to the climbing effect. When the parallel mode is activated, the speed of the vehicle increases as it overcomes the load effect.

![Graph showing speed in parallel mode](image2.png)

**Figure 16.** DC EV Test Simulation Results

4. Conclusions
DC drive series motor has a high potential to be utilized in EV. This is due to its simple design, low cost and excellent controllability. In summary, the performance of an optimized DC drive system with the proposed FQDC and Parallel mode is comparable to that of an AC drive and thus is very suitable for application in low cost EVs.

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