Series Motor Four Quadrants Drive DC Chopper Part3: Field Weakening mode

Saharul Arof**, N.H.N.Diyana**, Emilia Noorsalb, Philip Mawbyc, H. Arofd

**a**Universiti Kuala Lumpur, Malaysian Spanish Institute, Kulim Hi-Tech Park, 09000 Kulim, Kedah, Malaysia,

bFaculty of Electrical Engineering, Universiti Teknologi MARA, Pulau Pinang, Malaysia.

cSchool of Engineering, University of Warwick, Coventry, CV47AL, United Kingdom.

dEngineering Department, Universiti Malaya, Jalan Universiti, 50603, Kuala Lumpur

E-mail: saharul@unikl.edu.my

Abstract. This paper describes the operation of a field weakening mode of a new four quadrants DC chopper (FQDC) that can be used to extend the speed of an Electric Car (EC). A mathematical model and real experiment are used to verify the effectiveness of the field weakening mode of the proposed FQDC. First, Matlab/Simulink is used to simulate the system under study and the results indicate that the proposed approach is effective. This is followed by a real experiment using a prototype electric vehicle driven by a DC series motor. The results of the experiment show that the proposed FQDC successfully performed the operation as intended.

1. Introduction
Leading car manufacturers in the world have been investing heavily in research and development of efficient Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) to meet the ever-stringent emission regulation of America and Europe. Using EVs and HEVs have been regarded as one of the ways to curb pollution from the emission of hydrocarbons from conventional internal combustion engines.

1.1. Review Stage
Unfortunately, EVs and HEVs are not widely used as they are still expensive to many people. This shortcoming has led to the study on the possibility of developing cheaper EVs propelled by DC motors. A new breed of Low voltage and high-power DC motors are deemed very suitable for EV and HEV applications [1]. However, high efficiency DC motors alone are not enough for developing complete EV and HEVs. Other research and development areas in electrical engineering domain include power converters/chopper, battery chargers, control, AI, Expert system and electronics [2-13]. The FQDC chopper is designed to perform several modes of operation including driving, field weakening, regenerative braking, resistive braking, generator, reversing and parallel mode driving.
But the scope of discussion of this paper is limited to the Field Weakening mode of the chopper. Field Weakening is a mode of operation of the FQDC and it allows the speed of the DC motor to go beyond its nominal value. The flow of current during this mode is shown in Figure 1.

2. Methodology

2.1. Field Weakening mode of FQDC

The following general equations describe the voltage and current of the chopper. Equations (2) to (4) are general and applicable to all chopper operation modes.

\[ I_a = \frac{V_{\text{batt}} - I_a(R_a + R_f) - B_{\text{emf}}}{L_a + L_f} \]  

(1)

\[ B_{\text{emf}} = K_v I_f \omega \]  

(2)

\[ T_d = K_t I_f I_a \]  

(3)

\[ T_d = J \frac{d\omega}{dt} + B \omega + T_L \]  

(4)

Where \( B_{\text{emf}} \) is the back emf of the motor, \( K_v \) is the back emf constant, \( K_t \) is the torque constant of the motor, \( I_f \) 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.

Field weakening is an operation when the motor operates above base/nominal speed. Field weakening operation is not applicable for every type of driving condition. It is very much dependent on the load \([2, 11]\). If the load is too heavy due to passengers’ weight or the car climbing a steep hill, the field weakening operation should be avoided. In such situations normal driving or parallel mode should be activated instead. Most of the time, the mode selection is made by the chopper operation controller.

The increase in speed is achieved by increasing the torque in field weakening mode. The speed vs torque profile as shown in Figure 2. As seen, the field weakening mode is activated at speed around 50 rad/s. The commencement is accompanied by a jump in torque.
Figure 2. Torque increase at speed 50 during field weakening

The increase in torque is mainly achieved by decreasing the Bemf as stipulated by Equation 1. To reduce the back emf, we need to decrease the field current as stated in equation 2. When BEMF decreases, the armature current increases which leads to the increase in torque as suggested by Equation 3. Figure 3 shows bemf drops when the field weakening mode is activated. Field weakening mode is very much dependent on the correct value of the field current. When the mode is incorrectly executed with a wrong field current value, the chopper would use a lot of energy from the battery to compensate the loss of torque but the generated torque is not enough to counter the load torque.

Figure 3. Bemf voltage is reduced during field weakening

As a result, the motor speed drops. Figure 4 shows the speed of the motor during field weakening mode at 2.7s with different values of field current during the test.
Figure 4. Different field current during field weakening

The simulation results of using different values of Field current in the field weakening mode are also shown in Figure 5. The highest speed is achieved when the field current is set to 0.3A. But when it is further lowered to 0.2A the speed drops. The lowest speed is recorded at 2A field current.

In the figure, the field current that produces the highest motor speed is the one with the medium value, not the highest or the lowest. In short, increasing the Field current increases the Bemf, which in turn decreases the Armature current and consequently the torque. Conversely, reducing the Field current, decreases the Bemf which in turn increases the armature current and consequently the torque.

Figure 5. Different field current during field weakening

But if the field current is too low, the torque will also decrease because a low field current generates a low torque according to equation 3.

2.2. Flow of Current during Field Weakening

When the field weakening mode is needed, the drive control unit would control the IGBT V2, now called the field weakening IGBT. The control factor $\alpha$ of the main IGBT V1 is set to almost unity. During this period, the control factor $\beta$ of IGBT V2 is continuously set to a high value as shown in Figure 6. This induces a current distribution between IGBT V1 and IGBT V2. The value of the field current is inversely proportional to the value of the resistors connected in series with IGBT V2. The control of the different power semiconductors can be seen in Fig. 1. It shows the clock signal, the control $\alpha$ for the main IGBT V1 as well as four different values of control $\beta$ for the field weakening IGBT V2.
Fig. 1 shows how the motor current distributes through the main IGBT V1 and IGBT V2. When IGBT V2 is fired, some of the current that flows through the field winding detours through the field weakening resistor. In the meantime, the armature current Ia continuously rising when IGBT V2 is fired and its duty ratio is increased proportionally.

While the formula of Back emf and motor torque remains unchanged, the armature and field current when IGBT V1 and V2 are fired and at steady state be classified as below:

The condition when Kw1 > Kw2 and Kw2 = 0,

\[
I_a = \frac{(V_a - B_{emf}) \cdot K_{v1}}{R_a + R_f}, \\
I_f = \frac{(V_a - B_{emf}) \cdot K_{v1}}{R_a + R_f}
\]

The second condition is when Kw1 > 0 and Kw1= Kw2.

\[
I_a = \frac{(V_a - B_{emf}) \cdot K_{v2}}{R_a + \frac{R_f \cdot R_{fw}}{R_f + R_{fw}}}, \\
I_f = \frac{(V_a - B_{emf}) \cdot K_{v2}}{R_a + \frac{R_f \cdot R_{fw}}{R_f + R_{fw}}}
\]

The third condition is Kw1 > Kw2 and Kw2 > 0

\[
I_a = \frac{(V_a - B_{emf}) \cdot K_{v2}}{R_a + \frac{R_f \cdot R_{fw}}{R_f + R_{fw}}} + \frac{(V_a - B_{emf}) \cdot (K_{v1} - K_{v2})}{R_a + R_f}, \\
I_f = \frac{(V_a - B_{emf}) \cdot K_{v2}}{R_a + \frac{R_f \cdot R_{fw}}{R_f + R_{fw}}} + \frac{(V_a - B_{emf}) \cdot (K_{v1} - K_{v2})}{R_a + R_f}
\]

The forth condition is Kw1 and Kw2 > 0 and Kw1 < Kw2

![Figure 6. Timing diagram during field weakening](image-url)
The increase in the armature current is caused by two factors. First, according to Kirchoff current law, since the field weakening resistor (RFW) is connected in parallel with the field resistor their total resistance would become smaller. The second factor is the reduction in the field current which decreases the back emf. As the back emf becomes smaller the armature current rises. The influence of the field weakening resistor can be observed in Figure 7. As the field weakening resistor (normalized to field winding resistance) decreases rapidly, the field current decreases slowly but the armature current increases slowly too. So, there exists an optimum value of the RFW which produces the highest torque. Figure 8 shows the influence of the RFW on the values of the back emf (Bemf) and torque in steady state.

As the normalized RFW decreases, the Bemf decreases more slowly but the torque increases gradually until it reaches its maximum value beyond which further reduction in RFW would only reduce its value.

This happens because decreasing the field causes the Bemf to drop which in turn increases the armature current and subsequently the torque. It seems that the effect of the increase in the armature
current is bigger than that of the decrease in the field current and thus the torque increases. But further
decrease in the field weakening resistor would reduce the field current to the point where the magnetics
field and flux start to collapse. As this happens the motor torque drops as shown in Fig. 8. Therefore,
the optimum field weakening resistor value to be used is the one where the maximum torque is achieved.

2.3. Control strategy during Field Weakening
First, the system needs to turn on the IGBT V2. This causes some of field current to be diverted from
the field winding to the Field weakening resistor. Next, the armature current is set to the maximum by
firing IGBT V1 at the maximum PWM value. Then the field current value is loaded from a look up
table and sent to the PID controller. The complete process is described in the flowchart of Figure 9. For
the field current, a Look Up table like the one in Table 1 will be used so that the best field current is
selected for the speed of the motor. The value of the field current is sent to the PID controller that
calculates the PWM signal for IGBT V2 to be executed by the four quadrant chopper. The block
diagram in Figure 10 describes the whole process.

![Figure 9. Timing diagram during field weakening](image_url)
2.4. Software Development and Simulation Result
Both simulations and experiments were used to test the parallel mode of the Four Quadrants Dc chopper running a 0.65 kW DC series motor. A MATLAB/Simulink mathematical model was developed to study the parallel mode operation. It was constructed by solving linear Differential equations of a DC series motor and is shown in Figure 12. Then the dc series motor model was subjected to the load and controlled by the FQDC based on reference signals from the PID and LUT.
Figure 12. MATLAB/Simulink Mathematical model

Figure 13. Timing diagram during field weakening

Figure 13 shows the hardware experimental setup consisting of a 0.65kW motor attached to a variable load. The model comprises a chopper, vehicle dynamics, igbt firing controller, and lookup table controller.

The complete MATLAB/simulink model is shown in Figure 14.

Figure 14. MATLAB/Simulink model

In the vehicle dynamics model, the car experienced hill climbing for load increase test as depicted in Figure 15 below.
3. Results and discussion

Fig. 16 shows the simulation result of the speed motor according to the modes of the chopper operation. The straight blue line and the dotted green line represents the experimental result and the mathematical model result respectively. The values of the motor speed, armature current, and field current in the experiment were captured using Kaptoris software.

At the start of the driving mode, the speed of the motor increases until it saturates. Since the armature and field windings are connected in series, they share the same current. The current increases at the beginning and then it decreases due to the increase in Bemf once driving mode is engaged. When the field weakening mode is initiated, the field current drops because of the drop in Bemf as the armature current increases. The reduction in Bemf and increment in the armature current increase the torque and subsequently the motor speed.

Figure 15. Field weakening Test with climbing

Figure 16. Timing diagram during field weakening.

Figure 17. Different speeds during field weakening tested using DC EV Simulation model.
Figure 7 shows several signals of FQDC results. Positive torque is for driving, field weakening and parallel mode and negative are for generator, regenerative and resistive brake. Field current is always positive armature current can negative during generator, regenerative and resistive braking. The vehicle speed is always positive. Figure 9 shows the PI index results after defuzzification. The highest PI will be pick as the Chopper operation mode.

The car is tested according to the: accelerator signal (signal 9), brake signal (signal 7) and also with reference to the earth profile shown in Figures 10, 11 and 12 (signal 8).

![Figure 18. Perfromance Index(PI) and Chopper Operation (CO)](image)

Finally, the FQDC was tested in Field weakening mode on an EV prototype running a 35kW motor operating at the maximum power of 22kW to drive its total weight of 1325kg. In the test, it drove up an inclination of about 7.5 degree. The simulation result is shown in Fig. 17. Two different speeds are shown in the figure and the highest speed is achieved when the system is tested with Field weakening using LUT. The lower speed is when Field Weakening run without referencing LUT.

4. Conclusion
The proposed FQDC successfully performs its field weakening mode which increases the torque and speed of the DC motor. DC drive series motor has a high potential to be utilized in EVs. This is due to its simple design, low cost and excellent controllability.

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