Four-Quadrant Chopper for Two DC Motor Drives of Electric Wheelchair

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This paper presents a newly designed chopper circuits and its operation that can drive two DC motors at the same time, which is applied to an electric wheelchair system. By using the new topology, the switching devices count can be reduced. By some simulated and experimental results, the operation of the new topology circuit is examined in detail. As a result, it is cleared that the chopper circuit has satisfied performance for driving two DC motors.

(Keywords, chopper, DC motor, electric wheelchair)

1. Introduction

The authors have been developing the electric wheelchair using PEM fuel cell [(1)-(3)]. Because of the limitation of energy used in the electric wheelchair system, the DC motor drive circuit much be designed to save energy as much as possible. Moreover, for commercial application, a low cost of DC chopper is considered. The electric wheelchair using fuel cell has been proposed in Ref. (5) but their system still use the conventional DC chopper for motor drive circuit. According to the DC motor drives circuit, a newly designed DC chopper has been proposed. However, it has some disadvantages point such as the maximum output voltage of chopper circuit cannot be achieved.

Therefore, this paper proposes a novel chopper circuit and its operation capable to drive two DC motors at the same time, which is mainly applied to an electric wheelchair drive. The key feature of the proposed circuit is reduced counts of the switching devices without sacrificing a perfectly independent four-quadrant operation and a voltage boost operation of a power source. Several experimental results are presented to confirm proper operations of the proposed circuit.

2. Circuit Configuration

The conventional four-quadrant H-bridge DC chopper is shown in Fig. 1. This circuit topology is widely used in various applications. One of them is to use as a DC chopper for the four-quadrant control in a DC machine [(4)]. In the circuit topology, one set of DC motor requires 4 switching devices to operate in four-quadrant operation. If the system has two DC motor such as the electric wheelchair system, therefore, 8 switching devices are required to operate these motor. Fig. 2 shows a three-leg structure based full-bridge chopper to drive independent two DC motors simultaneously.

In the circuit, a center leg composed with Q_3 and Q_4 is operated at a relatively low-frequency, e. g., 1 kHz, while the other two legs composed with Q_1, Q_2, Q_5 and Q_6 are operated at a frequency approximately ten times of the center leg. The switching operation of Q_3 and Q_4 is complementary with a 50-% duty cycle; hence the proposed chopper allows independent drive of the two DC motors in four-quadrant operation similar to the conventional topology.

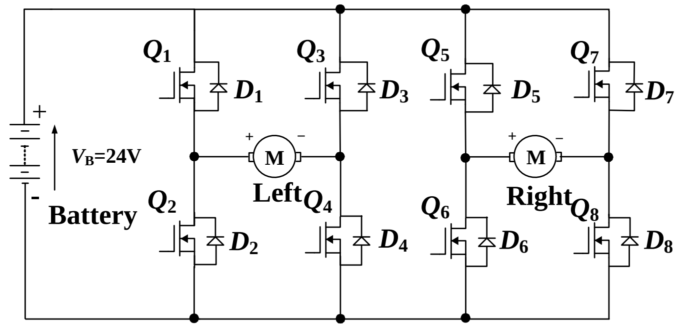


Fig. 1. Conventional four-quadrant H-bridge DC chopper.

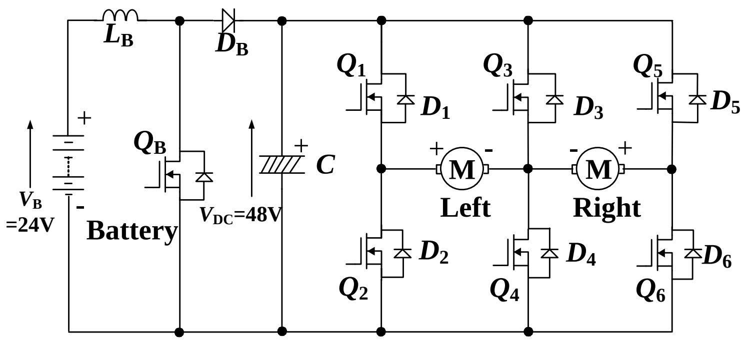


Fig. 2. Proposed three-leg full-bridge chopper.

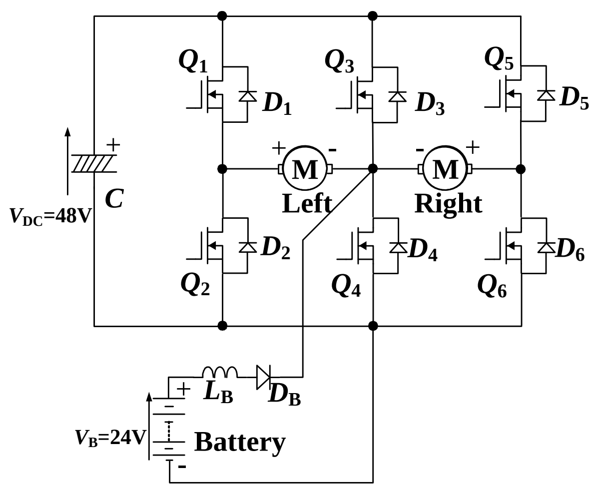


Fig. 3. Proposed three-leg full-bridge chopper incorporated voltage boost function.

However, the 50-% duty cycle switching operation of Q_3 and Q_4 limits the chopper output voltages to half of the power source. Assuming that a 200-W, 24-V battery is a power supply, the maximum voltages across the two DC motors are limited to 12 V, which implies that the maximum speed of the motors is reduced to half of the inherent rated value. Inserting a boost circuit between the power source and the three-leg full-bridge chopper may solve this problem, resulting in increase of the switching device counts and complexity of the circuit configuration. A novel approach to solve the above drawback is presented in Fig. 3. The two DC motors are driven by the three-leg full-bridge chopper, which is composed with superimposed two full-bridge choppers at the center leg. The total number of the switching devices is reduced to six. The switching frequency of Q_1, Q_2, Q_5 and Q_6 is 10 kHz, while that of Q_3 and Q_4 is set at 1 kHz.

The most significant point of this configuration is a voltage boost function of the center common leg, where the power source is connected to the mid node. The voltage boost ratio must be determined by the duty cycle of Q_3 and Q_4 to maintain the DC bus voltage at a Constant value even though the power source voltage varies.

Table 1. Comparison of basic features of circuit topology

	Conventional Circuit topology	Proposed circuit topology	Proposed circuit Topology with voltage boost function
Switching devices counts	8	7	6
Auxiliary devices	0	Required	Required
Diode	8	7	7
Inductor	0	1	1
Efficiency	Highest	Lowest	Medium

Therefore, the duty cycles of Q_1, Q_2, Q_5 and Q_6 are also adjusted in accordance with the voltage boost ratio of the center leg. Table 1 shows the comparison of basic features of circuit topology.

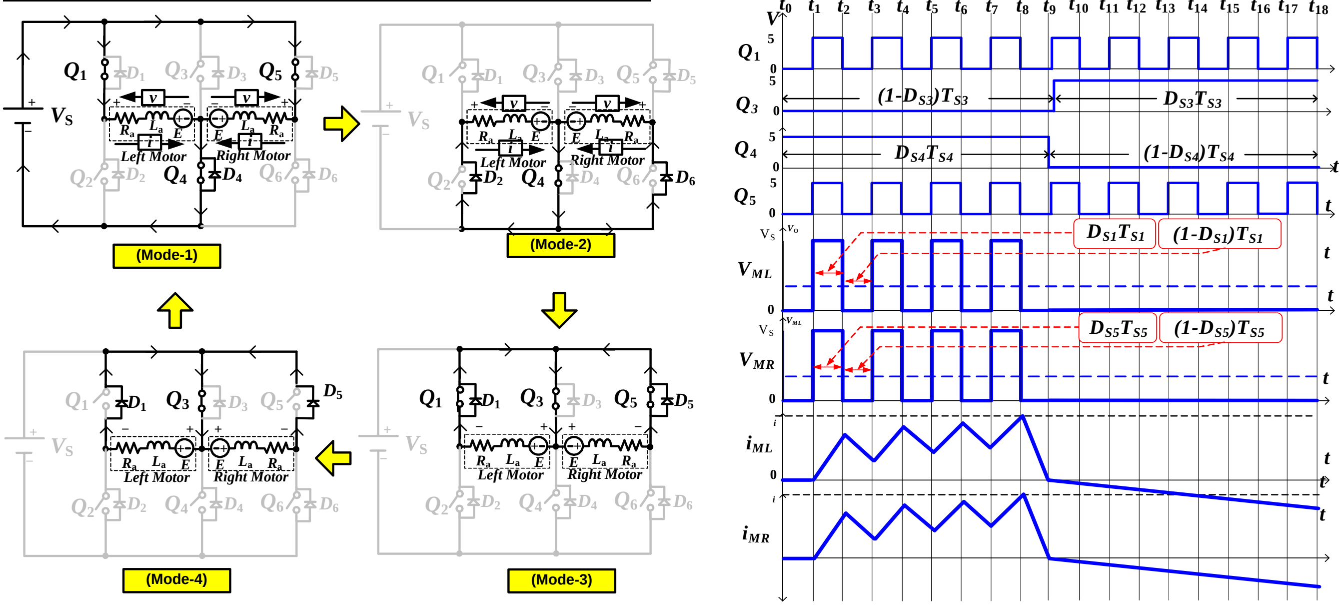
3. Operating Principle of the Proposed Chopper

(3.1) Proposed Three-Leg Full-Bridge Chopper

In this section, two basic operations of the proposed tree-leg full-bridge chopper are discussed. The first one is the case of a forward motion where both of the two DC motors are operated in the same direction to move the wheelchair forward. The second one is a backward motion where both of the two DC motors are operated in the same direction to move the wheelchair backward. Figure 4 shows the operating key waveform, operation modes and currents paths of the forward motion. Before analysing the operation of the circuit, several assumptions are employed;

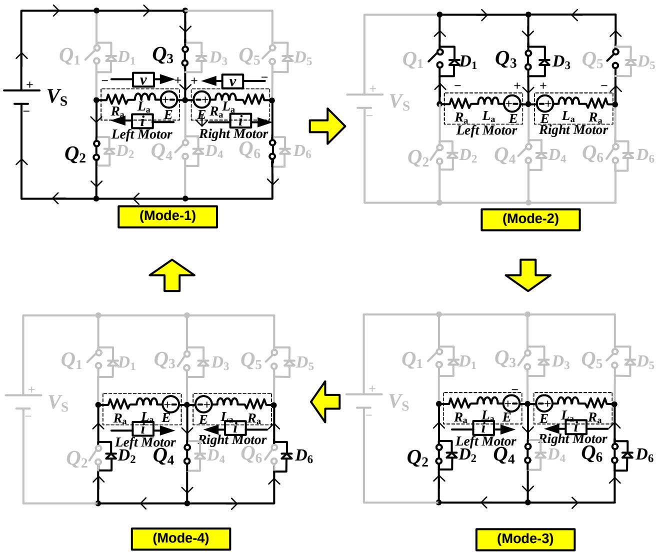
1) All devices are ideal;
2) Constant switch duty cycle;
3) The electrical parameters of two DC motors are equal.

Where, V_S is the input power supply voltage, V_{ML} is the voltage at the left motor, V_{MR} is the voltage at the right motor, I_{ML} is the current at the left motor, I_{MR} is the current at the right motor, D_{S1}, D_{S2}, D_{S3}, D_{S4}, D_{S5} and D_{S6} is the duty circle for Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6, respectively. T_{S1}, T_{S2}, T_{S3}, T_{S4}, T_{S5} and T_{S6} is the time period of switching frequency of Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6, respectively. Figure 4(a) shows the operating mode of the forward motion. The key operational waveforms of this mode are shown in Fig. 4(b).

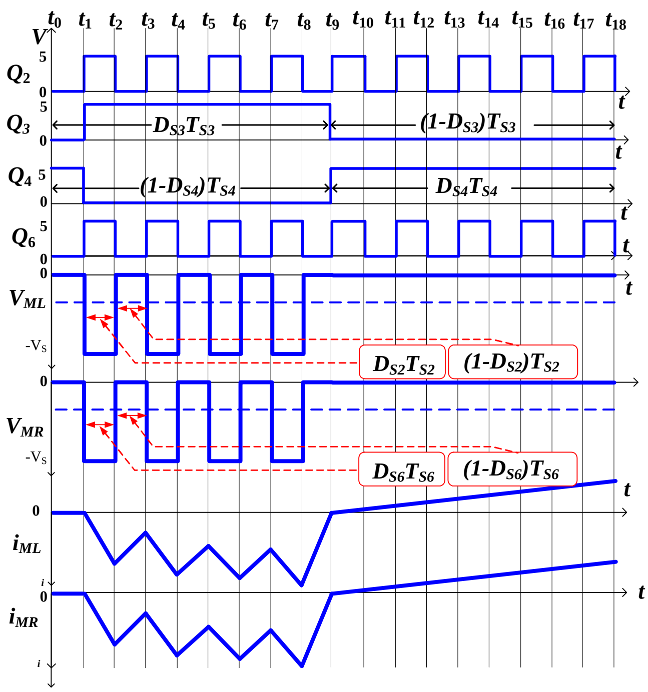


(a) (b)

Fig. 4. Forward operation (a) current paths (b) key operational waveforms



(a)



(b)

Fig. 5. Backward operation (a) current paths (b) key operational waveforms

1) Mode 1 (t_1-t_2, t_3-t_4, t_5-t_6 *and* t_7-t_8): The main switch (Q1, Q_4 and Q_5) are turned onQ_2, Q_3 and Q_6) are turned off, the current from power source flows to the left and right motor to move wheelchair goes forward. Both current and voltage amplitude of two motors are positive.

2) Mode 2 (t_0-t_1, t_2-t_3, t_4-t_5, t_6-t_7 *and* t_8-t_9): The main switch Q_4 is still turned on and (Q_1, Q_2, Q_3, Q_5 and Q_6) are turned off. The freewheeling effect is occurred. D_1 and Q_3 (for left motor) D_5 and Q_3 (for right motor) conduct the armature current and then the armature current beings to decrease until mode 1 is started again.

3) Mode 3(t_9-t_{10}, t_{11}-t_{12}, t_{13}-t_{14}, t_{15}-t_{16} *and* t_{17}-t_{18}): The main switch Q_4 is turned on and (Q_1, Q_2, Q_3, Q_5 and Q_6) are turned off. The freewheeling effect is occurred. D_2 and Q_4 (for left motor) D_6 and Q_4 (for right motor) conduct the armature current and then the armature current beings to decrease until mode 1 is started again.

4) Mode 4(t_{10}-t_{11}, t_{12}-t_{13}, t_{14}-t_{15} *and* t_{16}-t_{17}): Q_4 is still turned. on. This mode operation is similar to Mode 4

Fig. 5(a) shows the operating mode of backward motion. The key operational waveforms of this mode are illustrated in Fig. 5(b).

5) Mode 1 (t_1-t_2, t_3-t_4, t_5-t_6 *and* t_7-t_8): The main switch (Q_2, Q_3 and Q_6) are turned on, Q_1, Q_4 and Q_5 are turned off, the current from power source flows to the left and right motor to move wheelchair goes backward. Both current and voltage amplitude of two motors are negative.

6) Mode 2 (t_0-t_1, t_2-t_3, t_4-t_5, t_6-t_7 *and* t_8-t_9): The main switch Q_3 is still turned on and Q_1, Q_2, Q_4, Q_5 and Q_6 are turned off. The freewheeling effect is occurred. $D_1$and Q_3 (for left motor) $D_5$and Q_3 (for right motor) conducts the armature current and then the armature current beings to decrease until mode 1 is started again.

7) Mode 3 (t_9-t_{10}, t_{11}-t_{12}, t_{13}-t_{14}, t_{15}-t_{16} *and* t_{17}-t_{18}): The main switching devices Q_2, Q_4 and Q_6 are turned on. The armature current of left side motor flows in the loop consisted of L_a, R_a, D_2 and Q_4. The armature current of left side motor flows in the loop consisted of L_a, R_a, D_6 and Q_4.

8) Mode 4 (t_{10}-t_{11}, t_{12}-t_{13}, t_{14}-t_{15} *and* t_{16}-t_{17}): The main switch Q_4 is still turned on and Q_1, Q_2, Q_3, Q_5 and Q_6 are turned off. Although Q1 andQ_5 are off, the operation of this mode is similar to Mode 4.

Besides two modes, there are the other modes operations as shows in table 2. Only two basics mode operating are deeply discussed because its can cover of all modes. For example, in pivot left turn operation, the left side motor is operated for backward motion but the right side motor is operated for forward motion. The result is, the wheelchair moves around its in counter-clockwise direction.

In the table 1, it is shown that the proposed circuit is capable of producing positive or negative voltages across the DC motor, whilst delivering current to the motor in either direction. The disadvantage point of this topology is occurred in pivot operation. Because of the switching operation of Q_3 and Q_4 is complementary with a 50-% duty cycle. It is called "Time Sharing Technique". There for, the output voltage of this chopper will be half of the inherent rated value. The left or right turn mode operational condition is to operate only one motor. However, in order to obtain smooth turning operation, both of two motor much be operated as the same direction but one of each other is operate by lower speed than each one.

Table 2. Summarize of all operational modes condition

Mode	Condition	(Left motor voltage) $\overline{V}_{ML}$		(Right motor voltage) $\overline{V}_{MR}$	
		Proposed chopper	Proposed chopper with boost function	Proposed chopper	Proposed chopper with boost function
Stop	$V_{ML}=V_{MR}=0$	0	0	0	0
Forward	$+V_{ML}=+V_{MR}$	$D_{S1}D_{S4}V_B$	$D_{S1}D_{S4}\frac{V_B}{(1-D_{S4})}$	$D_{S5}D_{S4}V_B$	$D_{S5}D_{S4}\frac{V_B}{(1-D_{S4})}$
Backward	$-V_{ML}=-V_{MR}$	$-D_{S2}D_{S3}V_B$	$-D_{S2}V_B$	$-D_{S6}D_{S3}V_B$	$-D_{S6}V_B$
Pivot left turn	$-V_{ML},+V_{MR}$	$-D_{S2}D_{S3}V_B$	$-D_{S2}V_B$	$D_{S5}D_{S4}V_B$	$D_{S5}D_{S4}\frac{V_B}{(1-D_{S4})}$
Pivot right turn	$+V_{ML},-V_{MR}$	$D_{S1}D_{S4}V_B$	$D_{S1}D_{S4}\frac{V_B}{(1-D_{S4})}$	$-D_{S6}D_{S3}V_B$	$-D_{S6}V_B$
Left turn(Forward)	$0\le +V_{ML}<+V_{MR}$	$0\le D_{S1}D_{S4}V_B<D_{S5}D_{S4}V_B$	$0\le D_{S1}D_{S4}\frac{V_B}{(1-D_{S4})}<D_{S5}D_{S4}\frac{V_B}{(1-D_{S4})}$	$D_{S5}D_{S4}V_B$	$D_{S5}D_{S4}\frac{V_B}{(1-D_{S4})}$
Right turn(Forward)	$0\le +V_{MR}<+V_{ML}$	$D_{S1}D_{S4}V_B$	$D_{S1}D_{S4}\frac{V_B}{(1-D_{S4})}$	$0\le D_{S5}D_{S4}V_B<D_{S1}D_{S4}V_B$	$0\le D_{S5}D_{S4}\frac{V_B}{(1-D_{S4})}<D_{S1}D_{S4}\frac{V_B}{(1-D_{S4})}$
Left turn(Backward)	$-V_{MR}<-V_{ML}\le 0$	$-D_{S6}D_{S3}V_B<-D_{S2}D_{S3}V_B\le 0$	$-D_{S6}V_B<-D_{S2}V_B\le 0$	$-D_{S6}D_{S3}V_B$	$-D_{S6}V_B$
Right turn(Backward)	$-V_{ML}<-V_{MR}\le 0$	$-D_{S2}D_{S3}V_B$	$-D_{S2}V_B$	$-D_{S2}D_{S3}V_B<-D_{S6}D_{S3}V_B\le 0$	$-D_{S2}V_B<-D_{S6}\ V_B\le 0$

(3.2) Proposed Three-Leg Full-Bridge Chopper With Voltage Boost Function

This section describes the proposed tree-leg full-bridge chopper with voltage boost function. The two basic operation modes are discussed. The first one is the forward motion and the second one is the backward motion. The basic operation is similar to the proposed circuit in previous section but this circuit topology is incorporated voltage boost circuit. The main equivalent operation modes of forward motion are shown in Fig. 6, and described as follows.

1) Mode 1 (t_0-t_1): The main switch Q_4 is turned on while Q_1, Q_2, Q_3, Q_5 and Q_6 are off. The inductor current increases linearity with a slope V_S/L_B. The inductor current flows in the loop consisted of V_S, L_B, D_B and Q_4.

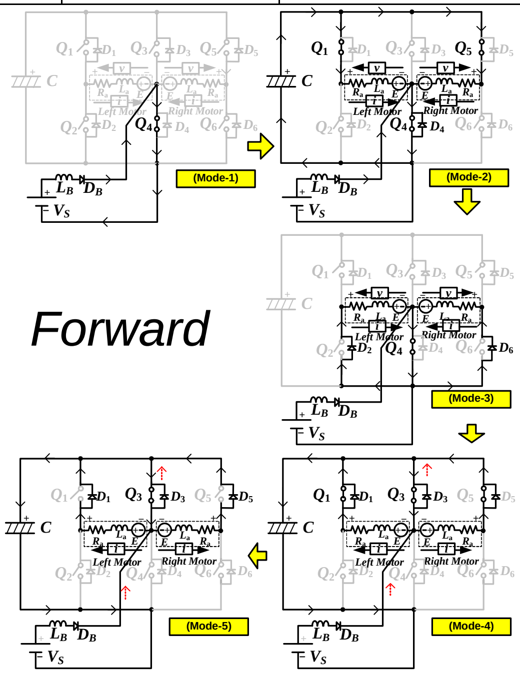
2) Mode 2 (t_1-t_2, t_3-t_4, t_5-t_6 *and* t_7-t_8): The main switch Q_1, Q_4 and Q_5 are turned on, Q_2, Q_3 and Q_6 are turned off, the current from capacitor C flows to the left and right motor to move wheelchair goes forward. The switching operation of Q_4 allows voltage boost action and provides current flows through the two DC motors at the same time. Both current and voltage amplitude of two motors are positive.

3) Mode 3 (t_2-t_3, t_4-t_5, t_6-t_7 *and* t_8-t_9): The main switch Q_4 is still turned on and Q_1, Q_2, Q_3, Q_5 and Q_6 are turned off. The freewheeling effect is occurred. The switching operation of Q_4 is on for voltage boost action which is similar to Mode 1.

4) Mode 4 (t_9-t_{10}, t_{11}-t_{12}, t_{13}-t_{14}, t_{15}-t_{16} *and* t_{17}-t_{18}): The main switching devices Q_2, Q_3 and Q_6 are turned on. The inductor L_B acts as a current source and continues to charge the capacitor C through D_3. At the same time, the armature current of left side motor flows in the loop consisted of L_a, R_a, D_1 and Q_3. The armature current of left side motor flows in the loop consisted of L_a, R_a, D_5 and Q_3.

5) Mode 5 (t_{10}-t_{11}, t_{12}-t_{13}, t_{14}-t_{15} *and* t_{16}-t_{17}): The main switch Q_3 is still turned on and Q_1, Q_2, Q_4, Q_5 and Q_6 are turned off. Although Q1 and Q_5 are off, the operation of this mode is similar to Mode 4.

The average voltage of the left and right side motor are determined by equation in the table 1. It is shown that the circuit has capable to boost voltage even though the power source voltage varies.



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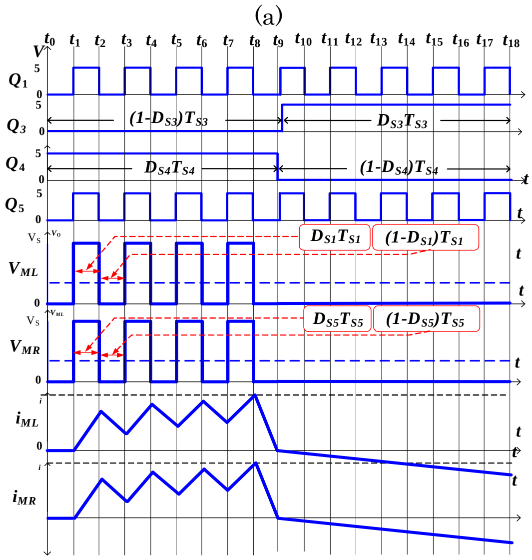
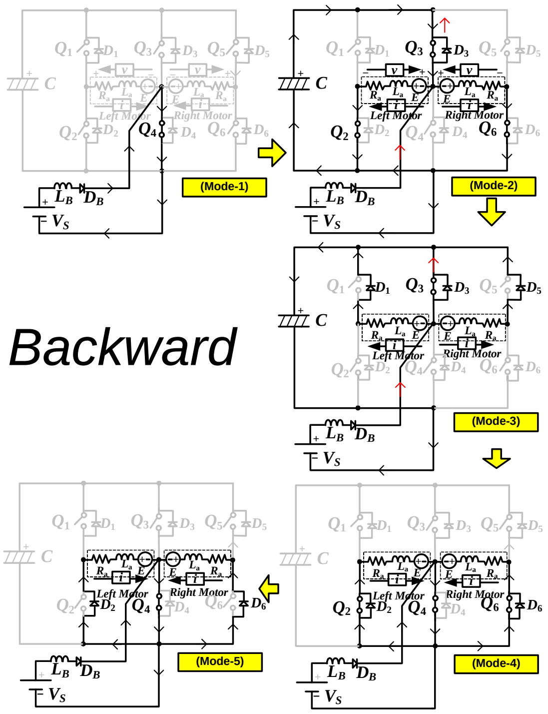


(b)

Fig. 6. Forward operation (a) current paths (b) key operational waveforms



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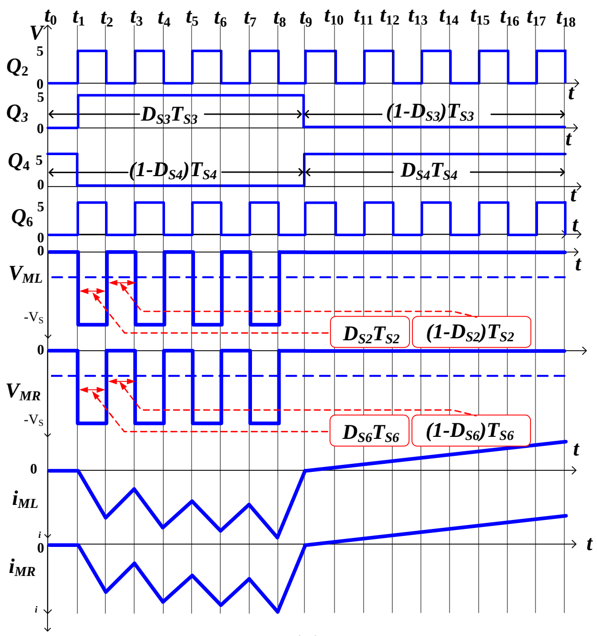


(b)

Fig. 7. Backward operation (a) current paths (b) key operational waveforms

Table 3. Electrical parameters of prototype

Voltage of power supply	24 V
Switching frequency (Q_1, Q_2 , Q_5, Q_6)	10 kHz
Switching frequency (Q_3, Q_4)	1 kHz
Capacitor C	3600uF, 350 V
Rated power of DC motors	60 W
Rated voltage of DC motors	24 V
Inductor L_B	0.5mH

Fig. 5(a) shows the operating mode of backward motion. The operating key wave form of this mode is illustrated in Fig. 5(b).

6) Mode 1 (t_0-t_1): The main switch Q_4 is turned on while Q_1, Q_2, Q_3, Q_5 and Q_6 are off. The inductor current increases linearity with a slope V_S/L_B.

7) Mode 2 (t_1-t_2, t_3-t_4, t_5-t_6 *and* t_7-t_8): The main switch Q_2, Q_3 and Q_6 are turned on, Q_1, Q_4 and Q_5 are turned off, the current from negative pole of capacitor C flows to the left and right motor to move wheelchair goes backward. Both current and voltage amplitude of two motors are negative.

8) Mode 3 (t_2-t_3, t_4-t_5, t_6-t_7 *and* t_8-t_9): The main switch Q_3 is still turned on and Q_1, Q_2, Q_4, Q_5 and Q_6 are turned off. The freewheeling effect is occurred. This mode is similar to Mode 4 of forward operation.

9) Mode 4 (t_9-t_{10}, t_{11}-t_{12}, t_{13}-t_{14}, t_{15}-t_{16} *and* t_{17}-t_{18}): The main switching devices Q_2, Q_4 and Q_6 are turned on. The inductor current increases linearity with a slope V_S/L_B. At the same time, the armature current of left side motor flows in the loop consisted of L_a, R_a, D_2 and Q_4. The armature current of left side motor flows in the loop consisted of L_a, R_a, D_6 and Q_4.

10) Mode 5 (t_{10}-t_{11}, t_{12}-t_{13}, t_{14}-t_{15} *and* t_{16}-t_{17}): The main switch Q_4 is still turned on and Q_1, Q_2, Q_3, Q_5 and Q_6 are turned off. Although Q1 and Q_5 are off, the operation of this mode is similar to Mode 4.

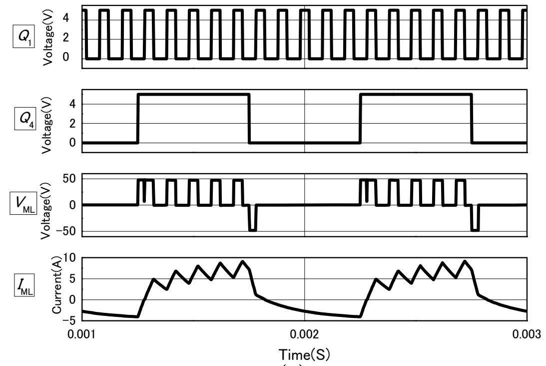
The same as the previously circuit topology, there are the other modes as shown in table 2. It is shown that the two proposed topologies are capable of producing positive or negative voltages across the DC motor, whilst delivering current to the motor in either direction.

4. Computer Simulation and Experimental Results

In order to verify the theoretical analysis and design of the previous sections, simulations and experiments have been done. The parameters used are listed in Table 3.

4.1 Simulation Results Fig. 8(a) shows the simulated waveforms of forward motion. Q_1 and Q_5 are operated at 10 kHz and Q_4 at 1 kHz with 50-% duty cycle. Fig. 8 (b) illustrates the simulated waveforms in backward motion, Q_2 and Q_6 are operated at 10 kHz and Q_4 at 1 kHz with 50-% duty cycle. For both of output current of forward and backward motion, they show those continuous current modes are achieved during on time period of Q_4 and Q_3, respectively. Fig. 9(a) and (b) show the simulated waveform of the proposed chopper with voltage boost function for forward and backward operation, respectively.

4.2 Experimental Results Fig. 10 (a) and (b) show the experimental waveforms of proposed chopper circuit. Fig. 10(a) illustrates the gate signal of Q_1 and Q_4, voltage and current waveforms of left side motor in forward motion. Fig. 10(b) illustrates the gate signals of Q_2 and Q_3, voltage and current waveforms of left side motor in forward motion. The experimental implementation of the proposed chopper with voltage boost function will be conducted in future work.



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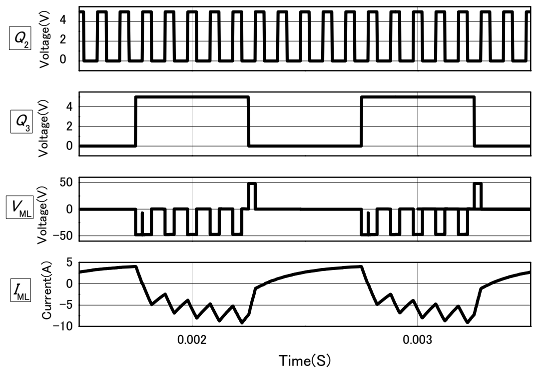
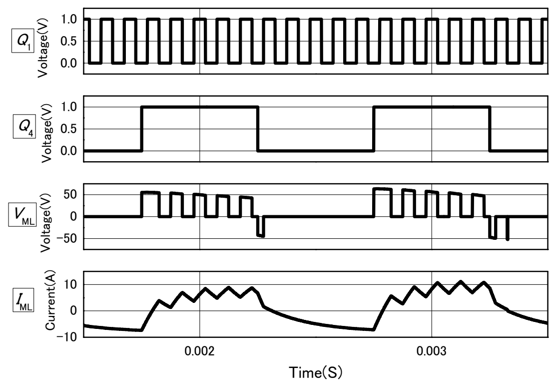


(b)

Fig. 8. Simulated waveforms of proposed chopper
(a) Forward motion (b) Backward motion



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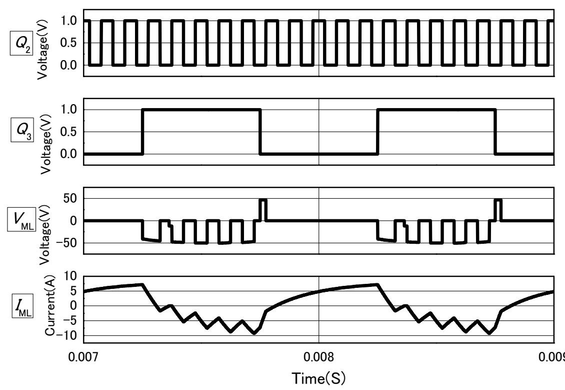
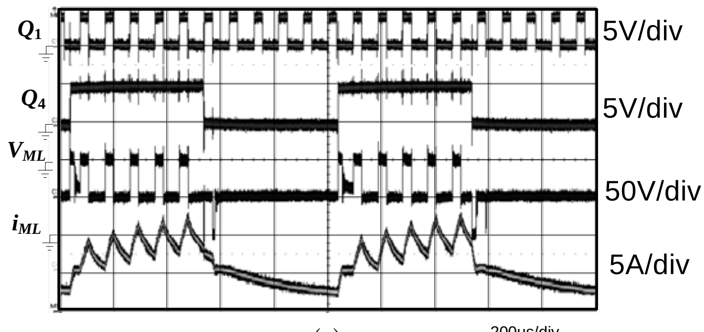


(b)

Fig. 9. Simulated waveforms of proposed chopper
with voltage boost function
(a) Forward motion(b) Backward motion



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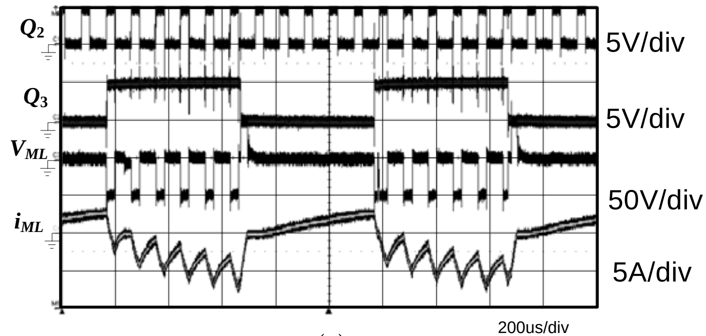

(b)

Fig. 10. Experimental waveforms of proposed chopper
(a) Forward motion (b) Backward motion

It can be seen that the simulated and experimental results are in close agreement with the above theoretical analysis.

5. Conclusion

In this paper, the new DC chopper to drive independent two DC motors was proposed. The proposed power circuit consists of three-leg full-bridge chopper, which has advantage over conventional circuit configuration in the reduced counts of the switching devices. In addition, the proposed three-leg configuration incorporates the voltage boost function of the power source. This function compensates for the reduced voltages applied to the motors. This circuit configuration can be applied to not only electric wheelchairs but also other traction systems that require multiple pairs of DC motors.

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