Four-quadrant Zero-current-transition Converter-fed Dc Motor Drives for Electric Propulsion

T. W. Ching

Department of Electromechanical Engineering, University of Macau, twching@umac.mo

Abstract
In this paper, a new four-quadrant (4Q) soft-switching converter for dc motor drives, namely the 4Q zero-current-transition (4Q-ZCT) converter, with the capabilities of 4Q power flow, and ZCT switching profile for dc motor drives is proposed. It has some definite advantages over their hard-switching counterparts and other soft-switching converters. Both the turn-on and turn-off losses of main switches are significantly reduced, while the auxiliary switches can always operate with zero-current-switching (ZCS). It possesses the advantages of reduced switching stresses, minimum voltage and current stresses as well as minimum circulating energy during both the motoring and regenerating modes. It also offers simple circuit topology, minimum component count and low cost.

Keywords
soft-switching, zero-current-transition, dc motor drives

1. INTRODUCTION
Recently, a number of soft-switching techniques, providing zero-voltage-switching (ZVS) or zero-current-switching (ZCS) condition, have been successfully developed for switched-mode power supplies (SMPS) [Canesin and Barbi, 1997; Chau, 1994; Mao et al., 1997; Wei and Ioinovici, 1998; Zhang and Sen, 2003]. A general assumption is that converters for SMPS can be directly applied to dc motor drives. However, unlike SMPS, dc motor drives, especially those used in electric railways and battery-powered electric vehicles, desire frequent regenerative braking. During braking, the dc motor operates as a generator to convert kinetic energy into electrical energy, and the converter must allow for backward power flow to restore the electrical energy to the power network or battery system. Thus, the incorporation of soft-switching into regenerating braking is particularly desirable for electric railways and battery-powered electric vehicles.

A two-quadrant (2Q) dc chopper (see Figure 1 (a)) is preferred as it converts battery dc voltage to variable dc voltage during the motoring mode and revert the power flow during regenerative braking. Furthermore, 4Q dc choppers (see Figure 1 (b)) are employed for reversible and regenerative speed control of dc motors. Instead of using mechanical contactors to achieve reversible operation, the 4Q dc chopper can be employed so that motoring and regenerative braking in both forward and reversible operations are controlled electronically. Both 2Q and 4Q dc choppers are shown in Figure 2.

Recently, two 2Q soft-switching dc-dc converters have purposely developed, namely the 2Q zero-voltage transition (2Q-ZVT) converter [Chau et al., 1999], and the 2Q-ZCT converter [Ching et al., 2001] for dc motor drives, which possess the advantages of high efficiency for both motoring and regenerative braking.

Very recently, a 4Q-ZVT converter has been developed for dc motor drives [Ching, 2005]. It possesses the advantages that all main transistors and rectifiers can switch with ZVS and unity device stresses during both the motoring and regenerating modes of operation.

Following the spirit of previous development on the 4Q-ZVT converter, the purpose of this paper is to propose a new 4Q-ZCT converter for dc motor drives. Differing from the 4Q-ZVT converter, this 4Q-ZCT converter takes the role to be particularly useful for those high-
power dc motor applications, employing the IGBT as power devices, which generally suffer from diode reverse recovery during turn-on and severe inductive turn-off switching losses. It also possesses the advantages of high efficiency for both motoring and regenerative braking, as well as minimum voltage and current stresses. Its principle of operation, computer simulation and experimental results will be given.

2. PROPOSED 4Q-ZCT CONVERTER

Figure 3 shows the schematic diagram of the proposed 4Q-ZCT converter for dc motor drives. To achieve ZCS operation, two resonant tanks are required. Firstly, a resonant inductor $L_a$, resonant capacitor $C_a$, auxiliary switches $S_a$ and $S_a'$ are added to allow for soft switching $S_1$ and $S_4$. Secondly, resonant inductor $L_b$, resonant capacitor $C_b$, auxiliary switches $S_b$ and $S_b'$ are added to allow for soft switching $S_2$ and $S_3$. The dc motor can be considered to be simultaneously fed by two 2Q-ZCT converters.

The proposed ZCT converter operates in four modes (Figure 1(b)):
- Forward motoring mode (Figures 4 to 6),
- Forward regenerating mode (Figures 7 to 9),
- Reverse motoring mode (Figures 10 to 12), and
- Reverse regenerating mode (Figures 13 to 15).

Their corresponding equivalent circuits and operating waveforms are shown in Figures 4 to 15. It can be found that all equivalent circuits involve nine operating stages (S1 to S9) within one switching cycle.

2.1 Forward motoring operation of ZCT converter (see Figures 4 to 6)

(a) Stage 1 [$T_0$-$T_1$]: $S_a$ and $S_b$ are turned on with ZCS at $T_0$. $L_a$, $C_a$ and $L_b$, $C_b$ start resonating. $i_{L_a}$ increases from zero to peak, then decreases towards zero, ($i_{L_b}$ decreases from zero to negative peak, then increases towards zero) and then change their direction. This stage finishes at $T_1$ when $i_{L_a}$ and $i_{L_b}$ reach zero.
(b) Stage 2 [$T_1$-$T_2$]: $S_a$ and $S_b$ are turned off while $S_1$ and $S_2$ are turned on with ZCS at $T_1$. The current of $D_3$ and $D_4$ are directed to the auxiliary circuit. $i_{L_a}$ increases ($i_{L_b}$ decreases) rapidly towards zero. This stage finishes at $T_2$ when $i_{L_a}$ and $i_{L_b}$ reach zero.
(c) Stage 3 [$T_2$-$T_3$]: Since $i_{L_a}$ becomes positive ($i_{L_b}$ becomes negative) at $T_2$, $D_3$ and $D_4$ are off while $D_1$ and $D_2$ become on. $L_a$, $C_a$, and $L_b$, $C_b$ continue resonating. When $i_{L_a}$ and $i_{L_b}$ return to zero at $T_3$, $D_2$ and $D_4$ turn off naturally.
(d) Stage 4 [$T_3$-$T_4$]: It is a forward powering stage. $V_g$ is directly connected to the $I_1$ via $S_1$ and $S_2$.
(e) Stage 5 [$T_4$-$T_5$]: $S_a$ and $S_b$ are turned on with ZCS. $L_a$, $C_a$, and $L_b$, $C_b$ start resonating. $i_{L_a}$ increases from zero to peak, then decreases towards zero ($i_{L_b}$ decreases from zero to negative peak, then increases towards zero), and then change their direction. When they reach $-I_1$ and $I_1$ respectively at $T_5$, $D_a$ and $D_b$ become on.
(f) Stage 6 [$T_5$-$T_6$]: $S_1$ and $S_2$ are turned off with ZCS at $T_5$. As $i_{L_a}$ keeps decreasing, its negative surplus flows
through D1 (\(i_{Lb}\) keeps increasing, its surplus flows through D2). At \(T_6\), \(i_{La}\) and \(i_{Lb}\) swing back to \(-I_1\) and \(I_1\) respectively, D1 and D2 stop conducting.

(g) Stage 7 \([T_6-T_7]\): \(i_{La}\) keeps at \(-I_1\) and \(v_{Ca}\) is linearly discharged towards zero, while \(i_{Lb}\) keeps at \(I_1\) and \(v_{Cb}\) is linearly discharged towards zero. This stage ends at \(T_7\) when \(v_{Ca}\) and \(v_{Cb}\) reach zero.

(h) Stage 8 \([T_7-T_8]\): At \(T_7\), D3 and D4 start to conduct. \(La\), \(Ca\) and \(Lb\), \(Cb\) resonate again and \(i_{La}\) and \(i_{Lb}\) reach zero at \(T_8\).

(i) Stage 9 \([T_8-T_9]\): \(I_1\) is freewheeling via D3 and D4.

### 2.2 Forward regenerating (braking) operation of ZCT converter (see Figures 7 to 9)

(a) Stage 1 \([T_0-T_1]\): \(S_s\) is turned on with ZCS. \(L_a\) and \(C_a\) start resonating. When \(i_{La}\) decreases from zero to negative peak, then increases towards zero, and then changes its direction. \(i_{La}\) reaches \(I_2\) at \(T_1\) and D1 becomes off.

(b) Stage 2 \([T_1-T_2]\): Both \(S_s\) is turned off with ZCS and \(S^4\) is turned on with ZCS at \(T_1\). \(i_{La}\) decreases towards zero. This stage finishes at \(T_2\) when \(i_{La}\) reaches zero.

(c) Stage 3 \([T_2-T_3]\): Since \(i_{La}\) becomes negative at \(T_2\). The antiparallel diode of \(S_s\) is off while D1 becomes on. \(L_a\) and \(C_a\) continue resonating. \(i_{La}\) returns to zero while D4 is turned off naturally at \(T_3\).

(d) Stage 4 \([T_3-T_4]\): \(I_2\) is freewheeling via \(S_s\).

(e) Stage 5 \([T_4-T_5]\): \(S_s\) is turned on with ZCS. \(L_a\) and \(C_a\) start resonating. \(i_{La}\) decreases from zero to negative peak, then increases towards zero, and then changes its direction. When it reaches \(I_2\) at \(T_5\), D3 becomes on.

(f) Stage 6 \([T_5-T_6]\): \(S_s\) is turned off with ZCS at \(T_5\). \(i_{La}\) keeps increasing, its surplus flows through D4. At \(T_6\), \(i_{La}\) swings back to \(I_1\) and D4 stops conducting.

(g) Stage 7 \([T_6-T_7]\): \(i_{La}\) keeps at \(I_2\) and \(v_{Ca}\) is linearly discharged towards zero. This stage ends at \(T_7\) when \(v_{Ca}\) reaches zero.

(h) Stage 8 \([T_7-T_8]\): At \(T_7\), D1 starts to conduct. \(L_a\) and \(C_a\) resonate again and \(i_{La}\) reaches zero at \(T_8\).

(i) Stage 9 \([T_8-T_9]\): It is a regenerating stage via D1 and D2.

---

**Fig. 6** Nine topological stages during forward motor-ing mode

**Fig. 7** Equivalent circuit during forward regenerating (braking) mode

**Fig. 8** Key waveforms during forward regenerating (braking) mode

**Fig. 9** Nine topological stages during forward regenerating (braking) mode
2.3 Reverse motoring operation of ZCT converter (see Figures 10 to 12)

(a) Stage 1 \([T_0-T_1]\): \(S_a'\) and \(S_b'\) are turned on with ZCS at \(T_0\). \(L_a\), \(C_a\) and \(L_b\), \(C_b\) start resonating. \(i_{La}\) decreases from zero to negative peak, then increases towards zero, \(i_{Lb}\) increases from zero to peak, then decreases towards zero) and then changes their direction. This stage finishes at \(T_1\) when \(i_{La}\) reaches \(I_3\) (\(i_{Lb}\) reaches \(-I_3\)) so that \(D_1\) and \(D_2\) become off.

(b) Stage 2 \([T_1-T_2]\): \(S_a'\) and \(S_b'\) are turned off while \(S_3\) and \(S_4\) are turned on with ZCS at \(T_1\). The current of \(D_1\) and \(D_2\) are directed to the auxiliary circuit. \(i_{La}\) decreases (\(i_{Lb}\) increases) rapidly towards zero. This stage finishes at \(T_2\) when \(i_{La}\) and \(i_{Lb}\) reach zero.

(c) Stage 3 \([T_2-T_3]\): Since \(i_{La}\) becomes negative (\(i_{Lb}\) becomes positive) at \(T_2\). \(D_a'\) and \(D_b'\) are off while \(D_a\) and \(D_b\) become on. \(L_a\), \(C_a\) and \(L_b\), \(C_b\) continue resonating. When \(i_{La}\) and \(i_{Lb}\) return to zero at \(T_3\), \(D_a\) and \(D_b\) turn off naturally.

(d) Stage 4 \([T_3-T_4]\): It is a reverse powering stage. \(V_g\) is directly connected to the \(I_3\) via \(S_3\) and \(S_4\).

(e) Stage 5 \([T_4-T_5]\): \(S_a'\) and \(S_b'\) are turned on with ZCS. \(L_a\), \(C_a\) and \(L_b\), \(C_b\) start resonating. \(i_{La}\) decreases from zero to negative peak, then increases towards zero (\(i_{Lb}\) from zero to peak, then decreases towards zero), and then change their direction. When they reach \(I_3\) and \(-I_3\) respectively at \(T_5\), \(D_a'\) and \(D_b'\) become on.

(f) Stage 6 \([T_5-T_6]\): \(S_3\) and \(S_4\) are turned off with ZCS at \(T_5\). As \(i_{La}\) keeps increasing, its surplus flows through \(D_3\) (\(i_{Lb}\) keeps decreasing, its surplus flows \(D_4\)). At \(T_6\), \(i_{La}\) and \(i_{Lb}\) swing back to \(I_3\) and \(-I_3\) respectively, \(D_3\) and \(D_4\) stop conducting.

(g) Stage 7 \([T_6-T_7]\): \(i_{La}\) keeps at \(I_3\) and \(v_{Ca}\) is linearly discharged towards zero, while \(i_{Lb}\) keeps at \(-I_3\) and \(v_{Cb}\) is linearly discharged towards zero. This stage ends at \(T_7\) when \(v_{Ca}\) and \(v_{Cb}\) reach zero.

(h) Stage 8 \([T_7-T_8]\): At \(T_7\), \(D_1\) and \(D_2\) start to conduct. \(L_a\), \(C_a\) and \(L_b\), \(C_b\) resonate again and \(i_{La}\) and \(i_{Lb}\) reach zero at \(T_8\).

(i) Stage 9 \([T_8-T_9]\): \(I_3\) is freewheeling via \(D_1\) and \(D_2\).

2.4 Reverse regenerating (braking) operation of ZCT converter (see Figures 13 to 15)

(a) Stage 1 \([T_0-T_1]\): \(S_b\) is turned on with ZCS at \(T_0\). \(L_b\) and \(C_b\) start resonating. \(i_{Lb}\) decreases from zero to negative peak, then increases towards zero and then changes its direction. This stage finishes at \(T_1\) when \(i_{Lb}\) reaches \(I_4\) so that \(D_3\) become off.

(b) Stage 2 \([T_1-T_2]\): \(S_b\) is turned off while \(S_1\) is turned on with ZCS at \(T_1\). The current of \(D_3\) is directed to the auxiliary circuit. \(i_{Lb}\) decreases rapidly towards zero. This stage finishes at \(T_2\) when \(i_{Lb}\) reach zero.

(c) Stage 3 \([T_2-T_3]\): Since \(i_{Lb}\) becomes negative at \(T_2\), \(D_3\) is off while \(D_3\) become on. \(L_b\) and \(C_b\) continue resonating. When \(i_{Lb}\) return to zero at \(T_3\), \(D_3\) turn off naturally.
(d) Stage 4 \([T_4-T_5]\): It is freewheeling stage.
(e) Stage 5 \([T_5-T_6]\): \(S_b\) is turned on with ZCS. \(L_b\) and \(C_b\) start resonating. \(i_{lb}\) decreases from zero to negative peak, then increases towards zero, and then change its direction. When it reaches \(I_4\) at \(T_5\), \(D_b\) becomes on.
(f) Stage 6 \([T_6-T_7]\): \(S_a\) is turned off with ZCS at \(T_6\). As \(i_{lb}\) keeps increasing, its surplus flows through \(D_2\). At \(T_6\), \(i_{lb}\) swing back to \(I_4\), \(D_2\) stop conducting.
(g) Stage 7 \([T_7-T_8]\): \(i_{lb}\) keeps at \(I_4\) and \(v_{cb}\) is linearly discharged towards zero. This stage ends at \(T_7\) when \(v_{cb}\) reaches zero.
(h) Stage 8 \([T_8-T_9]\): At \(T_8\), \(D_3\) starts to conduct. \(L_b\) and \(C_b\) resonate again and \(i_{lb}\) reach zero at \(T_9\).
(i) Stage 9 \([T_9-T_{10}]\): It a reverse regenerating stage. \(V_g\) is directly connected to \(I_4\) via \(D_3\) and \(D_4\).

3. SIMULATION AND VERIFICATION

Different modes of operation of the proposed 4Q-ZCT converter are PSpice-simulated. The corresponding results are shown in Figures 16 to 19.

Figure 16 shows the simulated waveforms of the proposed converter operating in the forward motoring mode. Both \(S_a\) and \(S_b\) are switched together to allow soft switching \(S_1\) and \(S_2\).

Figure 17 shows the simulated waveforms of the proposed converter operating in the forward regenerating (braking) mode. Both \(S_a\) and \(S_b\) are switched together to allow soft switching \(S_1\) and \(S_2\).
Figure 18 shows the operating waveforms of the 4Q-ZCT converter operating in reverse motoring mode. Both $S_a$ and $S_b$ are switched together to allow soft switching $S_3$ and $S_4$.

Operating waveforms of the proposed converter operating in reverse regenerating (braking) mode is shown in Figure 19.

The simulation results agree with those theoretical waveforms. The main and auxiliary switches can always maintain ZCS with minimum current and voltage stresses. To verify the theoretical results, the 4Q-ZCT converter is hardware prototyped as shown in Figure 20.

From the experimental waveforms shown in Figures 21 and 22, they also closely agree with those theoretical waveforms, the auxiliary switches can always maintain ZCS operation. The main switches can maintain ZCS during turn-on and turn-off. The resonant inductor current will be attenuated by the losses in the resonant tank, but still be very close to the load current. The turn-on loss is significantly reduced by lowering the rise rate of diode reverse recovery.

To illustrate the gain in efficiency of the proposed converter, the efficiencies with and without using ZCT for both motoring and regenerating modes are plotted in Figure 23. The auxiliary resonant branches are removed to compare the performance of the proposed converter, the circuit efficiency is improved by 2-4% and 1-3% for motoring and regenerating modes respectively. Moreover, as shown in Figure 23, the measured efficiency ($\eta$) of the proposed converter is quite high, ranging from 87% to 96%. It should be noted that the IGBT main switches fail to work under hard-switching, due to the voltage over-shoot and subsequent thermal breakdown, when motoring over 400W. It indicates that the proposed ZCT circuit can effectively extend the operating range of the converter.
4. CONCLUSION
The principle of operation, characteristics, computer simulation and experimental results of a novel 4Q-ZCT converter for dc motor drives has been presented. It possesses some definite advantages: both turn-on and turn-off losses of main switches are significantly reduced, the auxiliary switches can always achieve ZCS, while the corresponding device voltage and current stresses are kept minimum. Moreover, the proposed converter provides reduced switching losses and stresses, minimum voltage and current stresses, minimum circulating energy, simple circuit topology and low cost, leading to achieve high power density and high efficiency. Other key features are the use of the same resonant tank for both forward and backward power flows and the full utilization of all diodes of the power switch packages, thus minimizing the overall hardware count and cost.

References