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A Novel Two-Quadrant Zero-Current-Transition Converter for DC Motor Drives

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Abstract – A novel two-quadrant (2Q) zero-current-transition (ZCT) converter with the capabilities of 2Q power flow, and ZCT switching profile for DC motor drives is presented. It possesses the advantages that both the main and auxiliary switches can operate with zero-current switching (ZCS), reduced switching losses and stresses, minimum voltage and current stresses as well as minimum circulating energy during both the motoring and regenerating modes. This converter is particularly useful for DC traction systems in which both motoring and regenerative braking are desired to have high efficiency.

I. INTRODUCTION

Nowadays, the use of low-inductance DC motors is becoming attractive because of the advantages of higher power density, lower rotor inertia, smoother commutation and lower manufacturing costs. However, it usually suffers from high current ripples, resulting in increased losses and switching stresses. To alleviate this problem, the switching frequency of power converters needs to be increased from less than one to over one hundred kilohertz. With available power devices technologies, hard-switching PWM converters operating at such high frequencies impose high switching losses and switching stresses.

Recently, a number of soft-switching techniques, providing zero-voltage switching (ZVS) or zero-current switching (ZCS) conditions, have been successfully developed for switched-mode power supplies (SMPS) [1]-[5]. Surprisingly, the development of soft-switching converters for DC motor drives has been very little. Even so, it has been assumed that those being developed for SMPS can be directly applicable. Until recently, a systematic evaluation of available soft-switching converters for DC motor drives has been carried out [6], [7]. As a result, these soft-switching converters cannot satisfy the operating requirements of DC motor drives. Apart from suffering excessive voltage and current stresses, they cannot handle bidirectional power flow during regenerative braking.

Different to SMPS, DC motor drives especially for traction applications need regenerative braking. Technically, the DC motor operates as a generator to convert the kinetic energy into the electrical energy while the converter must allow for bidirectional power flow to restore the energy to the power networks or battery systems. This energy-recovery feature is particularly attractive to electric railways and battery-powered electric vehicles.

II. TWO QUADRANT CONVERTER DC DRIVES

Fig. 1 shows the circuit diagram of the conventional 2Q-PWM converter for DC motor drives. Conventional PWM converters process power by interrupting power flow by means of abrupt switching. This operation results in pulsating currents and voltages, thus imposing high voltage and current stresses on semiconductor devices and contributing to electromagnetic interference (EMI).

Resonant type converters, including the series resonant converter (SRC), parallel resonant converter (PRC), class-E converter (CEC), quasi-resonant converter (QRC) and multi-resonant converter (MRC), process power in a sinusoidal or quasi-sinusoidal form. The power switches are commutated with either ZVS or ZCS. Hence, the switching losses and stresses of these resonant type converters are reduced in comparison with the conventional PWM converters.

Recently, a 2Q-ZVS MRC has been applied to DC motor drive [6]. The corresponding schematic diagram is shown in Fig. 2. The major advantages of this converter are:

- ZVS operation of both power switches,
- full ranges of both voltage conversion-ratio and load,
- constant-frequency operation,
- capability of short-circuit operation, and
- absorption of all major parasitics.

However, the high circulating energy and hence the conduction losses are significantly increased, resulting the power devices and other circuit components to be rated for higher VA ratings, as compared with their PWM counterpart.

Very recently, a 2Q-ZVT converter has been newly proposed for DC motor drives [7]. It possesses the advantages that both main transistors and rectifiers can switch with ZVS and unity device stresses during both the motoring and regenerating modes of operation. Fig. 3 shows its circuit diagram. This new ZVT converter is particularly useful for those DC motor applications, employing power devices such as power MOSFET, suffering from severe capacitive turn-on switching losses.

Following the spirit of our previous development on the 2Q-ZVT in [7], the purpose of this paper is to propose a novel 2Q zero-current-transition (ZCT) converter for DC motor drives. Differing from the 2Q-ZVT converter, this 2Q-ZCT converter takes the role to be particularly useful for those DC motor applications, employing power devices such as IGBT, suffering from severe inductive turn-off switching losses.

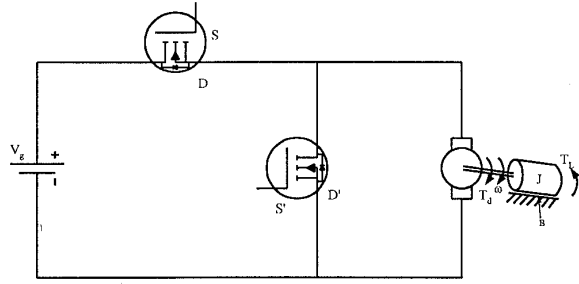


Fig. 1. Conventional 2Q-PWM converter for DC motor drives.

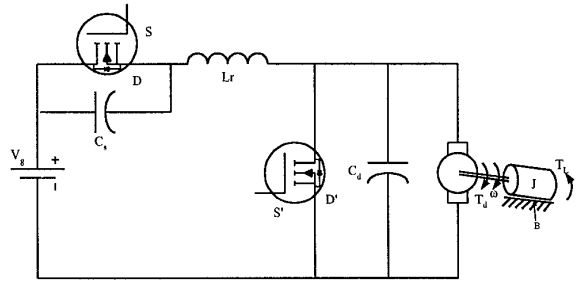


Fig. 2. 2Q-ZVS MRC for DC motor drives.

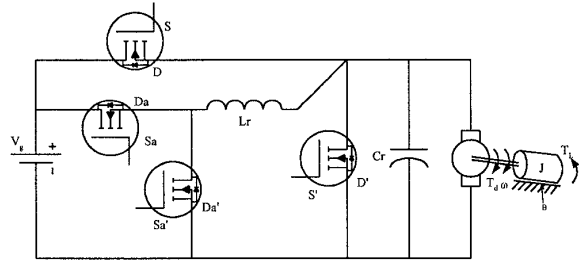


Fig. 3. 2Q-ZVT converter for DC motor drives.

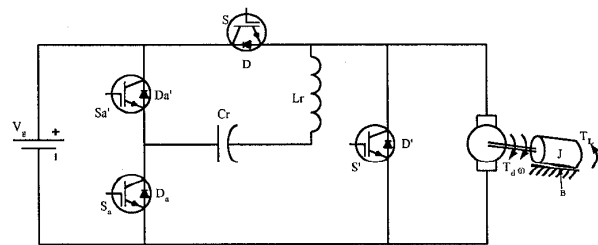


Fig. 4. Proposed 2Q-ZCT converter for DC motor drives.

III. PRINCIPLE OF OPERATION OF 2Q-ZCT CONVERTER

Fig. 4 shows the circuit diagram of the proposed 2Q-ZCT converter for DC motor drives. Compared with the conventional 2Q-PWM converter, the proposed converter needs additional components - a resonant inductor L_r , a resonant capacitor C_r and two auxiliary switches S_a and S_a' . It should be noted that these additional components are inevitable for soft-switching operation. In fact, the corresponding hardware count is minimum.

The theoretical waveforms and diagrams of the proposed 2Q-ZCT converter are illustrated by Figs. 5-8. The operating waveforms in both the motoring and regenerating modes are shown in Figs. 5 and 7, respectively. The corresponding topological stages are shown in Figs. 6 and 8, respectively. From Figs. 6 and 8, it can be found that both modes of operation consist of nine stages within one switching cycle.

A. Motoring Mode (Figs.5 and 6)

- (a) Stage 1 [T_0-T_1]: S_a is turned on and L_r and C_r start resonating. i_{L_r} increases from zero to peak, then decreases towards zero, and changes direction. i_{L_r} reaches $-I_o$ at T_1 and the antiparallel diode of S_a becomes on.
- (b) Stage 2 [T_1-T_2]: S_a is turned off while S is turned on with ZCS at T_1 . The current of D' is directed to the auxiliary circuit. i_{L_r} increases rapidly towards zero.
- (c) Stage 3 [T_2-T_3]: i_{L_r} returns to zero at T_2 and the antiparallel diode of S_a is turned off naturally. L_r and C_r continue resonating and the positive i_{L_r} is conducted by D_a' . When i_{L_r} returns to zero, D_a' turns off naturally at T_3 .
- (d) Stage 4 [T_3-T_4]: It is a forward powering mode.
- (e) Stage 5 [T_4-T_5]: Before S is turned on, S_a is turned on again. L_r and C_r start resonating. i_{L_r} increases from zero to peak, then decreases towards zero, and changes direction. When it reaches $-I_o$ at T_5 , the antiparallel diode of S_a becomes on.
- (f) Stage 6 [T_5-T_6]: At T_5 , i_{L_r} reaches $-I_o$ and the current of S is reduced to zero, thus S is turned off with ZCS. i_{L_r} keeps decreasing, and flows through the antiparallel diode of S .
- (g) Stage 7 [T_6-T_7]: At T_6 , i_{L_r} reaches to $-I_o$ and the antiparallel diode of S stops conducting.
- (h) Stage 8 [T_7-T_8]: At T_7 , v_{C_r} is discharged to zero, and D starts to conduct. The current in D increases gradually.
- (i) Stage 9 [T_8-T_9]: It is a freewheeling mode via D .

B. Regenerating Mode (Figs. 7 & 8)

- (a) Stage 1 $[T_0-T_1]$: S_a' is turned on, and L_r and C_r start resonating. When i_{L_r} decreases from zero to negative peak and then increases towards zero and changes direction. i_{L_r} reaches I_g at T_1 and the antiparallel diode of S_a' becomes on.
- (b) Stage 2 $[T_1-T_2]$: S_a' is turned off while S' is turned on with ZCS at T_1 . The current of D is directed to the auxiliary circuit. i_{L_r} decreases rapidly towards zero.
- (c) Stage 3 $[T_2-T_3]$: i_{L_r} returns to zero at T_2 and the antiparallel diode of S_a' is turned off naturally. L_r and C_r continue resonating and the negative i_{L_r} is conducted by D_a . i_{L_r} returns to zero and D_a is turned off naturally at T_3 .
- (d) Stage 4 $[T_3-T_4]$: It is a freewheeling mode
- (e) Stage 5 $[T_4-T_5]$: Before S' is turned on, S_a' is turned on again. L_r and C_r start resonating. i_{L_r} decreases from negative zero to peak, then increases towards zero, and changes direction. When it reaches I_g at T_5 , the antiparallel diode of S_a' becomes on.
- (f) Stage 6 $[T_5-T_6]$: At T_5 , i_{L_r} reaches I_g and the current of S' is reduced to zero, so S' is turned off with ZCS. As i_{L_r} keeps increasing, it flows through the antiparallel diode of S' .
- (g) Stage 7 $[T_6-T_7]$: At T_6 , i_{L_r} falls to I_g and the antiparallel diode of S' stops conducting.
- (h) Stage 8 $[T_7-T_8]$: At T_7 , v_{Cr} is discharged to zero and D starts to conduct. The current in D increases gradually.
- (i) Stage 9 $[T_8-T_9]$: It is a backward powering mode via D.

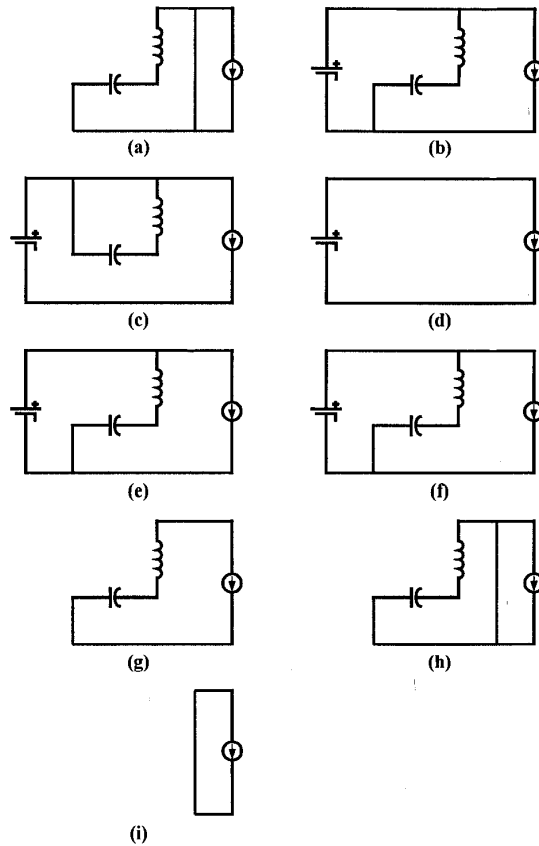


Fig. 6. Nine topological stages at motoring mode.

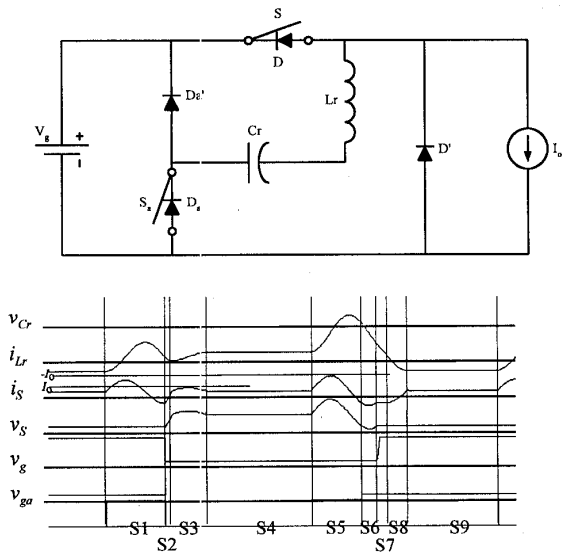


Fig. 5. Equivalent circuit and key waveforms at motoring mode.

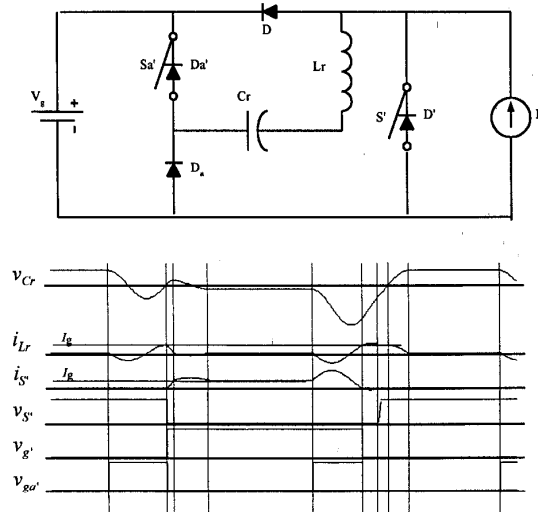


Fig. 7. Equivalent circuit and key waveforms at regenerating mode.

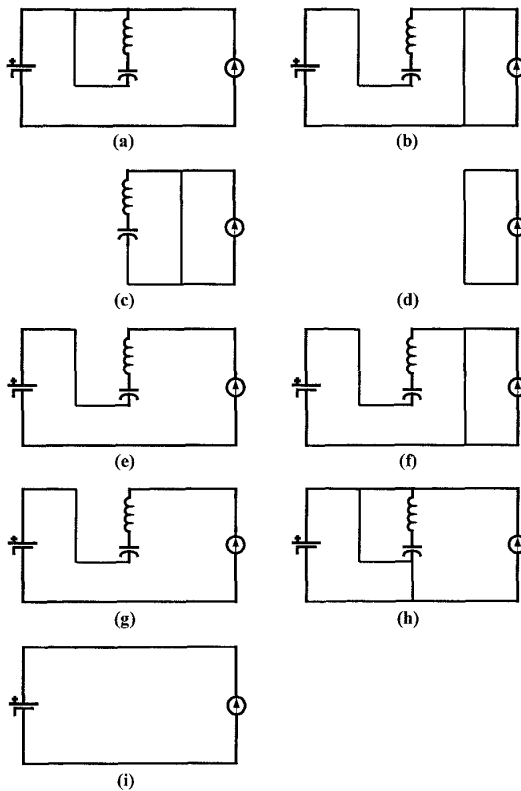


Fig. 8. Nine topological stages at regenerating mode.

IV. SIMULATION AND EXPERIMENTAL RESULTS

To verify the theoretical results, the 2Q-ZCT converter is PSpice-simulated and hardware prototyped. As shown in Fig. 9, the resonant components are selected as $10\ \mu\text{H}$ and $0.1\ \mu\text{F}$, and the IGBT is adopted as those power devices.

The PSpice-simulated waveforms for the 2Q-ZCT converter operating in both the motoring and regenerating modes are shown in Figs. 10 and 11, respectively. It can be found that they closely agree with those theoretical waveforms, especially all main and auxiliary switches (S , S' and S_a , S_a') can always maintain ZCS operation.

Moreover, in order to verify the simulation results, a 40 kHz, 500 W prototype of the proposed 2Q-ZCT converter has been constructed to drive a DC motor. From the experimental waveforms as shown in Figs. 12 and 13, they closely agree with those theoretical and simulation waveforms, especially the main and auxiliary switches can always maintain ZCS operation.

Fig. 14 shows the turn-off switching transients (device voltage and device current) of S' of the proposed 2Q-ZCT converter operating in the regenerating mode. It can be found that the turn-off voltage across S' starts to rise when the current decays down to practically zero. Compared with those switching transients of the conventional PWM converter as shown in Fig. 15, it can be seen that the IGBT turn-off switching loss due to voltage-current overlapping can be alleviated.

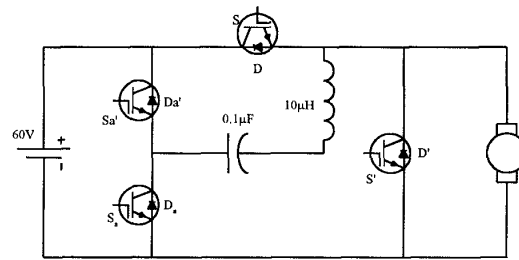


Fig. 9. Experimental 2Q-ZCT converter.

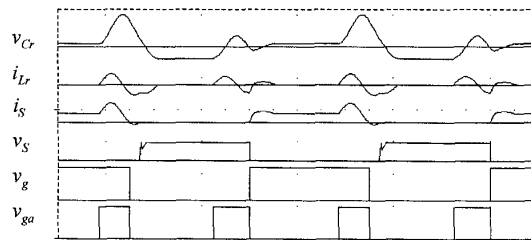


Fig. 10. PSpice simulation at motoring mode.

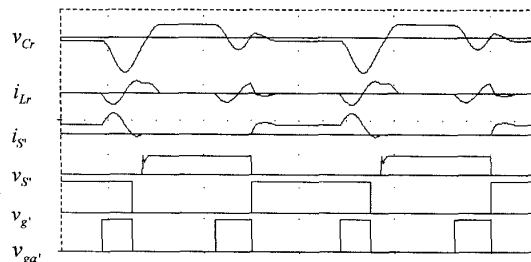


Fig. 11. PSpice simulation at regenerating mode.

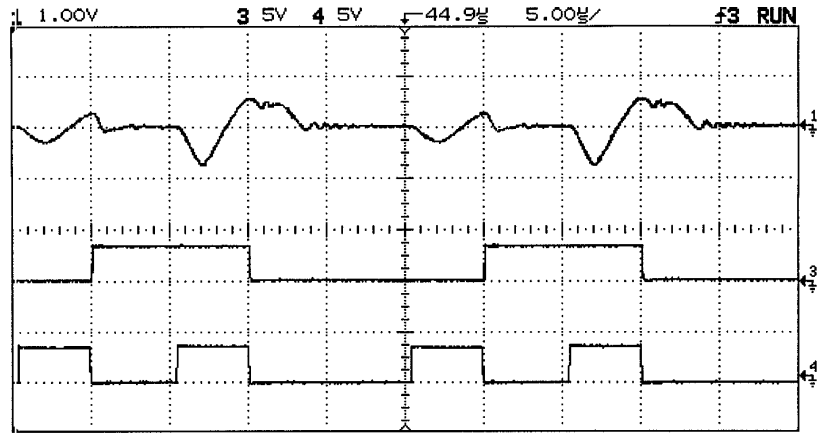


Fig. 12. Measured waveforms at motoring mode: ($\delta_m=0.7$); v_D (50V/div); i_{Lr} (10A/div); v_{ga} , v_g (5V/div).

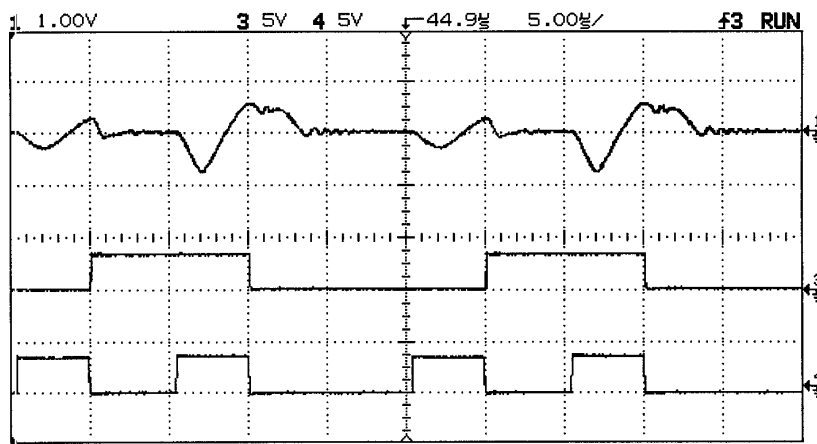


Fig. 13. Measured waveforms at regenerating mode: ($\delta_r=0.3$); v_D (50V/div); i_{Lr} (5A/div); v_{ga} , v_g (5V/div).

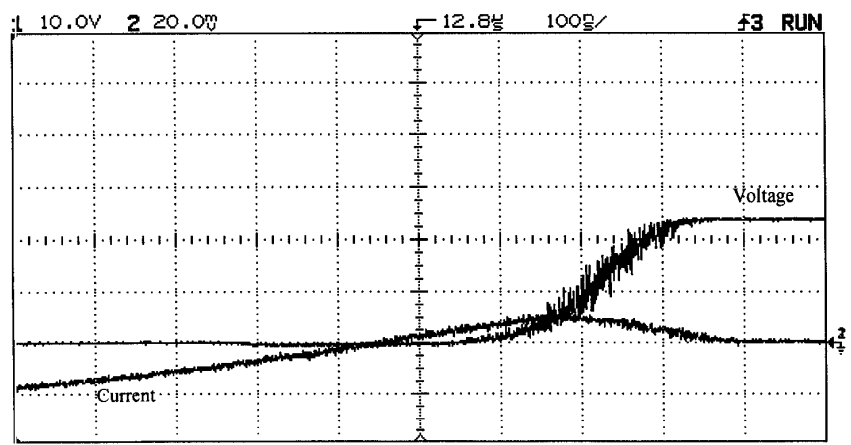


Fig. 14. Turn-off switching transients of the main IGBT using ZCT.

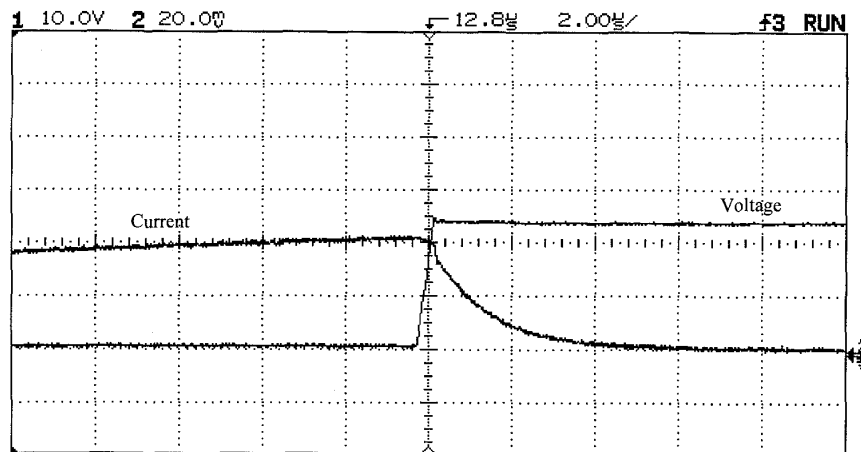


Fig. 15. Turn-off switching transients of the main IGBT using conventional PWM.

V. CONCLUSION

A novel 2Q-ZCT converter for DC motor drives has been presented. It possesses the definite advantages that all main and auxiliary switches can 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, low cost and improved switching characteristics - 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 built-in diodes of the power devices, thus minimizing the overall hardware count and cost. Both PSpice simulation and experimental measurement have verified the validity of the proposed converter. The proposed 2Q-ZCT technique can readily be extended to other types of converters.

VI. ACKNOWLEDGMENT

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