Bidirectional Dual Active Half-Bridge Converter Integrated High Power Factor Correction

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Abstract

Abstract—A bidirectional dual active converter with the power factor control capability is proposed as a battery charger. The source side half-bridge acts as a PWM converter that maintains the unity power factor. The battery side half-bridge converter acts as a dual active bridge (DAB) together shares the same DC link voltage with PWM converter. The imbalance voltage phenomenon is eliminated by employing asymmetric duty cycle technique. Simulation results are included to verify theoretical analysis.

Index Terms—Bidirectional half-bridge converter, battery charger, power factor correction, asymmetric duty ratio.

I. INTRODUCTION

Due to air pollution and exhaustion of fossil fuels, nowadays, an AC-DC converter is an attractive solution for many applications. Conventionally, the front-end is an active single-phase or three-phase pulse-width modulation (PWM) rectifier to obtain power factor correction [2], [12], [14]. In [11], several topologies for both bidirectional and unibidirectional converters have been reviewed.

In this work, a new bidirectional single-phase based on half-bridge converter is proposed for battery charger applications. The input current waveform can shape source voltage while energy transferred to battery package. The unbalanced-voltage problem is solved by utilizing asymmetric duty control technique [6], [5]. A 300 W converter was simulated to support the study. The introduced converter is very promising for low-power applications, especially bidirectional battery charger.

II. OPERATION PRINCIPLE OF PROPOSED CONVERTER

Fig.1 shows the single-phase circuit of proposed converter. A PWM rectifier connects to 60 Hz source voltage and maintain nearly unity power factor. This rectifier shares the same DC link voltage with a DAB converter which is constituted by two half-bridge converters laid back-to-back through a transformer. The converter can transfer energy in a bidirectional manner: from the source to load and inversely from the load to the source.

For better understanding, the operations of PWM converter and dual active half-bridge converter are explained seperately.

A. PWM Converter for Power Factor Correction

To achieve unity power factor, two switches S_1, S_2 are turned-on and -off complementarily. Voltages across capacitors

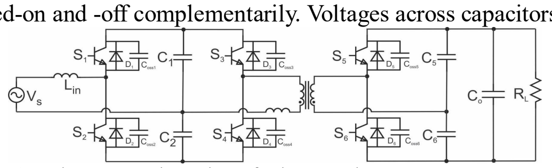

Fig. 1 The proposed topology for battery charger.

V_{C1} and V_{C2} are larger than the peak value of source voltage vs. Due to the symmetric, the operating principle in positive half-line cycle is presented with D defined as duty ratio of S_2.

When S_2 is on: the input current i_L steeply increases because positive voltage (vs $+V_{C2}$) applies directly to inductor. Boost inductor L_{in} is enerized and stores energy from the source. Current i_L is denoted by

$$i_L(t) = i_L(0) + \frac{v_s + V_{C2}}{L_{in}}.t \qquad (1)$$

This interval duration is DTs.

When S_1 is on: input current decreases linearly from its peak value due to negative voltage on inductor. The stored energy is released to capacitor and the load. Boost current is given by

$$i_L(t) = i_L(DT_s) + \frac{-v_s + V_{C1}}{L_{in}}.(t - DT_s) \qquad (2)$$

From the volt-sec balance condition, duty cycle D is determined

$$v_s = V_{C1} - D(V_{C1} + V_{C2}) \qquad (3)$$

To obtain unity power factor, the duty D is modulated by hysteresis current control (HCC) [12] or sinusoidal PWM (SPWM) [2], [4].

The main drawback of single-phase based on half-bridge converter is the unbalanced-voltage between v_{C1} and v_{C2}. This causes input current distortions and harmonics. Several methods to eliminate this fluctuation phenomenon have been reported [2], [4], [12], [13]. In this paper, asymmetric duty technique is employed and thoroughly discussed later.

B. Dual Active Half-Bridge Converter with Asymmetric Duty Control

All the parameters are referred to secondary side of transformer. The gating-pulse signals, voltages in both sides of transformer and leakage current of DAHB are drawn in Fig.2. One more variable, θ, is added to the control scheme to feature asymmetric duty control. Then on-time duration of the primary side switches are $T_{S3} = \pi + \theta$ and $T_{S4} = \pi - \theta$ while in secondary side $T_{S5} = T_{S6} = \pi$. The equivalent circuits of DAHB with asymmetric duty technique shown in Fig.3 are divided in six detailed stages for determining the charging and discharging intervals of capacitors. The operating principle is presented as follow.

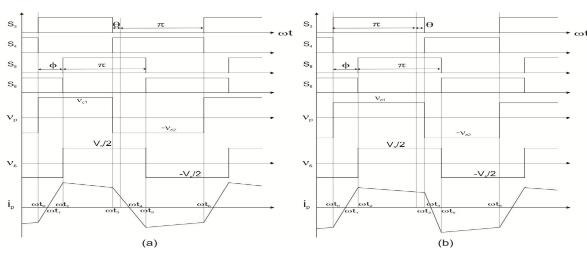

Fig. 2 Key waveforms of DAHB converter with asymmetric duty cycle: (a) θ is negative, (b) θ is positive.

Stage 1 ($\omega t_0 \div \omega t_1$) : At ωt_0, S_4 is turned off and S_3 is turned on. The current flows through D_3 and D_6, the anti-parallel diodes of S_3 and S_6, respectively. In this stage, both capacitors C_1 and C_4 are charged by stored energy in L_{lk}. The current i_s is given by

$$i_s(\omega t) = \frac{v_{C1} + V_o/2}{\omega L_{lk}} \omega t + i_s(\omega t_o) \qquad (4)$$

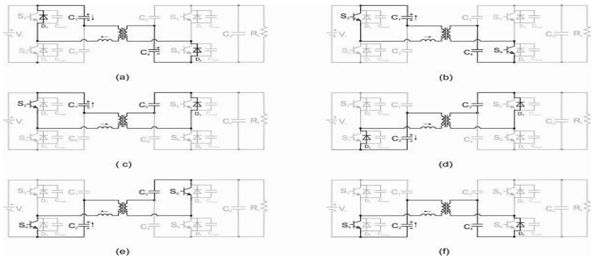

Fig. 3 The equivalent circuits of DAHB converter with positive θ.

Stage 2 ($\omega t_1 \div \omega t_2$) : the i_s current changes its direction from negative to positive value and discharges both capacitors C_1 and C_4. is is the same as (4). Two switches S_3 and S_6 are conducting as drawn in Fig.3(b). This stage is ended when is reaches its peak positive value.

Stage 3 ($\omega t_2 \div \omega t_3$) : i_s flows through S_3 and D_5 due to ON state of S_6 at ωt_2. During this interval, is charges and discharges C_3, C_1, respectively. Voltage applies on inductor L_{lk} is (v_{C1}- V_o/2) and i_s is denoted by

$$i_s(\omega t) = \frac{v_{C1} - V_o/2}{\omega L_{lk}}(\omega t - \phi) + i_s(\omega t_2) \qquad (5)$$

Note that the amount of current discharges C1 can be controlled by regulating the period of this stage.

Stage 4 ($\omega t_3 \div \omega t_4$) : This stage start from the time when S_3 is turned off and S_4 is turned on. The current i_s flows through two body parallel diodes D_4 and D_5 as shown in Fig.3(d) and decreases due to voltage applies on leakage L_{lk} is negative. During this interval, the stored energy in L_{lk} charges up both capacitor C_2 and C_3. is is calculated as

$$i_s(\omega t) = \frac{-v_{C2} - V_o/2}{\omega L_{lk}}(\omega t - \pi - \phi) + i_s(\omega t_3) \qquad (6)$$

This stage is terminated when i_s equals zero at ωt_4.

Stage 5 ($\omega t_4 \div \omega t_5$) : i_s increases from zero in negative direction through S_4 and S_5. Because of the changing in i_s flow, both capacitors C_2 and C_3 are discharging for energizing inductor L_{lk}. The current is the same as (6) in this interval. This period is ended when is reaches its negative peak value.

Stage 6 ($\omega t_5 \div \omega t_6$) : The current is continues discharging C_2 and charging C_4 through S_4 and D_6. In this stage, i_s is indicated by

$$i_s(\omega t) = \frac{v_{C2} - V_o/2}{\omega L_{lk}}(\omega t - \pi - \phi - \theta) + i_s(\omega t_5) \qquad (7)$$

This interval finishes at ωt_6.

In case of asymmetric duty control, the boundary condition for leakage inductor current is $i(\omega t_o) = i(\omega t_6)$, then results in

$$v_{C1}(\phi + \theta) = v_{C2}(\pi - \theta) \qquad (8)$$

or $$\theta = -\frac{(v_{C1} - v_{C2})}{(v_{C1} + v_{C2})}\pi = -\frac{(v_{C1} - v_{C2})}{V_{dc}}\pi = -\frac{\Delta v}{V_{dc}}\pi \qquad (9)$$

The additional angle θ depends linearly on the difference voltage Δv, i.e, between two capacitors C_1, C_2 while the DC link voltage is assuming constant.

With the same procedure as symmetric half-bridge converter [3], [10], [6], the output power is calculated as

$$P_o = \frac{V_o}{8\pi\omega L_{lk}}\left[\frac{v_{C1}}{n}\left(-2\phi^2 - \pi^2 - \theta^2 + 4\pi\phi - 2\pi\theta + 4\theta\phi\right) + \frac{v_{C2}}{n}\left(-2\phi^2 + \pi^2 - \theta^2 - 2\pi\theta + 4\theta\phi\right)\right] \qquad (10)$$

In the steady state, $v_{C1} = v_{C2} = nV_o/2$. The output power is rewritten

$$P_o = P_c + P_a = \frac{V^2_o}{4\pi\omega L_{lk}}\phi(\pi - \phi) + \frac{V^2_o}{8\pi\omega L_{lk}}[4\theta\phi - \theta^2 - 2\theta\phi] \qquad (11)$$

It should be noted from (11) that the output power P_o constitutes of two parts: P_c, caused by conventional phase-shift control [3], [9], [7], [6] and P_a, due to asymmetric duty cycle.

The control block diagram of whole system is shown as following in Fig.4 .

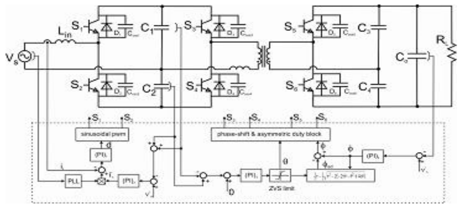

Fig. 4 The entire control block diagram of proposed converter.

The conventional control for power factor correction requires two proportional-integral (PI) controllers: one for inner current loop and the other for DC link voltage loop. Traditional PI is employed to adjust output power. The angle θ is used for curing imbalance voltage. A PI controller can be adopted to that controller because θ increases linearly with the voltage difference Δv. The decoupling term between two-later PI controllers is derived as same technique as in [6].

III. SIMULATION AND EXPERIMENT RESULTS

A 300 W, 90 V input voltage converter was simulated in ANSOFT SIMPLORER 6.0. The simulation results are shown in Fig.6. Compared to Fig.5 where the unbalanced-voltages across capacitors are in range of 0 to 25 V, the differences of two those capacitors with proposed method are very small, in range of -0.25 ÷ 0.25 V while input current shaping input voltage.

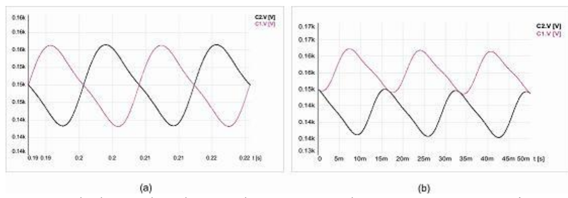

Fig. 5 Unbalanced-voltage phenomenon between two capacitors: (a) SPWM method, (b) HCC method.

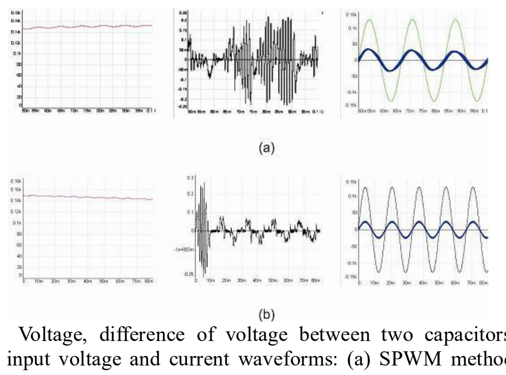

Fig. 6 Voltage, difference of voltage between two capacitors and input voltage and current waveforms: (a) SPWM method, (b) HCC method.

Experiments are now conducting to support the theoretical analysis and will be reported later.

IV. CONCLUSION

A new battery charger for low-power applications based on half-bridge converter has been introduced in this paper. The converter can operate near unity power factor while imbalance voltage phenomenon is eliminated by employing asymmetric duty technique. The effectiveness of proposed converter was verified by simulation results.

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