Soft Start Strategy for Bi-directional DC-DC Converter

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***Abstract*-Traditional soft start method will give rise to large inverse inductor current at startup of bi-directional converter at double sources application, and result in damage of devices. This paper proposes a novel soft start strategy--two-phase soft start strategy to implement soft start at double sources application, which can avoid inverse induct -or current. Experimental results are given to verify the effectiveness of two-phase soft start strategy.**

I. INTRODUCTION

Bi-directional DC-DC converter can find application from uninterrupted power supplies, battery charging/ discharging system to auxiliary power supply in hybrid electrical vehicles. In the near future, photovoltaic generation, wind generation and fuel cell these emerging areas will provide wide applica -tion field for bi-directional DC-DC converter[1~4].

Ref. [5] proposes a hybrid fuel cell power system, which is composed of a fuel cell, a uni-directional converter, a bi-directional converter, an inverter and a battery, the block diagram is showed in fig.1. The uni-directional converter converts the wide voltage of fuel cell (200-400VDC) to 360VDC and is delivered to the inverter to produce 220V/50Hz AC. A 220V battery is paralleled with the DC Bus via bi-directional converter, which can transmit energy in both directions. Buck-Boost bi-directional converter is selected in fuel cell power system, for the merits of simple configuration, easy control and rapid response[6][7].

Soft start method can reduce input inrushing current of DC-DC converter at startup, and it is widely used in uni-directional converters. In fuel cell power system in Fig.1, bi-directional converter is at double sources application—DC Bus and battery at two ports, where traditional soft start method fails to serve. This paper will analyze the problem of traditional soft start and proposes a novel soft start strategy—two-phase soft start strategy.

II. THE PROBLEM OF TRADITIONAL SOFT START

Fig.2 shows the block diagram of Buck-Boost bi-directional converter. V_H is at high-voltage port and V_L is at low-voltage port. Switches Q_1, Q_2 are in complemented operation. In Buck mode, Q_1 is controlled to regulate the output voltage, therefore Q_1 is defined active switch, and Q_2 is defined passive switch. Likewise in Boost mode, Q_2 is defined active switch and Q_1 is passive switch.

Traditional soft start method makes the switch's duty cycle increase gradually, so output voltage increases slowly. At double sources application, if the bi-directional converter works in Buck mode, V_H supply energy to V_L. In traditional soft start, the duty cycle of Q_1 is small and that of Q_2 is large at startup. V_H-V_L is applied on inductor with short time per switch period while -V_L with long time. As shown in Fig.3, the inductor current inversely increases rapidly, as a result, the inductor is saturated and devices are damaged by large current. In Boost mode, traditional soft start also gives rise to the problem.

As to other bi-directional DC-DC converters: Buck/Boost bi-directional converter, Cuk bi-directional converter, Zeta-Sepic bi-directional converter, Forward bi-directional converter and Flyback bi-directional converter, because the opposite switches are in complemented operation, traditional soft start will also produce inverse current from the output source. Traditional soft start cannot serve at double sources application. New soft start strategy should be employed.

III. PASSIVE SWITCH DRIVE DELAY METHOD

In traditional soft start, conduction of passive switches brings in inverse current from output source. Therefore, passive switch can be shut and inductor current freewheels

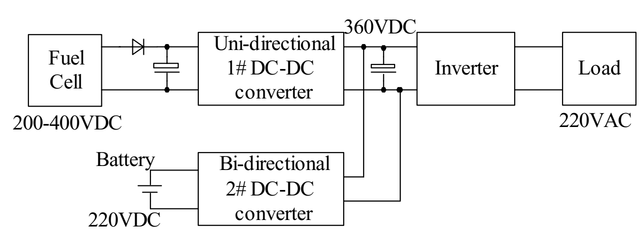

Fig.1 Fuel cell power system

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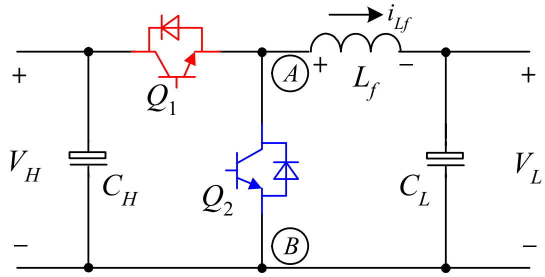

Fig.2 Buck-Boost bi-directional converter

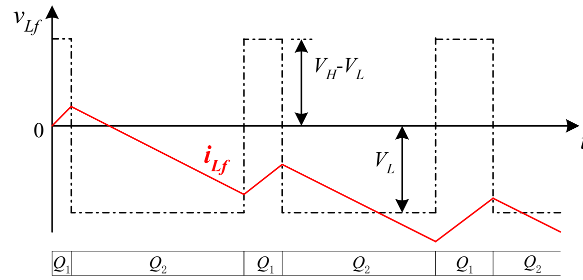

Fig.3 Inverse inductor current in traditional soft start

through the source-drain diode. After soft start, passive switch drive signal will be released.

This method is effective when the converter is in CCM. If It is in DCM at light load, release of passive switch drive signal will make it change from DCM into CCM immediately. In the transition, inverse current will increase inversely. Fig.4 shows the simulation result of passive drive delay strategy. Before t_1, the converter is in Boost DCM, V_L=220V and V_H =340V. At t_1, the passive switch drive signal S_2 is released, inductor current i_L rapidly changes to -14.2A, while i_L= 0.44A in steady state。

As analyzed above, Passive drive delay method will give rise to inverse inductor current at light load.

IV. PRINCIPLES AND CIRCUIT OF TWO-PHASE SOFT START STRATEGY

Traditional soft start makes active switch duty cycle increase gradually. If passive switch's duty cycle gradually increases in the same way as active switch, discontinuous inductor current will smoothly transit into continuous current—this is two-phase soft start strategy.

Two-phase soft start strategy has two methods. In method 1, given a delay after active switch stabilizes, passive switch duty cycle begins to increases. In method 2, passive switch duty cycle increases immediately after active switch stabilizes.

Fig.5(a) and Fig.6(a) shows method 1's block diagram and illustrative graphs. At t_0 startup, Current source I_S begins to charges external soft start capacitor C_{S1}. Soft start capacitor voltage V_{S1}, output voltage close loop output V_{EA_Vo} and saw-tooth signal V_{RAMP1} are delivered to *PWM Comparator* to obtain active switch drive signal S_1. S_1's duty cycle increases from zero gradually. Pulse B_2 is complement to S_1. In this stage, output voltage/current slowly increases and because passive switch is shut, inverse inductor current is prevented.

At t_1, S_1 increases to rated duty cycle and will keep stable later. At this time the output voltage stabilizes.

At $t_0+\triangle t$, current source $I_S(t_0+\triangle t)$ begins to charge external soft start capacitor C_{S2}. V_{S2} ascends from zero linearly. It intercepts with saw-tooth signal V_{RAMP2} and obtain pulse D_{SS}. *Dss*'s duty cycle increases gradually from zero to "1".

From t_2, as the result of D_{SS} "and" B_2, S_2's duty cycle begins to increase gradually from zero. In this stage at light load, inductor current can transit smoothly from DCM into CCM, avoiding large inverse current.

From t_3, because D_{SS} end "1" duty cycle, S_2 reaches stable and it is complement to S_1. Two-phase soft start finishes.

Fig.5(b) and Fig.6(b) shows method 2's block diagram and illustrative graphs. At t_0 startup, voltage close loop output V_{EA_Vo} is high level. It intercepts with saw-tooth signal V_{RAMP1}, so pulse B_1 is "1" duty cycle and B_2 is zero. Current source I_S begins to charges external soft start capacitor C_{SS}. V_{SS} ascends linearly from zero. It intercepts with saw-tooth signal V_{RAMP2} and obtain auxiliary pulse D_{SS}. *Dss*'s duty cycle increases gradually from zero to "1". Active switch drive signal S_1 is obtained by B_1 "and" D_{SS} logically, so S_1's duty cycle increases gradually. Passive switch drive signal S_2 is obtained by B_2 "and" D_{SS} logically and S_2 is zero.

At t_1, S_1 increases to the stable duty cycle and the output voltage stabilizes. V_{EA_Vo} will be lowered. S_2 is zero.

At t_2, V_{EA_Vo} intercepts with V_{RAMP1} and determine B_2 of stable duty cycle, while D_{SS} keeps increasing. Consequently, S_1 retains stable duty cycle and S_2's duty cycle begins to increase from zero.

From t_3, because D_{SS} end "1" duty cycle, S_2 reaches stable and it is complement to S_1. Two-phase soft start finishes.

Two-phase soft start strategy is applicable to other bi-directional converters. With multiple auxiliary pulses working on switches, two-phase soft start strategy can be extended to multi-level bi-directional converter.

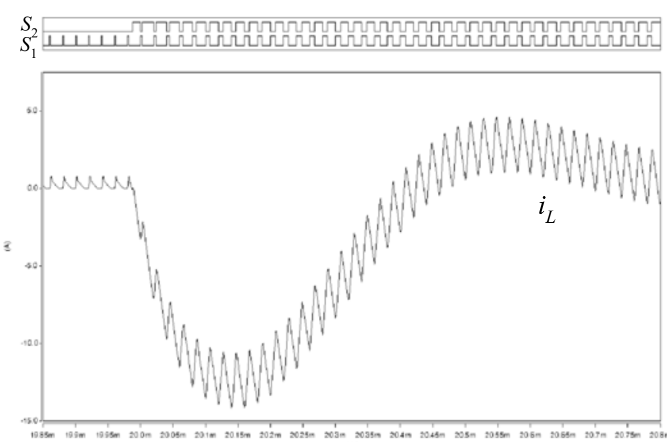

Fig.4 Passive switch drive delay method simulation waveforms

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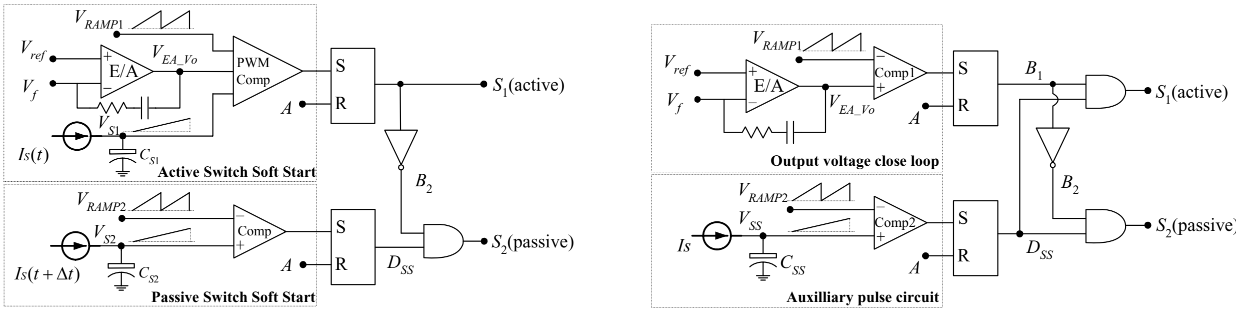
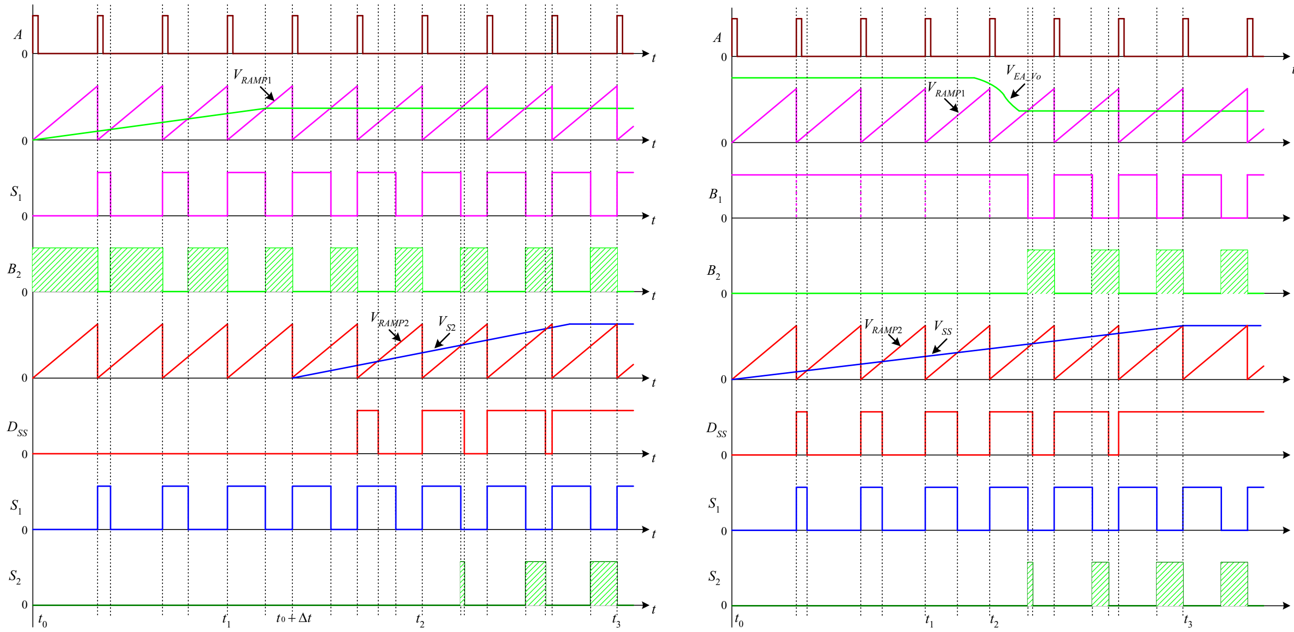


(a) Method 1 (b) Method 2

Fig.5 Block diagram of two-phase soft start strategy



(a) Method 1 (b) Method 2

Fig.6 Illustrative graphs of two-phase soft start

V. EXPERIMENTAL RESULT

In order to verify the effectiveness of two-phase soft start strategy, a prototype converter is built in lab: C_H=1120*uF*, C_L=1120*uF*, *Lf* = 400*uH*, *fs*=50*kHz*, Switch: *IRF*460. At double sources application in Buck mode, V_H=340V, V_L= 240V. Battery at output port is charged. In Boost mode, battery is discharged at input port; V_H is boosted from 320V to 340V. A 220V/7Ah battery is employed and constant-current/ constant voltage charge mode is employed.

Fig.7 shows inductor current experimental waveforms of passive switch drive delay method and two-phase soft start in Boost mode at light load. In Fig.7(a) passive switch drive delay method, before t_1, the converter is in DCM. At t_1, passive switch drive signal S_2 is released. In the transition from DCM into CCM, maximum inverse current is as large as -76A. Because inductor is partially saturated, current slope ratio is enlarged in the transition. In Fig7(b) two-phase soft start strategy, because S_2's duty cycle increases gradually, inductor current smoothly changes and large inverse current is avoided.

Fig.8 shows bi-directional converter two-phase soft start experiment result in fuel cell power system, V_H is DC bus and V_L is battery. Fig. 8(a) is Buck mode output voltage and inductor current waveforms. After startup, the converter maintains 1.5A charging current. Battery voltage increases from 200V slowly and will enter floating charge. Fig. 8(b) is Boost mode output voltage and inductor current waveforms. After startup, the converter first maintains 2A discharging current. After DC Bus voltage raises to 340V, it maintains 340V output, and discharging current is 1.6A.

As can be seen above, two-phase soft start strategy works well to implement soft start of bi-directional converter in double sources application.

VI. CONCLUSION

This paper discusses the problem of traditional soft start for bi-directional converter at double sources application, analyzes the drawback of passive switch drive delay method and proposes two-phase soft start strategy. Two-phase soft start strategy has two methods to can implement soft start in double sources application, avoiding inverse inductor current.

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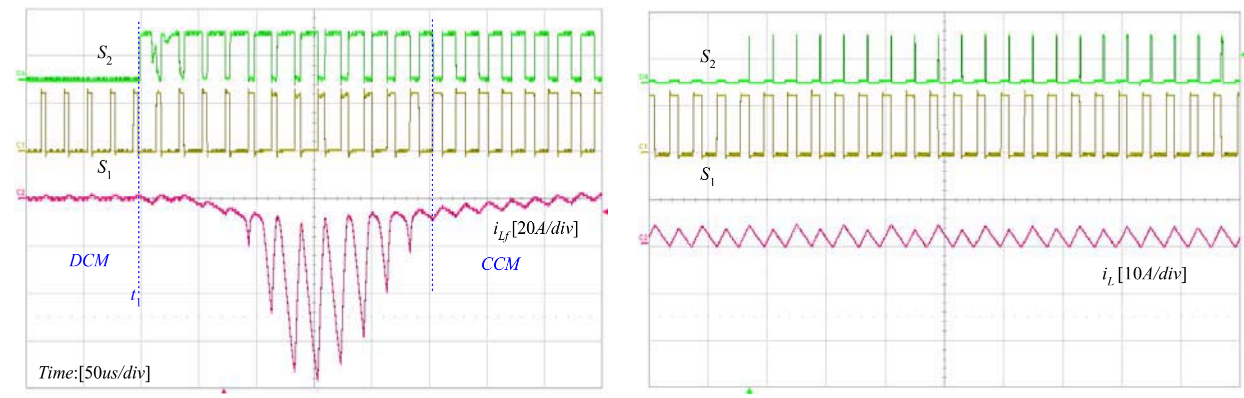
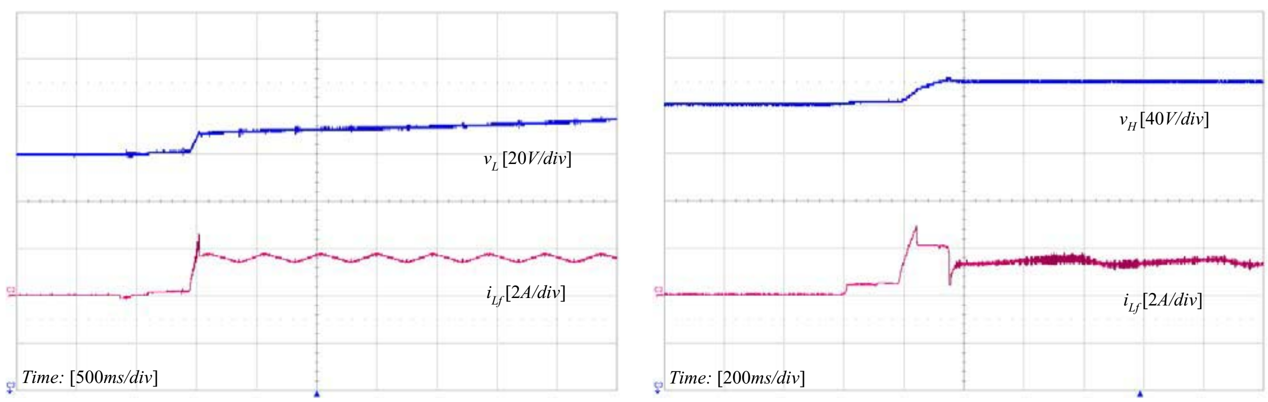


(a) Passive switch drive delay mathod (b) Two-phase soft start strategy

Fig.7 Experimental waveforms of passive switch drive delay method & two-phase soft start strategy at light load



(a) Buck mode startup (b) Boost mode startup

Fig.8 Two-phase soft start in fuel cell power system

Experimental results are given to verify the effectiveness of two-phase soft start strategy.

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