Research on Applications of An Improved Current Type Push-pull Full bridge bidirectional DC-DC Topology in UPS

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Abstract. Uninterruptible power supply (UPS) boasts the superiority of fast dynamic response and clean output power, which can ensure the stable operation of the system and the safety and reliability of data. Currently, it takes up a large proportion in the backup power market and is extensively applied in key industries such as energy and the Internet. UPS is connected between commercial power and power load, and furnishes uninterrupted, reliable and high-quality power to vital loads when the input power fails. Bi-directional DC-DC converter can realize bi-directional flow of energy, which is functionally equivalent to two uni-directional DC-DC converters, rendering the system to carry the advantages of high power density and low cost, which has become a research focus at home and abroad in the passing years. The traditional current-mode push-pull full bridge topology fails to realize the soft start of the on-line UPS and stable operation of it under empty and light load. Based on this topology, the inductor secondary coil and two freewheeling diodes are added to make the push-pull tube work in any duty ratio state, thus meeting the design requirements of the bi-directional DC-DC converter in UPS. The working principle of the improved topology is described in this thesis, and Saber and Matlab are used for simulation analysis. Prototype is made and debugged to verify the feasibility of the design so as to achieve the expected design goals.

1. Working Principle and Simulation Analysis of Bi-directional Push-pull Full Bridge DC-DC

1.1. Improvement of Bi-directional Push-Pull Full Bridge Topology

The current-mode topology is characterized by electrical inductance and small current ripple, the push-pull topology is suitable for low voltage, medium and high power applications [1], while the full bridge topology is suitable for high voltage, and high power applications. Thus, the current-mode push-pull full bridge topology is up to the requirements of the afore-said bi-directional DC-DC converter in UPS [2]. In the UPS commercial power mode, the bi-directional DC-DC works in a step-
down state to complete the charging of the storage battery; in the battery mode, the bi-directional DC-DC works in the boost state to complete the boost from the battery to the DC bus \[3\][4]. However, when this topology is applied in UPS, there exist two problems:

(1) Stable operation of UPS under different loads: Existing Topology is shown in Figure 1. Owing to the large inductance, its push-pull tube can merely maintain a working state with a duty ratio of half in the battery mode of UPS \[5\]. Taking into account the full load range operation of UPS, it is possible that the duty ratio of push-pull tube is less than 50% under empty and light load conditions. When this situation occurs, both push-pull tubes will be turned off in one working cycle. Since there is no special energy release channel in the large inductance, the residual energy is released through the junction capacitance of the switch tube, so the switch tube bears a large voltage spike and may be broken down. Meanwhile, along with the long-term operation of the system, the residual energy of the inductor increases until the inductor saturates, which eventually leads to system abnormality.

(2) Soft start of UPS: When UPS starts up, PFC or bi-directional DC-DC can be used to boost the bus voltage \[6\], and high-quality alternating current conforming to frequency and voltage grade can be output through inversion to supply the load for use. As shown in Figure 2, if this circuit is used to raise the bus voltage, the commercial power will be directly applied to the bus capacitors C3 and C4 through the filter inductor L at the moment of starting up, resulting in a large impact current, shortening the service life of the capacitors, bringing potential hazards to other components of the circuit and reducing the system performance.

To this end, the topology structure exhibited in Figure 3 is improved. In comparison with the original topology, inductor secondary coil and two diodes are added to the new topology. These added components ensure that when both push-pull tubes are turned off, the residual energy of the inductor can be released to the bus side through the inductor secondary coil and freewheeling diodes D7 and D8. Hence, the improved topology can make the push-pull tube work in any duty ratio state, which can realize any load operation of UPS in battery mode. Apart from that, when UPS is started up, push-pull
duty ratio is controlled by software programming to increase linearly and slowly from zero, then bus voltage rises slowly, and the soft start function of battery can be realized. Before and after topology improvement, saber simulation was carried out on the voltage stress of push-pull tube under no-load operation of bi-directional DC-DC respectively. The simulation results are exhibited in Figure 4. It can be seen that before the topology is improved, there is no suitable release path for the residual energy of the inductor due to no-load duty ratio less than 50%, which leads to larger voltage spike of the push-pull tube. After the topology is improved, the voltage spike of the push-pull tube under no-load condition is obviously decreased, which proves the feasibility of the improved topology.

![Figure 3. Improved Topology](image)

![Figure 4. Comparison of Switching Stresses](image)

1.2. Operation Analysis of Bi-directional DC-DC Converter in Battery Mode

In battery mode, UPS uses bi-directional DC-DC to boost voltage. Under no-load or light load, the working duty ratio of push-pull tube may be less than 50%, while under other loads, the working duty ratio of push-pull tube is greater than 50%. The following two steady-state working states are analyzed respectively.

1.2.1. The duty ratio of push-pull tube is less than 50%. There are 4 operating modes in a switching cycle, and the equivalent circuit diagram is exhibited in Figure 5 a).

Operating mode 1(t₀–t₁): the push-pull tubes S₁ and S₂ are both turned off; the primary and secondary sides of the transformer have no energy transfer; inductive energy is released to the high-
voltage bus through the secondary coil and freewheeling diodes D7 and D8; the primary coil has no current and the secondary coil current decreases linearly.

Operating mode 2(t1~t2): push-pull tube S1 is in an on state and S2 is in an off state; at this time, the inductor stores energy, the current of the primary coil of the inductor linearly increases, the energy is transferred to the full bridge side through the transformer, and rectified through D4 and D5.

Operating mode 3(t2~t3): both push-pull tubes S1 and S2 are turned off, and the operating mode 1 is repeated.

Operating mode 4(t3~t4): push-pull tube S1 is in an off state and S2 is in an on state; at this time, the inductor stores energy, the current of the primary coil of the inductor linearly increases, the energy is transferred to the full bridge side through the transformer, and rectified through D3 and D6.

This is a whole switching cycle, after which the above switching cycle process is repeated.

1.2.2. The duty ratio of push-pull tube is greater than 50%. The inductor secondary coil does not work, and there are 4 operating modes in one switching cycle. The equivalent circuit diagram is exhibited in Figure 5 b).

Operating mode 1(t0~t1): push-pull tubes S1 and S2 are both on, the inductance stores energy, and the primary current of the inductance linearly increases. Ideally, the two coils on the primary side of transformer TX1 flow currents of equal magnitude and opposite directions; the combined magnetomotive force of the two coils is 0, which is equivalent to the primary side short circuit; the primary and secondary sides of the transformer have no energy transfer, the full bridge rectifier tubes are all off, and the bus capacitance maintains output.

Operating mode 2(t1~t2): push-pull tube S1 is turned on and S2 is turned off; at this time, the inductor and the battery transmit energy through the transformer, the inductor current decreases linearly, and rectifier tubes D4 and D5 are turned on to complete the rectification process.

Operating mode 3(t2~t3): both push-pull tubes S1 and S2 are on, and the operating mode 1 is repeated.

Operating mode 4(t3~t4): push-pull tube S1 is turned off and S2 is turned on; at this time, the inductor and battery transfer energy through the transformer, and inductive current decreases linearly; rectifier tubes D3 and D6 are turned on to complete the rectification process.

This is a whole switching cycle, after which the above switching cycle process is repeated.

1.3. Operation Analysis of Bi-directional DC-DC Converter in Commercial Power Mode

In commercial power mode, UPS completes battery charging by employing the current step-down function of bi-directional DC-DC. The secondary coil of the inductor does not work, merely the primary coil works, and the working frequency of the inductor is 2 times of the switching frequency. There are 4 operating modes in one switching cycle. The equivalent circuit diagram is exhibited in Figure 5 c).

Operating mode 1(t0~t1): the full bridge tubes are all turned off, and the primary and secondary sides of the transformer have no energy transfer; the inductor freewheels through the body diodes D1 and D2 and the transformer coils N1 and N2 and charges the battery, and the inductor current decreases linearly. Since the currents in N1 and N2 are equal in magnitude and opposite in direction, the secondary coil of the transformer is equivalent to a short circuit.

Operating mode 2(t1~t2): the full bridge tubes Q4 and Q5 are turned on and Q3 and Q6 are turned off; at this time, the primary and secondary sides of the transformer conduct energy transfer, the inductance stores energy, and the inductance current increases linearly; D1 is turned on to complete rectification, D2 is turned off, and the battery is in a charged state.

Operating mode 3(t2~t3): all 4 full bridge tubes are turned off and the operating mode 1 is repeated.

Operating mode 4(t3~t4): the full bridge tubes Q4 and Q5 are turned off, Q3 and Q6 are turned on, the primary and secondary sides of the transformer launch energy transfer, the inductance stores energy, the inductance current linearly increases; the body diode D2 is turned on to complete rectification, D1 is turned off, and the battery is in a charging state.
This is a whole switching cycle, after which the above switching cycle process is repeated.

![Equivalent Topology](image1)

Figure 5. Equivalent Topology

1.4. Matlab simulation analysis
Matlab is employed to launch closed-loop simulation of the working state of bi-directional DC-DC converter in battery mode and commercial power mode. Figure 6 is a waveform diagram of bus voltage, load current and inductor current under full load, which displays that bus voltage overshoot is small, fluctuation is small, dynamic response is fast, and inductor current impact is small, meeting the stability requirements of the system. Figure 7 is a simulation waveform of lead-acid battery charging in commercial power mode, in which a two-stage charging method is adopted. In the simulation, when the terminal voltage of the battery is lower than 39.157 V, it is set to constant current charging, otherwise, it is converted to constant voltage charging. From the simulation waveform, it can be seen that when the battery voltage is lower than 39.157 V, it is charged at a constant current of 12 A; once the battery voltage is greater than or equal to 39.157 V, it is converted to constant voltage charging, and the charging current is slowly decreased from 12 A, thus avoiding overcharge of the battery. The feasibility of the two-stage charging method is verified.

![Waveform in Battery Mode](image2)

Figure 6. Waveform in Battery Mode
2. Experimental Results and Analysis

Build an experimental platform for experiments. The experiment principally includes three parts: battery mode experiment, commercial power mode experiment and switching experiment between the two modes.

2.1. Hardware and the soft start

As exhibited in Figure 8, the hardware circuit of 1kV.A on-line UPS adopts a set of double closed-loop control for the commercial power and battery modes of bi-directional DC-DC. After the UPS is started, the operating mode of the system is selected by judging the state of the commercial power and the battery. When the commercial power is normal and the battery is abnormal, the operating mode of commercial power is selected; when the commercial power supply is abnormal and the battery is normal, the battery operating mode is selected; when the commercial power supply and battery are normal, the battery is used to soft start the bus voltage first, then the PFC circuit works and the commercial power supply mode starts. The waveform of soft start is exhibited in Figure 9. It can be known from the diagram that taking advantage of the push-pull switch tube working at any duty cycle in battery mode, the bus voltage rises slowly when UPS is started up, avoiding the large impact current when PFC rises the bus voltage, protecting the bus capacitance, reducing the selection requirements for devices and reducing the cost.
2.2. Charging current

Bi-directional DC-DC realizes the charging function of storage battery in commercial power mode. Three 12V/100A.h series-wound maintenance-free lead-acid batteries are selected in the experiment, and the design target of maximum charging current is 12A. Figure 10 a) gives the driving voltage and battery charging current waveforms of the full bridge switch tube. As can be learned from Figure 10 b) c), the maximum charging current can reach 12A, which meets the design requirements. Taking 6A constant current charging as an example, the charging current ripple is 3.6/6.5=0.55 and the battery voltage ripple is 5.62/39.10=0.14, which meets the requirements of lead-acid battery.
2.3. Switch between two modes
To verify the overall performance of the bi-directional DC-DC converter, the switch experiment between the modes of commercial power and battery is carried out. The experimental waveforms are exhibited in Figure 11, which are the bus voltage waveforms when the two operating modes are switched. As can be known from the experimental waveforms, the bus voltage can quickly transition to the equilibrium state in the process of the battery-to-commercial-power mode and the commercial-power-to-battery mode, which meets the requirements of system stability and rapidity.

![Figure 11. Bus Voltage Waveform during Switching of Two Operating Modes](image)

2.4. Comparative of Tube Voltage Stress
The comparative test waveforms of voltage and stress of push-pull tube under no-load operation before and after topology improvement are as below. The electrical PWM waveforms and stress waveforms of push-pull tube are exhibited in the figure. From the experimental waveforms, it can be observed that the switching stress of the improved topology push-pull tube is significantly decreased, which accords with the simulation results.

![Figure 12. Comparative of Tube Voltage Stress before and after](image)

3. Conclusion
This thesis principally studies the push-pull full bridge bi-directional DC converter based on small-scale online UPS, and explores the problems existing in the converter topology. In respect of the problems that the traditional current-mode push-pull full bridge topology cannot meet the soft start and stable operation under empty and light loads of online UPS, an inductor secondary coil and two freewheeling diodes are added to the original topology, thus realizing the push-pull tube to operate in any duty ratio state in battery mode. Simulation and actual measurement have proved its effectiveness.
The results suggest that the improved topology can realize soft start of the system and bi-directional stable operation under different load conditions, thus reaching the expected design goal.

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