A New Single-Phase On-Line UPS Structure

Pre-staged with PFC-and-Boost Converter

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Abstract

This paper presents a new on-line uninterruptible power supply (UPS) structure in which a dual-functional PFC substitutes for an inevitable battery-voltage booster thereby simplifying the complexity of power stage. Via the proof of experimental results, the proposed UPS structure consequently shows its feasibility, low cost and high power density.

1. Introduction

With information industry prospering, uninterruptible power supply (UPS) is used widely and getting more and more important [1-8]. But the utility system is usually contaminated by those critical equipment, thus power-factor-correction (PFC) pre-regulator served as the rectifier of UPS is a growing trend [3,4]. For a designer, however, it is always a dilemma between adding an extra-PFC and reducing cost.

Fig. 1 shows the functional block diagram of conventional on-line UPS which consists of a PFC, inverter, charger, boost converter, and a battery set [1,2]. When the mains is present, AC power source goes through PFC then inverter in order to supply the regulated

AC power to the load, and the charger simultaneously energizes the batteries, i.e. the functional block marked with # will be active. In the meantime, the boost converter is inactive. Unless when the mains fails, i.e. the functional block with mark @ will be active, it will startup to lift battery-voltage toward original DC-link voltage level to energize DC capacitor. Thus the following inverter stage can still work normally because of keeping same DC-link voltage level of inverter input. Due to the pre-regulator of PFC, this is an inevitable procedure because commonly-used boost-type PFC always has high DC output.

In another words, if DC-link voltage of the PFC's output is around 240V DC and without lifting of booster, it will need about 20 12V-batteries connected in series (totally 240V DC) to retain working normally during blackout phase. A 1KW UPS, e.g., will need 20 rarely-used 12V/1.5AH-batteries to supply 10 minutes of back-up time (general specification for UPS) [1]. If there is a battery-voltage booster, however, it can just use 5 commonly-used 12V/7AH-batteries, or other cheaper and available ones, to do so. The more common battery types are, the cheaper they usually are. Furthermore, the more batteries UPS has, the more complicated

and less reliable connection it has.

Now that the battery-voltage booster is inevitable as well as input current harmonics reduction may be also mandatory, this paper uses PFC as pre-regulator and its sub-function substitutes for the conventional boost converter such that it can simplify UPS structure. It is needless to use unusual and expensive battery types to fit DC-link voltage for specified back-up time.

II. The Proposed UPS

A. System Description

Fig. 2 shows the functional block diagram of the proposed on-line UPS. It consists of a dual-functional PFC, inverter, charger, battery-switch, and a battery set. The operation principles can be also traced by the marks # and @ of the functional blocks. And, the practiced power circuit of the proposed UPS is shown as in Fig. 3.

By comparison, it is obviously more economical than the conventional UPS structure because it exploits the PFC to the most for saving a conventional boost converter. When the mains is normal, switch S_1 of the dual-functional PFC is controlled to shape the input current to be sinusoidal, switches S_2 and S_3 of the push-pull inverter are operated in a sinusoidal PWM fashion accompanied with output L_o/C_o filter to generate output voltage, and the flyback charger works normally to charge the battery set (battery-switch open).

As soon as the mains is gone, the battery-switch will be closed immediately, switch S_1 are controlled as DC voltage booster's main-switch to step-up battery voltage, switches S_2 and S_3 are still operated in the same sinusoidal PWM fashion but the charger

will shutdown for no AC input. Both AC/DC battery charger and DC/AC inverter have been the source of interest in so many literatures of power electronics field, thus they would be very resourceful [3-8]. Therefore, the know-how parts of the proposed UPS is just the dual-functional PFC whose descriptions and analyses are in the following section.

B. Dual Functional PFC

Fig. 3 shows the equivalent circuit of the proposed dual functional PFC which needs a state-switch to change its operation mode. While battery-switch is open, the state-switch is on (I) position. While battery-switch is closed, the state-switch is on (II) position. Single-switch boost-type PFC and conventional single-switch DC-DC boost converter have same main components of power-stage circuits. And, no matter whether the main-switches turn on or off, they also exhibit the same equivalent circuits -- they can be combined together.

The operation principles can be divided into two modes along with its main-switch's current-related variety shown as follows:

mode (I): The state-switch is on (I) when the mains is normal. The converter serves as a PFC function which shapes input current waveforms to be sinusoidal and generates DC output by controlling switch S_1 in PWM fashion. In this period, its main-switch's peak current $I_{S(PFC, peak)}$ can be expressed as

$$I_{S(PFC, peak)} = 1.414 \times P_{out} / V_{in(minimum)} \quad (1)$$

where P_{out} is the output power and $V_{in(minimum)}$ is the minimum value of input voltage.

mode (II): The state-switch is on (II)

when the mains is absent. The dual-functional converter serves as a DC-voltage booster of the PFC's sub-function. By using the same PFC's control logic and feedback circuits, the main switch S_1 can also be controlled in PWM fashion to boost battery voltage, V_B , up to same DC output level. In this period, its main-switch's peak current $I_{s(boost, peak)}$ can be expressed as

$$I_{s(boost, peak)} = I_o \times V_o / V_{B(minimum)} \quad (2)$$

where I_o is output current, $V_{B(minimum)}$ is the minimum value of low-battery voltage, and V_o is output voltage. Therefore, from Eq.(2) - Eq.(1), the current difference $\Delta I_{s(peak)}$ of mode (I) and mode (II) can be expressed as

$$\Delta I_{s(peak)} = I_{s(boost, peak)} - I_{s(PFC, peak)} \quad (3)$$

For example, $V_{in(minimum)} = 90V$ AC, $V_{B(minimum)} = 40V$ DC, $V_o = 250V$ DC, and load is 1kW. Then $\Delta I_{s(peak)} \cong 9.3A$. Therefore, if V_B is not too low, the current difference of main-switch for the two modes will be acceptable. Thus they can share a common circuit if we can choose a proper current-rating capacity for the main-switch.

Because the control logic and feedback circuits of the proposed converter are based on mode (I) -- input-current-shaping feature, we should consider if mode (II) is stable for this kind of application. Though there are two points to confirm it is stable: 1) Mode (II)'s power-circuit cell is delayed only 90° for small-signal model because it has an inner controlling loop, which is continuous conduction mode (CCM) PFC's inherent stuff, can cancel one pole of original 180° power-circuit cell [9,10]. There is no stability problem of feedback for a 90° -delayed controlling plant. 2) Mode (II) is just one operation

point of mode (I) because V_B should be within the swing of input voltage for a plausible design. Furthermore, the PFC circuits usually have narrow bandwidth because the outer controlling loop has to be filter low-frequency AC-line ripple voltage, i.e. it leads to low step-response [9,10]. However, the following DC-AC inverter should be designed to compensate this deficiency by using wider bandwidth feedback circuit to make it have better response.

III. Experimental Results

To verify the feasibility of the proposed UPS, an 1KW UPS ($V_{in} = 110V$ AC / 60HZ) power-stage shown as Fig. 3 along with proper logic and feedback circuits was well implemented. Its DC-link voltage is 250V DC. The battery set has 5 12V/6AH-batteries with 10 minutes of back-up time for full-load. And, the flyback charger can supply 68V DC constantly to charge the battery set (current limit is 1 A) during AC-line normal operation.

Fig. 5 shows the input waveforms of the proposed UPS when the mains is normal. The dual-functional PFC performs mode (I) operation. We can find the input current is virtually sinusoidal and synchronized with the input voltage. Comparably, Fig. 6 also shows the input waveforms while the PFC does not startup. Fig. 7 illustrates internal PWM waveforms generation of the UPS's control board along with its zoomed figure of Fig. 8. Fig. 9 is the output waveforms with full-load during normal operation. Fig.10 shows the transferring waveforms of output voltage from mode (I) to mode (II), i.e. from mains normal to blackout. There is just a little bit glitch on t_1 . Fig. 11 exhibits the waveforms of load changing during outage, including the output

voltage and current. Initially, $t = t_0 \sim t_1$, the UPS was not imposed on any load. In the meantime, $I_o = 0$ and V_o keeps stable voltage. At $t = t_1$, a full-load (cold lamp) rushed into the UPS resulting in a cycle of voltage sagged around 70% of stable voltage. Then after 3 cycles of fluctuation, at $t = t_2$, it back into stable status again. Additionally, the main-switch S_1 can keep its temperature around 60°C under 20°C of surrounding, i.e. indicates small current difference of operational modes.

IV. Conclusions

In this paper a new single-phase on-line UPS structure with pre-staged dual-functional PFC has been proposed. The key parts, dual-functional PFC, is pre-staged for the proposed UPS and works as a boost converter during outage such that it can simplify the complexity of UPS structure. With economy-oriented power stage and good performance, the proposed structure can be a good candidate in the on-line UPS application.

Fig.1: Functional diagram of conventional single-phase on-line UPS. When mains normal, the blocks with # indicate active otherwise is inactive. When main failed, the blocks with @ indicate active otherwise is inactive.

Fig.2: Functional diagram of the proposed UPS. When mains normal, battery-switch open, the blocks with # indicate active otherwise is inactive. When main failed, battery-switch closed, the blocks with @ indicate active otherwise is inactive.

Fig.3: The proposed UPS structure using dual functional PFC.

Fig.4: The equivalent circuit of the proposed dual-functional PFC.

Fig.5: The input waveforms of the proposed UPS when the mains is normal, V_{in} (50V/div) and I_i (5A/div).

Fig. 6: The input waveforms without starting up the PFC when the mains is normal, V_{in} (50V/div) and I_i (5A/div).

Fig. 7: The internal PWM waveforms generation of the the proposed UPS, (0.2 ms/div, 2.0 V/div).

Fig. 8: The zoomed PWM waveforms of Fig. 7 (20 μ s/div, 2.0 V/div).

Fig. 9: The output waveforms of the the proposed UPS with full-load, V_o (50V/div) and I_o (5A/div).

Fig.10: The transferring waveforms of output voltage from from mains normal to blackout (50V/div).

Fig.11: The output waveforms of changing load for the proposed UPS

V. References

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