A battery-powered single-stage three-phase high step-up converter topology for micro DC-UPS

Ching-Ming Lai

Department of Vehicle Engineering, National Taipei University of Technology, 1, Sec. 3, Chung-Hsiao E. Rd., Taipei 106, Taiwan, R.O.C.

Abstract: A conventional battery-powered AC uninterruptible power supply (AC-UPS) that steps up low DC voltage to high DC voltage and cascades with the high frequency inverter is complicated in control and of low efficiency due to two-stage power conversion. This paper presents a three-phase high step-up converter with a single-stage DC/DC power conversion suitable for micro DC-UPS applications. In this paper, the circuit operating theory and steady-state analysis of the proposed topology are first addressed then a 100 V/110 W circuit prototype is designed, built and applied in 24 V-battery-powered micro DC-UPS for a 19 V/85 W laptop PC appliance. The feasibility and effectiveness of the proposed converter topology are confirmed with experimental results. The maximum conversion efficiency of the proposed converter is about 93.5%, and the overall efficiency of the designed system is high due to the losses in the power conversion process when reduced. Compared with the conventional AC-UPS, the proposed micro DC-UPS achieves potentially about 3% maximum energy savings.

Keywords: battery-powered, high step-up converter, micro DC-UPS

Classification: Electron devices, circuits, and systems

References

[1] S. Mondal and E. Keisling: IEEE International Conference on Power Electronics (2012) 1. DOI:10.1109/PEDES.2012.6484458
[2] D. Talapko: IEEE International Telecommunications Energy Conference (2012) 1. DOI:10.1109/INTLEC.2012.6374509
[3] T. Filchev, D. Cook, P. Wheeler and J. Clare: IET Power Electron., Machines and Drives Conf. (2008) 209.
[4] J. C. Rosas-Caro, P. M. Garcia-Vite, J. M. Lozano-Garcia, A. Gonzalez-Rodriguez, R. Castillo-Gutierrez and R. Castillo-Ibarra: IEICE Electron. Express 9 (2012) 1522. DOI:10.1587/elex.9.1522
[5] T. Funaki: IEICE Electron. Express 11 (2014) 20140350. DOI:10.1587/elex.11.20140350
[6] J. Mon, J. Gago, D. González, J. Balcells, R. Fernández, I. Gil and P. Bogónez: IEICE Electron. Express 6 (2009) 511. DOI:10.1587/elex.6.511
1 Introduction

An uninterruptible power supply (UPS) is essentially a back-up battery to power electronic gadgets like personal computer (PC) in the event of a power failure [1, 2]. UPS may be AC or DC types based on the output power supply [2]. In AC type (AC-UPS), that steps up low DC voltage to high DC voltage and cascades with the high frequency inverter is complicated in control and of low efficiency due to two-stage power conversion. This paper presents a single-stage DC-UPS structure with a high voltage gain DC/DC conversion for a better energy saving application. A high voltage gain is difficult to achieve with the traditional topologies of DC/DC converters because of several reasons such as: parasitic components and the requirement of an extreme duty cycles or transformers. This limits the switching frequency and systems size [3]. Some voltage multiplier techniques were also introduced for a boost converter in order to increase the static gain with reduced switch voltage [4]. However, in order to further reduce the voltage stress of active switches as well as electromagnetic interference (EMI) [5, 6], in this paper, a novel single-stage three-phase high step-up DC/DC converter topology is proposed and experimentally tested by a 100 V/110 W circuit prototype in 24 V-battery-powered micro DC-UPS to verify the feasibility.

2 Operating principles of the proposed high step-up converter

2.1 Circuitry and control arrangements

As shown in Fig. 1, as a battery-powered interface, the proposed high step-up converter consists of three-phase circuits with a interleaved pulse-width modulation (PWM) operation. The first phase is a boost integrated forward-type converter, which includes inductor $L_1$ and switch $S_1$ for the boost and the auxiliary forward circuit with turn ratio $N$. The second phase of the proposed converter is a boost circuit which contains inductor $L_2$, switch $S_2$, blocking capacitor $C_2$ and diode $D_2$, and the third phase of the proposed converter contains inductor $L_3$, switch $S_3$, blocking capacitor $C_3$ and diode $D_3$ followed by the common output capacitor $C_o$. From Fig. 1, one can see that the proposed converter is basically based on the voltage-doubler circuit [7] for the second and third phase circuit. However, in order to further reduce the voltage stress of active switches, the auxiliary forward circuit is now added to enhance the voltage conversion gain as well as conversion efficiency of the proposed converter.

2.2 Operating principles

Before analyzing the proposed three-phase high step-up converter the following assumptions are made:

1) For simplicity, assume all the components in Fig. 1(a) including the isolation transformer of the forward-type converter are assumed ideal.
2) The voltages and currents in the circuit are all periodic under steady-state.
3) For high step-up conversion, the duty of the main switch is defined as $D$ and it’s greater than 50% and the switching period is defined as $T_s$.

To analyze the circuit of the proposed three-phase high step-up converter, Fig. 2 illustrates all operating modes and their equivalent circuit according to the ON/OFF status of the active switches.

i) Mode 1, switches $S_1$ and $S_2$ are turned on. Diodes $D_2$ and $D_4$ are forward-biased, while diodes $D_1$, $D_3$, $D_5$ are reverse-biased. In this mode, both $i_{L1}$ and $i_{L3}$ are increasing to store energy in $L_1$ and $L_3$ respectively. Meanwhile, the input power is delivered to the secondary-side through the isolation transformer and inductor $L_f$ to charge capacitor $C_1$. The energy stored in $L_2$ is now released through $C_2$ and $D_2$ to charge capacitor $C_3$. Also, the output power is supplied from capacitor $C_o$.

ii) Mode 2, switch $S_1$ remains conducting, $S_2$ and $S_3$ are turned off. Diodes $D_1$, $D_5$ remain reverse-biased and $D_2$, $D_3$, $D_4$ are forward-biased. The energy stored in inductor $L_2$ and $L_3$ are now released through $C_2$, $C_3$, and $D_2$, $D_3$ to the output.

iii) Mode 3, both $S_1$ and $S_2$ are turned on. Diodes $D_1$, $D_2$, $D_3$ remain reverse-biased; $D_3$, $D_4$ are forward-biased. Currents $i_{L1}$ and $i_{L2}$ are increasing to store energy in $L_1$ and $L_2$ respectively. The energy stored in inductor $L_3$ is now released through $C_3$ and $D_3$ to the output.

iv) Mode 4, $S_1$ and $S_2$ are turned off and $S_2$ is turned on. Diodes $D_2$, $D_4$ are reverse-biased and $D_1$, $D_3$, $D_5$ are forward-biased. Since diode $D_4$ is reverse-biased, diode $D_5$ must turn on to conduct the inductor current $i_{L1}$. The energy stored in $L_1$ is released through $C_1$ and $D_1$ to charge capacitor $C_2$. The energy stored in third phase remains the same, the energy stored in $L_3$ is released through $C_3$ and $D_3$ to the output.

Fig. 1. (a) The circuit of the proposed three-phase high step-up converter topology as battery-powered interface; (b) PWM signals of the main power switches.
v) Mode 5, S2 and S3 are turned on and S1 is turned off. Diodes $D_2$, $D_3$, $D_4$ are reverse-biased and $D_1$, $D_5$ are forward-biased. Diode $D_5$ remains turned on to conduct the inductor current $i_{L1}$. The energy stored in $L_1$ is released through $C_1$ and $D_1$ to charge capacitor $C_2$. Both $i_{L2}$ and $i_{L3}$ are increasing to store energy in $L_2$ and $L_3$ respectively. Also, the output power is supplied from capacitor $C_o$.

vi) Mode 6, Switch S3 remains conducting; S1 and S2 are turned off. Also, diodes $D_3$, $D_4$ are reverse-biased and $D_1$, $D_2$, $D_5$ are forward-biased. The first phase circuit including the forward-type converter remains the same. The energy stored in inductor $L_1$ and $L_2$ are now released through $C_1$, $C_2$, and $D_1$, $D_2$ to charge the capacitor $C_3$. Also, the output power is still supplied from capacitor $C_o$.

![Diagrams of operating modes](image)

**Fig. 2.** Operating modes and equivalents circuits of the proposed converter topology.

### 3 Steady-state analyses and specifications of key devices
#### 3.1 Derivation of voltage conversion ratio

In order to get a better understanding about the merits of the proposed converter, steady-state analyses are made according to the equivalents circuits shown in Fig. 2. From Fig 2, it appears that capacitor average voltages $V_{C1}$, $V_{C2}$, and $V_{C3}$ can be expressed as Eq. (1) to Eq. (3). Also, the voltage conversion ratio of the proposed converter can be obtained as Eq. (4) to Eq. (6).

\[
V_{C1} = nD\frac{V_{IN}}{L_1}
\]
\[
V_{C2} = K_2a_mV_{IN} + K_2b_mV_O
\]
\[
V_{C3} = K_3a_mV_{IN} + K_3b_mV_O
\]
where,\[ K_{2am} = \frac{nD(9D^2 - 21D + 12)}{18D^2 - 36D + 19}, \quad K_{2bm} = \frac{(9D^2 - 15D + 7)}{18D^2 - 36D + 19}; \]
\[ K_{3am} = \frac{nD(9D^2 - 15D + 6)}{18D^2 - 36D + 19}, \quad K_{3bm} = \frac{(9D^2 - 18D + 10)}{18D^2 - 36D + 19}. \]

\[ \frac{V_O}{V_{IN}} = \frac{1 + (1 - D)K_{2al} - DK_{3al}}{1 - 2D - (1 - D)K_{2bl} + DK_{3bl}}; \quad 0 < D \leq \frac{1}{3}. \]  \( (4) \)

\[ \frac{V_O}{V_{IN}} = \frac{3 + 3(1 - D)K_{2am} - K_{3am}}{2 - 3D - 3(1 - D)K_{2bm} + K_{3bm}}; \quad 0 < D \leq \frac{1}{3}. \]  \( (5) \)

\[ \frac{V_O}{V_{IN}} = \frac{3}{1 - D} + nD; \quad \frac{2}{3} < D \leq 1. \]  \( (6) \)

where, \( K_{2al} = nD(1 - D), K_{2bl} = D \), \( K_{3al} = nD(1 - D)^2, K_{3bl} = (2D - D^2) \).

### 3.2 Voltage stress of key devices

It is quite straightforward from Fig. 2 and Kirchhoff’s voltage law to get the open circuit voltage stress of the corresponding active switches as Eq. (7) to Eq. (9).

\[ V_{DS1,max} = V_{C3} - V_{C1} = K_{3bm}(V_O - nDV_{IN}) \]  \( (7) \)

\[ V_{DS2,max} = V_O - V_{C2} = (1 - K_{2bm})(V_O - nDV_{IN}). \]  \( (8) \)

\[ V_{DS3,max} = V_O - V_{C3} = (1 - K_{3bm})(V_O - nDV_{IN}). \]  \( (9) \)

As Fig. 3(a) shows, the ideal voltage conversion ratio characteristic as a function of duty ratio for turn ratio \( n = 3 \). For comparison, the voltage gains of the voltage-doubler and the conventional two-phase interleaved boost converter are also shown in the same figure. It is seen from Fig. 3(a) that a much higher voltage gain can be achieved than that of the other two boost converters. Fig. 3(b) shows the corresponding voltage stress for three converters as a function of voltage conversion ratio, respectively.

**Fig. 3.** Characteristic analyses of the proposed converter: (a) voltage conversion ratio, (b) normalized switch voltage stress under different voltage conversion ratio.

### 4 Experimental system and measured results

In this paper, to verify the feasibility of the proposed converter, a 110 W circuit with the specifications as shown in Fig. 4 is built for 24 V-battery-powered micro DC-UPS test purpose.
4.1 Measured results of the proposed three-phase high step-up converter

Figs. 5~7 respectively show the experimental waveforms of PWM signals, blocking capacitors voltage, and output voltage of the proposed converter topology. In this figure, one can see that with the converter, the 200 V output can be achieved easily with a relatively smaller duty cycle of 59% and both blocking capacitors can indeed share most of the output voltage for reducing the voltage stress of active switches and diodes. Also, the simulated output voltage and blocking capacitors voltage are in close agreement with calculated values as shown in the above derivations. Due to the lower duty ratio, not only the output voltage regulation range can be further extended but also the resulting conduction loss can be further reduced. Naturally, the corresponding efficiency can be improved as well. The conversion efficiency of the proposed converter is measured by using a precision power analyzer (Yokogawa-WT500). As shown in Fig. 8, the measured conversion efficiency can be achieved to about 93.5%.
4.2 Performance of the proposed converter integrated with micro DC-UPS

For better understanding of the merits of the proposed single-stage high step-up converter, the constructed converter is further integrated in a 24 V-battery-powered micro DC-UPS for a 19 V/85 W laptop PC appliance. As shown in Table I, with the precision power analyzer (Yokogawa-WT500), the input to output power consumption records of the proposed micro DC-UPS is listed and compared with a conventional AC-UPS structure. With the proposed single-stage high efficiency converter can directly raise the low-voltage battery DC to a high voltage of 200 V for feeding the back-end stage. A commercial AC/DC universal adapter (85 W/19 V) with active power factor corrector (PFC) is adopted as the back-end stage for the proposed micro DC-UPS and the conventional AC-UPS. Due to a high voltage of 200 V injected to the universal adapter; compared with 110 V AC input, the conduction loss of the rectifier and PFC can be reduced. The conversion efficiency is improved naturally. Fig. 9 shows the proposed micro DC-UPS achieves about 3% maximum energy savings.

Fig. 6. Waveforms of blocking capacitor voltages (100 V/div, 5 us/div).

Fig. 7. Waveform of output voltage (50 V/div, 5 us/div).

Fig. 8. Conversion efficiency of the constructed converter under load variations.

4.2 Performance of the proposed converter integrated with micro DC-UPS

For better understanding of the merits of the proposed single-stage high step-up converter, the constructed converter is further integrated in a 24 V-battery-powered micro DC-UPS for a 19 V/85 W laptop PC appliance. As shown in Table I, with the precision power analyzer (Yokogawa-WT500), the input to output power consumption records of the proposed micro DC-UPS is listed and compared with a conventional AC-UPS structure. With the proposed single-stage high step-up converter, the front-end DC/AC conversion of first stage is eliminated; the proposed high efficiency converter can directly raise the low-voltage battery DC to a high voltage of 200 V for feeding the back-end stage. A commercial AC/DC universal adapter (85 W/19 V) with active power factor corrector (PFC) is adopted as the back-end stage for the proposed micro DC-UPS and the conventional AC-UPS. Due to a high voltage of 200 V injected to the universal adapter; compared with 110 V AC input, the conduction loss of the rectifier and PFC can be reduced. The conversion efficiency is improved naturally. Fig. 9 shows the proposed micro DC-UPS achieves about 3% maximum energy savings.
In this paper, the circuit operating theory and the steady-state analysis of the proposed topology are first addressed; a 100 V/110 W circuit prototype is built and applied to a 24 V-battery-powered DC-UPS for a 19 V/85 W laptop PC appliance. The feasibility and effectiveness of the proposed converter topology are confirmed with experimental results. The maximum conversion efficiency of the proposed converter is about 93.5%, and the overall efficiency of the designed system is high due to the losses in the power conversion process when reduced. Compared with the conventional AC-UPS, the proposed DC-UPS achieves potentially about 3% maximum energy savings under 85 W full-loaded condition.

### Acknowledgments

This research is sponsored by the Ministry of Science and Technology, Taiwan, under contracts NSC 102-2218-E-033-004. It is also sponsored by the Ministry of Education, Taiwan, under NTUT Technological University Paradigms.