Energy Storage Unit for Uninterruptible Power Supply

Sun Pil Kim and Feel-soon Kang
Hanbat National University, Dept. of Control and Instrumentation Engineering, Daejeon 305-719, KOREA
feelsoon@ieee.org, *feelsoon@hanbat.ac.kr*

ABSTRACT: Uninterruptible power supply employing a series connected battery and capacitor as a dc-link is proposed to achieve a simple circuit configuration and higher system reliability. It reduces the number of switching devices by applying a common-arm scheme, and it shows fast response for a power failure owing to a dc-to-dc converter. Operational principles to normal, stored-energy, and bypass mode are discussed in detail. The validity of the proposed UPS system is verified by experimental results using a prototype.

1 INTRODUCTION

Generally uninterruptible power supply (UPS) is used to maintain a stable electric power supply to critical loads with high quality power protecting them against unexpected power failure. For example, medical facilities and data-storage computer systems require fast response, compensation and immediate availability of electrical power. Considerably affect these characteristics is energy storage units like a battery bank. Energy storage units in UPS system should supply power to the load when the ac line fails. If they are not capable to implement this important role, then the whole UPS system fails even though it employs well-designed power electronics circuits. To satisfy the requirements, we propose a common-arm based UPS equipped with a dc-to-dc converter employing an energy storage unit. The proposed UPS consists of ac-to-dc and dc-to-ac converter sharing a common-arm, a static switch for bypassing, and the proposed dc-to-dc converter. The ac-to-dc converter is used for maintaining the input current sinusoidal and in phase with the input ac voltage to obtain high power factor. It also supplies the desired dc-link voltage suitable for proper operation of back-end inverter. The dc-link is a part of the proposed dc-to-dc converter. It has a series connection of a battery bank and a capacitor. The dc-to-ac inverter needs to synthesize high quality output voltage wave. Operational mode is analyzed and the validity of the proposed UPS with the energy storage unit is verified by experimental results.

2 UPS WITH THE PROPOSED CONVERTER

2.1 *Circuit Configuration*

Generally, UPS system is divided into four parts: an ac-to-dc converter, an energy storage unit, a dc-to-ac inverter, and a static switch for bypassing. The ac-to-dc converter is used to produce high quality dc voltage for adequate operation of the back-end dc-to-ac inverter, and it also needs to obtain high power factor satisfying the corresponding regulation. The dc-to-ac inverter is to synthesize high quality ac output voltage to feed the load. The ac-to-dc converter charges the battery maintaining constant dc link voltage. To sustain high dc-link voltage, lots of battery cells need to be connected in series. It causes some problems related to system cost, space, reliability, and safety considerations to increase dc-link voltage. To alleviate the high voltage battery problem, the most useful technique is to employ a bi-directional dc-to-dc converter. The main circuit configuration for power conversion is based on single-phase voltage regulator, which has a common-arm between the ac-to-dc converter and the dc-to-ac inverter. It steps down the high dc-link voltage to low battery voltage during the normal mode operation, and step up the low battery voltage to high dc-link voltage during the stored-energy mode operation. The bi-directional dc-to-dc converter is usually applied to on-line UPS system.

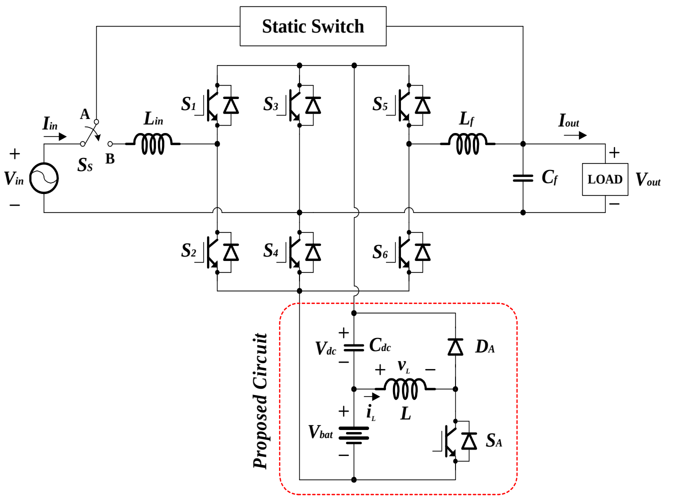


Figure 1. UPS with the proposed converter.

The proposed UPS system consists of ac-to-dc and dc-to-ac power converter sharing a common-arm, an energy storage unit, and a static switch for bypassing as given in Figure 1. The ac-to-dc converter includes an input boost inductor (L_{in}), switching devices (S_1 and S_2), and a dc-link which has a series connection of a battery bank and a capacitor (V_{dc} and V_{bat}). During a stored energy mode operation, the voltage across the dc-link is controlled by the proposed dc-to-dc converter which consists of a switch, a diode, and an inductor. The objective of the ac-to-dc converter is to maintain the input current sinusoidal and in phase with the input ac voltage to obtain high power factor. It also supplies the desired dc-link voltage suitable for proper operation of back-end inverter during a normal mode operation. It needs to synthesize high quality output voltage wave. The dc-to-ac inverter consists of switching devices (S_5 and S_6), and common-arm switches (S_3 and S_4) are used to ac-to-dc converter and dc-to-ac inverter at the same time.

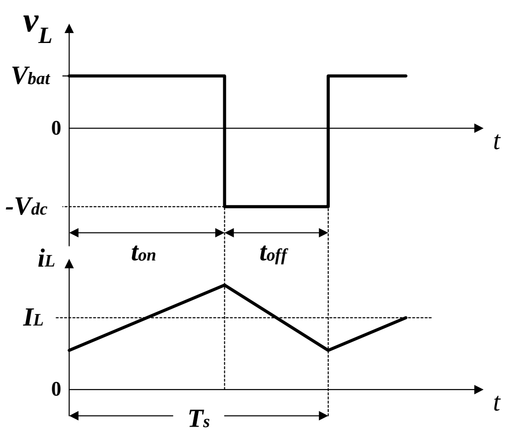


Figure 2. Key waveforms of the proposed converter.

The output terminal of the converter is composed of a series-connected a battery bank and a capacitor. The dc-link voltage becomes the sum of voltage across the capacitor (V_{dc}) and the battery voltage (V_{bat}), namely $V_{dc\text{-}link} = V_{dc} + V_{bat}$. Figure 2 shows the steady-state waveforms for continuous current conduction mode (CCM) operation where the inductor current flows continuously at $i_L(t)>0$. By applying a volt-second balance law to the inductor, the ratio of the output to the input voltage of the proposed converter is given by

$$M_V(D) = \frac{V_{dc-link}}{V_{bat}} = \frac{1}{1-D} \tag{1}$$

where D = t_{on}/T_S. From (1), we can notice that the voltage conduction ratio of the converter is exactly same with the boost converter. Therefore, the output voltage is always greater than the input voltage. On the other hand, the output voltage is always clamped by the sum of the battery voltage and the capacitor voltage. Reflecting this fact, the boosting rate of the output voltage to the battery voltage internally depends on that of the capacitor voltage, and thus we derive (2) from (1).

$$M_{VC}(D) = \frac{V_{dc}}{V_{bat}} = \frac{D}{1-D} \tag{2}$$

Using (1) and (2), the ratio of the output voltage to the capacitor voltage is defined by

$$\frac{V_{dc-link}}{V_{bat}} \cdot \frac{V_{bat}}{V_{dc}} = \left(\frac{1}{1-D}\right) \cdot \left(\frac{1-D}{D}\right) = \frac{V_{dc-link}}{V_{dc}} = \frac{1}{D} \tag{3}$$

From (2) and (3), the voltage conversion ratio M_{VC}(D), the ratio of the output capacitor voltage (V_C) to the battery voltage is equal to that of the buck-boost converter, and the voltage relation between the dc-link voltage and the capacitor voltage is equal to that of buck converter.

2.2 Normal Mode Operation

When the input ac voltage is within the allowable tolerance range, the UPS system operates in normal mode. The input power is transferred to the output load via the ac-to-dc converter and the dc-to-ac inverter. During this mode, voltage across the dc-link is maintained by the ac-to-dc converter. It means the battery bank is at 100 % state of charge. The selection switch (S_s) in the input stage is lying at position B.

2.3 Stored Energy Mode Operation

When the input ac voltage is out of the allowable tolerance range or is not available at all, the UPS system changes its operational mode from normal mode to stored-energy mode. Power line disturbances include various statuses of power line faults and input voltage derivations such as power outage, voltage fluctuations, under or over voltage, surge, occasional frequency fluctuations, and voltage harmonics. When these kinds of faults are occurred, the input switch disconnects the UPS from the grid transferring the input from the ac line to current power source unit. During this mode, the switches of the ac-to-dc converter (S_1 and S_2) are not working. So the proposed converter should supply energy to the output load instead of the grid. By controlling of the switch S_A, it can maintain voltage across the dc-link constant using the battery source.

2.4 Bypass Mode Operation

The static switch is used to bypass the UPS system in case of failure or if maintenance is required. The UPS system also operates in bypass mode in case of malfunction. In this case, the output frequency should be equal to that of the ac line frequency to ensure transferring from normal to bypass mode and vice versa.

3 DESGN GUIDELINE

Various approaches are allowable to design power stages, and some iteration may be required when performance differs from design predictions. From the analysis of the boundary condition of the proposed converter, the inductor (L) value can be calculated by

$$L = \frac{T_S \cdot V_{dc-link} \cdot D}{2 \cdot I_{OB}} \quad (4)$$

Here, T_s means the switching period, $V_{dc\text{-}link}$ is the dc-link voltage controlled by the ac-to-dc converter. D is the duty ratio of the switch (S_A), and I_{OB} is the average output current. Generally, the capacitor is selected to regulate ripple voltage to the level required by the specification, but in a ripple regulator such as this, the control circuit determines the output voltage ripple. The output voltage ripple is relatively independent of the output capacitor characteristics. Since output voltage ripple is set, the output capacitor is chosen to provide satisfactory response to fast load transients. In the proposed converter, assuming that all ripple current component of the diode current flows through the load resistor, the peak-to-peak voltage ripple is given as

$$\frac{\Delta v_{dc-link}}{V_{dc-link}} = \frac{D \cdot T_S}{RC_{dc}} = D \cdot \frac{T_S}{\tau} \quad (5)$$

Here, τ is the time constant. Rearranging (5), the capacitor value yields as

$$C_{dc} = \frac{D \cdot T_S}{R} \times \frac{V_{dc-link}}{\Delta v_{dc-link}} \quad (6)$$

Considering off state of the converter switch, the voltage rating of the switch (V_{SA}) should meet the following relation.

$$V_{S_A} \geq v_L + v_{bat} \quad (7)$$

Similarly, voltage rating of the freewheeling diode (V_{DA}) should satisfy the next relation.

$$V_{D_A} \geq v_{dc-link} \quad (8)$$

4 EXPERIMENTAL RESULTS

The validity of the UPS system with the proposed converter was verified by a laboratory prototype. Input voltage is 220V, 60 Hz, and the output voltage is generated to get the same values of the input voltage. Voltage across the dc-link is controlled to 385 V. The operating frequency of the switch in the proposed converter is set to 10 kHz. A digital controller based on a TMS320C240 was designed to ensure the stability and dynamic response of the UPS system.

Figure 3 shows the operational waveforms of the proposed converter when the UPS is in the stored energy mode operation. It shows voltage across the capacitor, diode current, and inductor current in sequence. When the voltage across the dc-link is dropped by certain reasons, the switch in the proposed converter starts to meet the voltage requirement.

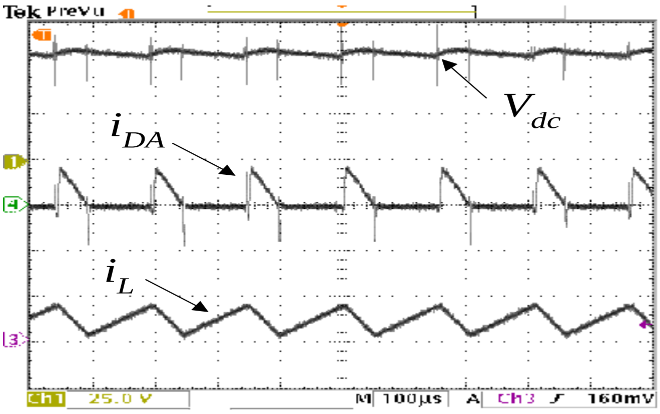
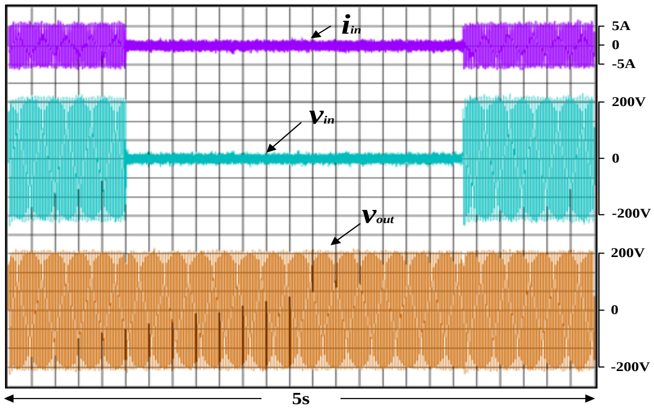
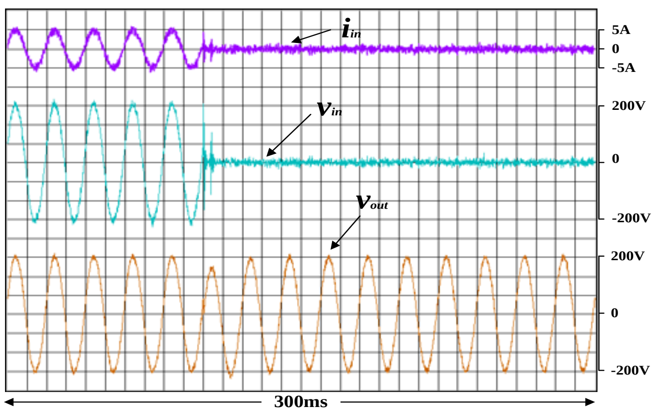


Figure 3. Key waveforms of the proposed converter.

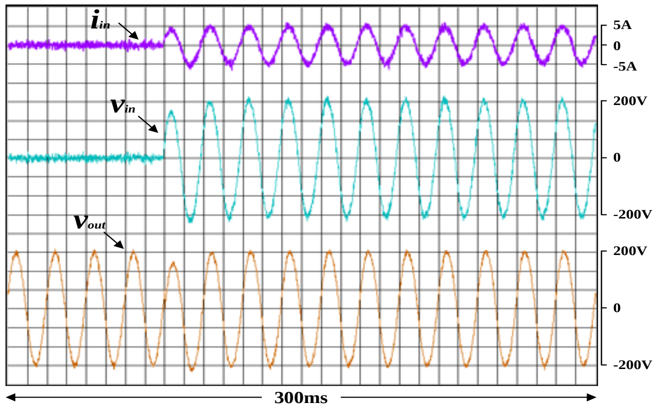
Figure 4(a) shows experimental result waveforms of input voltage (V_{in}), input current (I_{in}), and output voltage (V_{out}), respectively. During the outage of 3 [sec], the proposed UPS system maintains the output voltage constant. Its magnified waveforms before and after the power interrupt are given in Figure 4(b) and Figure 4(c), respectively. The output voltage is regulated sufficiently well within 10 % regardless of the variation of input voltage.



(a)



(b)



(c)

Figure 4. Operational waveforms with the outage of 3 seconds, (a) input current, input voltage, and output voltage during 5 seconds, (b) magnified waveforms when the outage is occurred, (c) magnified waveforms when the outage is finished.

The input power factor is measured over 0.98, and the input current THD (total harmonic distortion) is less than 3 % regardless of the power rating. The overall system efficiency at normal mode operation was measured about 90 %, and 91 % at stored-energy mode operation. 1 % increasing of the efficiency comes from the reduction of switching losses by the ac-to-dc converter.

5 CONCLUSIONS

Uninterruptible power supply employing a series connected battery and capacitor as a dc-link is proposed and the validity of the UPS system equipped with the proposed converter is verified by experimental results using a prototype. Presentable achievements are summarized as:

(1) Simple circuit configuration,
(2) Fast response to outage,
(3) High efficiency: over 90 [%].

As results, the proposed UPS system with the proposed converter employing an energy storage unit can be a powerful candidate in the UPS market.

REFERENCES

D. M. Divan, "A new topology for single-phase UPS systems," *IEEE IAS Conf.*, pp. 931-936, 1989.

H. W. Park, S. J. Park, J. G. Park, and C. U. Kim, "A novel high-performance voltage regulator for single-phase ac sources," *IEEE Trans. Ind. Elect.*, vol. 48, no. 3, pp. 554-562, 2001.

I. Andoh, A. et al., "Development of a high efficiency flywheel UPS using three arms inverter/converter inverter/converter," *IEE Trans. Japan*, vol. 116-D(11), pp. 1153-1158, 1996.

J. Holtz, "Pulse width modulation-A survey," *IEEE Trans. Ind. Elect*., vol. 39, pp. 410-420, 1992.

K. Hirachi, A. Kajiyama, T. Mii, and M. Nakaoka, "Cost-effective bidirectional chopper-based battery link UPS with common input-output bus line and its control scheme," *IEEE International Conference on Industrial Electronics*, vol. 3, pp. 1681-1686, 1996.

Noriyuki Hirao, Tetsuichi Satonaga, Takeshi Uematsu, Teruhiko Johama, Tamotsu Ninomiya, and Masahito Shoyama, "Analytical considerations on power loss in a three-arm-type uninterruptible power supply," *IEEE Power Elect. Special Conf.*, pp. 1886-1890, 1998.

R. Krishnan and S. Srinivasan, "Topologies for uninterruptible power supplies," *IEEE International Symposium on Industrial Electronics*, pp. 122-127. 1993.

S. Bowes, "Development in PWM switching strategies for micro-processor-controlled inverter drives," *IEEE IAS Conf*. pp. 323-329, 1987.

Shamim Choudhury, "Implementing triple conversion single-phase on-line UPS using TMS320C240," *TI Application Report*, SPRA589A, 1999.