Single-phase Uninterruptible Power Supply employing Superconducting Magnet Energy Storage Unit

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Abstract—A single-phase uninterruptible power supply system equipped with a superconducting magnet energy storage unit is proposed to achieve a simple circuit configuration and higher system reliability. It reduces a number of switching devices by applying a common-arm scheme. Removing some switches or substituting passive elements for active switches can increase the sophistication and reduces degree of freedom in control strategy. However, high-performance DSP controller can execute the complicated control task with no additional cost. Operational principles to normal, stored-energy, and bypass mode are discussed in detail. The validity of the proposed system is verified by experimental results.

Index Terms—digital signal processor (DSP), power factor correction (PFC), superconducting magnet energy storage (SMES), uninterruptible power supply (UPS).

I. INTRODUCTION

Uninterruptible power supplies (UPS) have been used to sustain a continuous power supply to certain critical loads protecting them against unexpected power outages as well as over and under voltage conditions. Some applications such as data-storage computer systems, medical facilities, and telecommunications require fast response, compensation and instant availability of electrical power. One of important components that considerably affect these characteristics is energy storage units like a battery bank. Traditional batteries such as lithium, lead-acid, nickel-hydrogen, nickel-cadmium, and vanadium are available for the use of energy storage. However, they are usually distressed by their short lifecycle, late responses in charging or discharging, and environmental problems. Energy storage units in UPS system must supply electric power to load when ac line fails. If it is not capable of implementing this important role, then the whole UPS system fails even though it employs high-performance controller and well-designed power electronic circuits [1],[2].

In recent years, superconducting magnet energy storage (SMES) unit has been received a great attraction as an energy storage unit instead of conventional batteries owing to the dynamic capabilities and long-term lifecycle of SMES. A lot of UPS systems employing SMES unit have been reported and developed [3]-[12]. Most of them are focused on high power and three-phase applications. Those applications are unlikely to consider on the circuit complexity and production cost because the most important factor is the stabilization of the system rather than the system configuration and cost. However, a case where it is applied to low power applications, the SMES-based UPS system will be more focused on the design of simple and robust circuit with low system cost. Except the SMES itself, the largest cost reduction is achieved by minimizing the number of switching devices used in a power conversion system. Reducing a number of switching devices and other elements in UPS system can save the system cost, and it has several other merits such as superb compactness and higher reliability as well.

In this paper, a single-phase DSP-controlled uninterruptible power supply system equipped with SMES unit is presented to achieve a simple circuit configuration and higher system stability. The proposed power conversion circuit is based on the integration of half-bridge configurations. It can reduce a number of switching devices by applying a common arm scheme. Operational principles are illustrated with useful discussions, and then the validity of the proposed SMES-based UPS system is verified by experiments using a laboratory prototype.

II. PROPOSED SMES-BASED UPS SYSTEM

General UPS system is divided into several parts according to functional purposes: ac-to-dc converter, energy storage unit, dc-to-ac inverter, and static switch for bypassing as shown in Fig. 1. The objective of ac-to-dc converter is to produce high quality dc voltage for adequate operation of dc-to-ac inverter, and it also needs to obtain high power factor satisfying the corresponding regulation. The purpose of dc-to-ac inverter is to synthesize high quality ac output voltage to feed output loads.

In Fig. 1, 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 space, cost, reliability, and safety considerations to increase. To alleviate the high voltage battery problem, the most useful technique is to employ a bi-directional dc-to-dc

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converter as shown in Fig. 2 [10]. The main circuit configuration for power conversion is based on single-phase voltage regulator, which has a common-arm between ac-to-dc converter and dc-to-ac inverter. It steps down the high dc-link voltage (V_{dc}) to low battery voltage (V_{bat}) during normal mode operation, and step up the low battery voltage to high dc-link voltage at stored-energy mode operation. This bi-directional dc-to-dc converter is usually applied to on-line UPS systems.

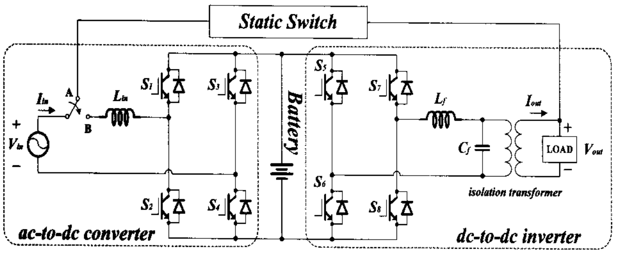


Fig. 1 Configuration of a typical single-phase UPS system using full-bridge structures.

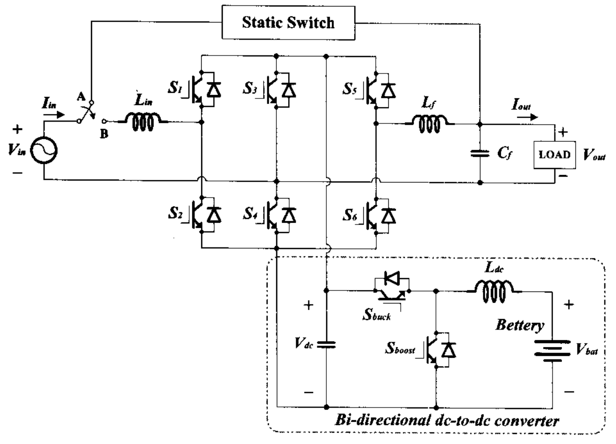


Fig. 2 Configuration of a common-arm approached single-phase UPS system employing bi-directional dc-to-dc converter.

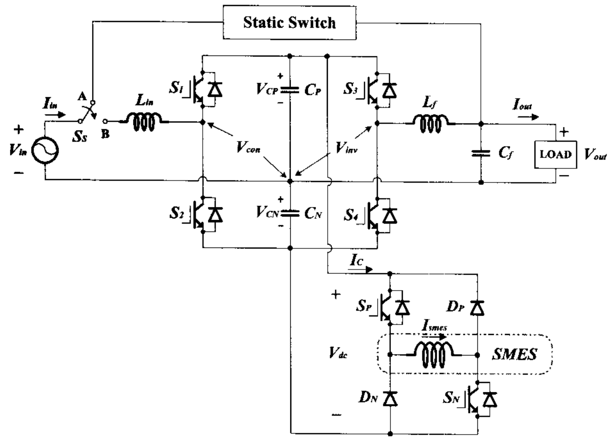


Fig. 3 Proposed single-phase SMES-based UPS system.

The UPS system based on full-bridge converters has useful merits over the one based on half-bridge converters, such as better utilization of dc link voltage, twofold-lower voltage stresses across the switches; however, it is suffered from the large number of switching devices. It also requires an isolation transformer at the back-end as shown in Fig. 1. The use of low switching frequency transformer results in bulky, heavy, and the increase of system cost. That is why the UPS system based on half-bridge converters is recommendable for low power applications. It not only has twofold-lower number of switches than the UPS topology from Fig. 1, but also has a common neutral point for the input and the output, eliminating the requirement for a galvanic isolation transformer [11],[12].

To more minimize the number of power switching devices, full-bridge configuration can be substituted for the half-bridge structure employing two dc capacitors as shown in Fig. 3. The proposed UPS system consists of ac-to-dc and dc-to-ac power converter sharing a common-arm, a SMES unit, and a static switch for bypassing. The ac-to-dc converter includes an input boost inductor (L_{in}), switching devices (S_1 and S_2), and two capacitors (C_P and C_N). 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. The dc-to-ac inverter consists of switching devices (S_3 and S_4), split dc-link capacitors, and output LC filter. It needs to synthesize high quality output voltage wave. The SMES is used for the use of energy storage unit. The SMES controller consists of two switches (S_P and S_N), and two diodes (D_P and D_N).

The SMES stores energy in the magnetic field generated by the dc current flowing through a superconducting coil. The inductively stored energy in joules is commonly given as

$$E_{smes} = \frac{1}{2} \cdot L_{smes} \cdot I_{smes}{}^2 \qquad (1)$$

Here L_{smes} is the inductance of the SMES coil. I_{smes} is the dc current flowing through the coil. Since the energy is stored as circulating current, energy can be drawn from the SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours. The SMES unit consists of a large superconducting coil at the cryogenic temperature. This temperature is maintained by a cryostat that contains helium liquid vessels. A power converter connects the SMES unit to an ac power system, and it is used to charge or discharge the coil. The SMES coil is charged or discharged by applying positive or negative voltages across the superconducting coil.

2.1. Operational principle

2.1.1. Normal mode operation

A case where the input ac voltage is within allowable tolerance ranges, the proposed UPS system operates in normal mode. The input power is transferred to output load via ac-to-dc converter and dc-to-ac inverter. The SMES control switches keep the SMES at 100 % state of charge. The selection switch (S_s) in the input stage is lying at position B.

2.1.1.1. Ac-to-dc converter

During positive cycle of the input ac voltage, S_2 is conducting; thus, voltage across the input boost inductor yields

$$V_{Lin} = L_{in}\cdot\frac{di_{in}}{dt} = V_{in} + V_{CN}\cdot \qquad (2)$$

The inductor current will increase with the slope of V_{Lin}/L_{in} following the current path of $V_{in} - L_{in} - S_2 - C_N - V_{in}$. When S_2 stops conducting, the upper capacitor (C_P) is charged with the energy stored in the boost inductor. Therefore, voltage across the inductor yields

$$V_{Lin} = L_{in}\cdot\frac{di_{in}}{dt} = V_{in} - V_{CP}\cdot \qquad (3)$$

Because the amplitude of V_{CP} is higher than that of V_{in}, voltage across the inductor becomes negative and the inductor current decreases. The input power factor and dc voltage of the upper capacitor are controlled by the duty ratio of switch (S_2). On the other hands, during negative cycle, input power factor and dc voltage of the lower capacitor are controlled by the duty ratio of upper switch (S_1).

2.1.1.2. SMES controller

During the normal mode, the SMES controller charges the SMES coil by means of switching of S_P and S_N. The voltage across SMES coil yields

$$V_{smes} = L_{smes}\cdot\frac{di_{smes}}{dt} = V_{dc}\cdot \qquad (4)$$

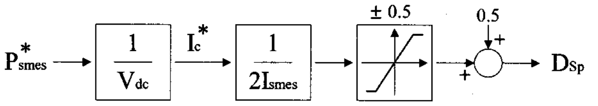


Fig. 4 SMES controller.

Fig. 4 shows the principle of determination of duty ratio. It controls the duty ratio of S_P, whereas S_N is continuous conducting. The duty ratio is given as

$$D_{Sp} = 0.5 + \frac{I_C}{2\cdot I_{smes}}\cdot \qquad (5)$$

Here I_C means the supplied current from the input source.

2.1.1.3. Dc-to-ac inverter

The dc-to-dc inverter is also based on half-bridge configuration. It consists of two switching devices (S_3 and S_4), and two identical dc capacitors C_P and C_N connected in series. By controlling of S_3 and S_4, the voltage across the load becomes + $V_{dc}/2$ or – $V_{dc}/2$. Because these switches operate alternately, there is always a dead time to avoid arm-short.

2.1.2. Stored-energy mode operation

A case where the input ac voltage is out of allowable tolerance ranges 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-and over-voltage, voltage surge, sporadic frequency fluctuations, and voltage harmonics. When these kinds of faults are occurred, the input switch disconnects the UPS system from the grid transferring the input from the ac line to SMES unit.

2.1.2.1. Ac-to-dc converter

During this mode, the switches of ac-to-dc converter (S_1 and S_2) are not working.

2.1.2.2. SMES controller

During the stored-energy mode, the SMES controller should supply energy to output load instead of the grid. The switches of S_P and S_N work at the same time. When these switches are turned off, the SMES current flowing through D_P and D_N charging C_P and C_N, and the duty ratio is also determined by (5).

2.1.2.3. Dc-to-ac inverter

The operation of the dc-to-ac inverter in the stored-energy mode is the same as that in the normal mode operation.

2.1.3. 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.

2.2. Control strategy

2.2.1. Input PFC control

To obtain high input power factor, it requires a proper PFC control scheme.

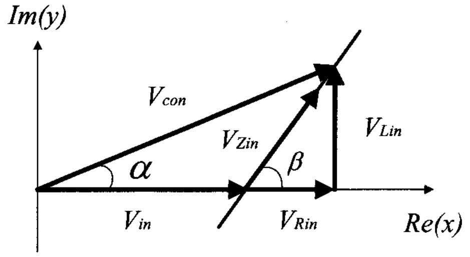


Fig. 5 Phasor diagram for power factor correction.

Fig. 5 shows the phasor diagram to achieve high power factor. It considers on the case when power is supplied from the ac source to load. V_{con} is presumed that it can be controlled instantaneously. Here, V_{Rin} is the voltage drop of the equivalent resistance. V_{Lin} and V_{Zin}

mean the voltage drops of equivalent inductance and impedance at the input terminal, respectively. α is the angular frequency of the input source. The angle of the input impedance of ac-to-dc converter is given as β. In this diagram, V_{in} should be controlled on the solid line to control the input current being in phase with the input voltage [13]. The solid line is defined as

$$y = \frac{V_{Lin}}{V_{Rin}}(x - V_{in}) \cdot \qquad (6)$$

Here x is the axis of the real component, and y means the axis of the imaginary one. Note that the input voltage is internally expressed as

$$V_{in} = V_{Lin} - \frac{V_{dc}}{2}\left(= V_{CP} \quad or \quad = V_{CN}\right) \cdot \qquad (7)$$

Thus, the magnitude and phase angle of V_{con} to obtain unity power factor are given as

$$\left|V_{con}\right| = \sqrt{\left(\frac{V_{Rin}}{V_{Lin}} y + V_{in}\right)^2 + y^2} \qquad (8)$$

$$\alpha = \tan^{-1} \frac{y}{\left(\frac{V_{Rin}}{V_{Lin}}\right) y + V_{in}} \cdot \qquad (9)$$

$$\beta = \tan^{-1} \frac{V_{Lin}}{V_{Rin}} \cdot \qquad (10)$$

In (9), a case where the initial angle of the source voltage (α_0) is assumed zero, α means the delay angle of the input voltage. Consequently, the phasor V_{con} can be easily calculated by choosing the value of y. The relationship between the duty ratio of the converter switches and V_{con} is given as

$$D_{S1(S2)} = \frac{\left|V_{con}\right|}{V_{dc}} \cdot \qquad (11)$$

In (10), it is obvious that the absolute value of V_{con}, i.e., the vector sum of V_{in} and V_{Zin}, should be limited to be equal to or less than V_{dc} ($D_{S1(S2)} \leq 1$) to ensure the stable operation.

2.2.2. Output voltage regulation

The dc-to-ac inverter is required to synthesize desired amplitude and frequency of the output waveform regardless of the kinds of loads. To minimize the harmonic distortion of the output waveform, the dc-to-ac inverter usually employs pulse-width-modulation(PWM) technique [14]. Although various PWM techniques can be applied to the proposed system, a popularly used sinusoidal-PWM method is employed for conciseness. As a result, the amplitude of the output voltage is directly proportional to the duty ratio of D_{S3} and D_{S4}, and given as

$$D_{S3(S4)} = \frac{\left|V_{inv}\right|}{V_{dc}} \cdot \qquad (12)$$

To ensure transferring from normal to bypass mode, V_{in}, V_{con}, and V_{inv} would be in phase because the output frequency should be equal to the ac line frequency.

III. RESULTS AND DISCUSSIONS

To verify the performance of the proposed SMES-based UPS system, it was implemented using a laboratory prototype.

Table 1 Specifications of the proposed UPS system

Item	Symbol	Feature
Switch	S1-S4, SP, SN	IGBT CM100DY-24A IC=100A / VCES=1200V
Diode	DP, DN	IGBT CM100DY-24A Internal body-diode
Input boost inductor	Lin	1 mH
Output filter inductor	Lf	0.5 mH
Output filter capacitor	Cf	47 μF
Switching frequency	fs	2 kHz
Rated dc-link voltage	Vdc	385 V
Input voltage	Vin	110 V / 60 Hz
Output voltage	Vout	0 ~ 110 V

Table 1 lists the specification of the proposed UPS system. A digital controller equipped with a TMS320C240, which has a 50 ns instruction cycle time was designed to ensure the stability and dynamic response of the proposed UPS system. It also provides programmability and immunity to noise [15],[16].

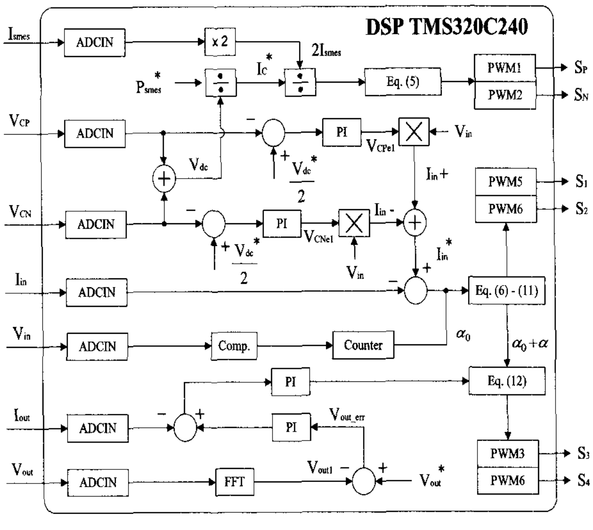
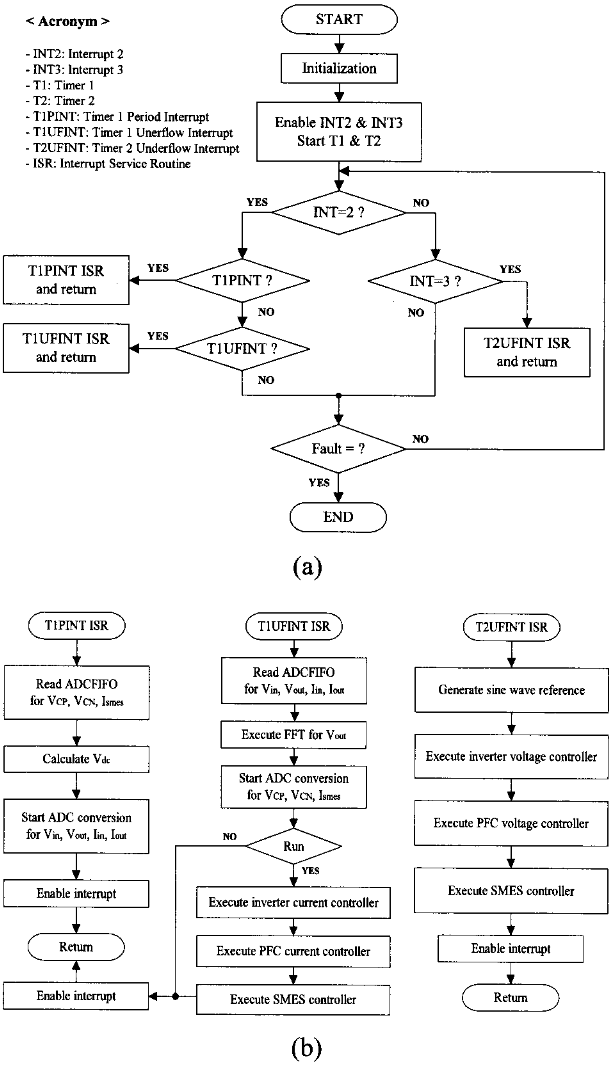


Fig. 6 Control block diagram.

Fig. 6 shows a control block diagram for the proposed UPS system. Here, the asterisk (*) means the reference value. Four signals are required to carry out the PFC control algorithm: input voltage (V_{in}), input inductor current (I_{in}), upper dc capacitor voltage (V_{CP}), and lower dc capacitor voltage (V_{CN}). These signals are obtained through the voltage and current sense amplifier, and then fed back to the DSP via ADC channels (ADCIN). The sensed dc capacitor voltages (V_{CP} and V_{CN}) are compared with the reference voltage ($V_{dc}*/2$). The difference between the reference and each capacitor voltage is fed into PI (Proportional and integration) regulator. Each output of the PI regulator is V_{CPel} and V_{CNel}, respectively. These are multiplied by the input voltage (V_{in}); then it synthesizes the reference input current command for the positive and negative half cycles of $I_{in}*$, i.e., $I_{in}+$ and $I_{in}-$, respectively. It is transferred to the equation block (6)-(11). The input voltage (V_{in}) is passed through the comparator to determine the polarity of the input voltage, and it also detects the initial phase angle (α_0) by using the counter function. Based on these signals, Eq. (6)-(11) block calculates the duty ratio of the switches (*S1* and *S2*).



(a)

(b)

Fig. 7 Software organization, (a) main program, (b) interrupt service routines.

For the regulation of the output voltage, the output voltage (V_{out}) and the output current (I_{out}) are sensed and then they are fed back to the DSP via corresponding ADCINs. The sensed output voltage (V_{out}) is passed through FFT block to extract the fundamental component. The difference between the output voltage reference ($V_{out}*$) and the fundamental output voltage (V_{out1}) is given as an input of PI regulator. The output of the PI regulator is compared with the sensed output current, and then it is passed to the Eq. (12) block via PI regulator. The Eq. (12) block also receives the phase angle information from the Eq. (6)-(11) block. That is to say, it is based on the current mode control, which has two-loop control system. It is useful to simplify the design of the outer voltage loop and to improve the dynamic characteristics. Based on this procedure, Eq. (12) block calculates the proper duty ratio for the switches (*S3* and *S4*).

To operate the SMES control switches, it requires two feedback signals: the current flowing through SMES coil (I_{smes}) and voltage across the dc-link capacitor (V_{dc}). It uses the internal preset command power to regulate the SMES charging current rating. Voltage across the series connected capacitors (V_{dc}) is indirectly obtained by the sum of the V_{CP} and V_{CN}.

Fig. 7(a) shows the flowchart for the main program [16]. The general-purpose Timer 1 is used to provide the time base for PWM generation, ADC sampling, and current control loop. The time base for the voltage control loop is generated from the Timer 2. Interrupt sources of INT2 are the period and underflow interrupts of Timer 1. As show in Fig. 7(a), once an interrupt is occurred, it branches to the corresponding interrupt service routines (ISR). A case where T1PINT is occurred, it goes to Timer 1 period interrupt service routine (T1PINT ISR). In this service routine, the program reads three converted signals (V_{CP}, V_{CN}, and I_{smes}) from ADC registers (ADCFIFO) and then it calculates V_{dc} by adding V_{CP} to V_{CN}. After finishing this work, it starts ADC conversion for the input and output information (V_{in}, V_{out}, I_{in}, and I_{out}). T1UFINT ISR performs the required current control algorithm during normal mode operation of the proposed UPS system. It executes inverter controller, PFC controller, and SMES controller for controlling the duty ratio of S_P (while S_N maintains continuous conduction) in sequence. When the UPS system is operated in stored-energy mode, the program will not execute the PFC controller. Instead, it executes the duty ratio control of S_N to SMES controller. There is no change in the operation of the inverter controller.

The source of INT3 is only T2UF (Timer2 underflow), and it is made interruptible by the T1 interrupts. Therefore, once INT3 is occurred, prior contexts are stored in the stack before branching to T2UFINT ISR. During this service routine, the program enables the interrupts to allow serving of T1 interrupts when they are occurred. After enabling interrupts, the program generates the reference sine wave, and then it executes PFC voltage controller, SMES control algorithms. After finishing these sequences, the program returns to the main program.

Table 2 shows the specification of the equipped SMES unit such as electrical and magnetic parameters and dimensions of the magnet.

Table 2 Specification of the equipped SMES

Item	Value	Unit
Inner diameter	494	mm
Outer diameter	310	mm
Axial length	255	mm
Rated current	2976	A
Centeral magnetic field	5.0	T
Maximum magnetic field	6.1	T
Stored energy	515	kJ

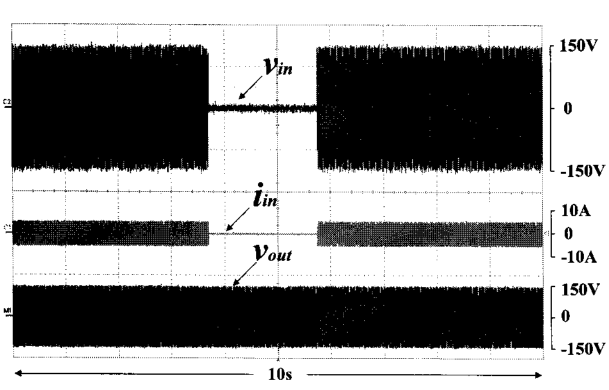
The command power of the SMES unit ($P_{smes}*$) is internally preset as 10 [kW]; thus, the current flowing through the SMES coil is regulated by the dc-link voltage (V_{dc}), and the relationship is given as

$$I_{smes} = \frac{P^*_{smes}}{V_{dc}} = \frac{10 \times 10^3}{385} \approx 25.974\,[\mathrm{A}]. \qquad (13)$$

Fig. 8 shows experimental result waveforms of input voltage (V_{in}), input current (I_{in}), and output voltage (V_{out}), respectively. During the outage of 2 [sec], the proposed SMES-based UPS system maintains the output voltage constant as shown in Fig. 8(a). Its magnified waveforms before and after the power interrupt are given in Fig. 8(b) and Fig. 8(c), respectively. The output voltage is regulated sufficiently well within 10 % regardless of the variation of input voltage.

Fig. 9 shows the input voltage with the superimposed input current waveform at normal mode operation. 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.

Fig. 10 shows output voltage, load current, and their FFT results at normal mode operation. From the FFT results, we can notice that they satisfy the general requirements of 5 [%] below. The overall system efficiency at normal mode operation was measured about 90.6 %, and 91 % at stored-energy mode operation.



(a)

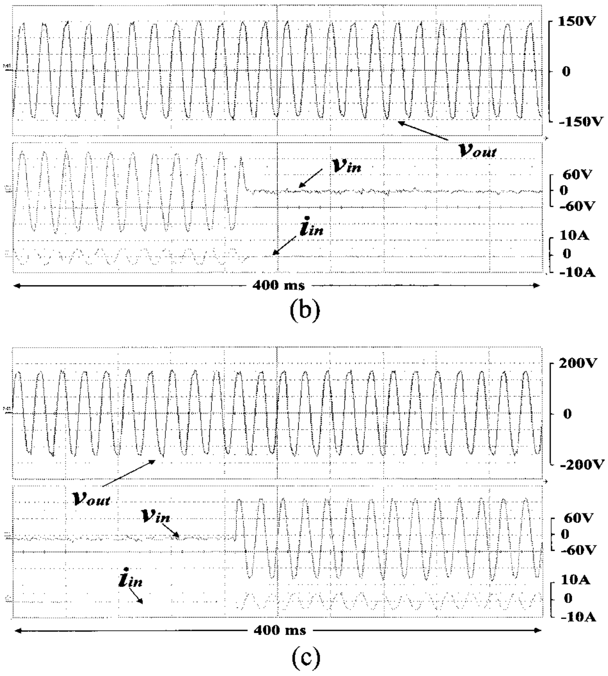


Fig. 8 Operational waveforms with the outage of 2 [sec], (a) input voltage, input current, and output voltage during 10 [sec], (b) magnified waveforms when the outage is occurred, (c) magnified waveforms when the outage is finished.

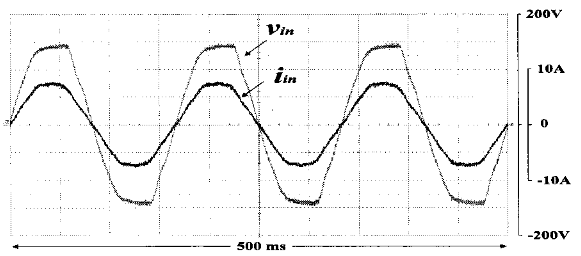


Fig. 9 Input voltage and input inductor current at normal mode operation.

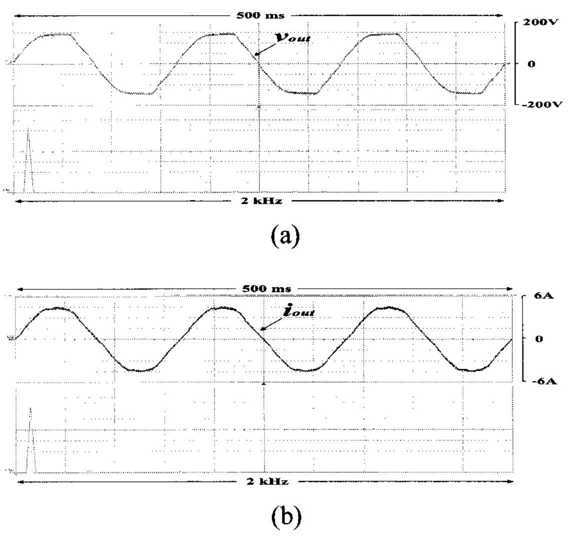


Fig. 10 Output voltage, load current, and FFT results, (a) output voltage, (b) load current.

IV. CONCLUSION

A single-phase DSP-controlled uninterruptible power supply system equipped with a SMES 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.

Presentable achievements are summarized as:

1. Simple circuit configuration,
2. Fast response to outage,
3. Long-term lifecycle by means of applying SMES unit,
4. High input power factor: over 0.98,
5. Good harmonic characteristics: less than 5 [%],
6. High efficiency: over 90 [%].

As results, the proposed single-phase SMES-based UPS system can be a powerful candidate, which can substitute for the conventional battery-based UPS system.

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