Superconducting Magnet Energy Storage Unit

Cheol-soon Kwon 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: To accomplish a simple circuit configuration and higher system reliability, a single-phase uninterruptible power supply employing a superconducting magnet energy storage unit is proposed. It can reduce the 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.

1 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. It requires 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. However, battery is usually distressed by their short lifecycle, late responses in charging or discharging, and environmental problems.

In recent years, superconducting magnet energy storage (SMES) unit has been received a great attraction as an energy storage unit instead of conventional batteries due to the dynamic capabilities and long-term lifecycle of SMES. A lot of UPS systems employing SMES unit have been reported and developed. Most of them are focused on high power usually with 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 UPS system employing SMES unit is presented to achieve a simple circuit configuration with higher system stability. The proposed power conversion circuit is based on the integration of half-bridge configurations. It can reduce the number of switching devices by applying a common arm scheme. Operational mode and principles are illustrated with useful discussions, and then the validity of the proposed SMES-based UPS system is verified by experiments using a prototype.

2 PROPOSED SMES-BASED UPS SYSTEM

In general UPS systems, the objective of ac-to-dc converter is to produce high quality dc voltage for proper 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. 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 space, cost, reliability, and safety considerations to increase. To solve 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 ac-to-dc converter and dc-to-ac inverter. It steps down the high dc-link voltage to low battery voltage 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. 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. 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, but also has a common neutral point for the input and output, eliminating the requirement for a galvanic isolation transformer.

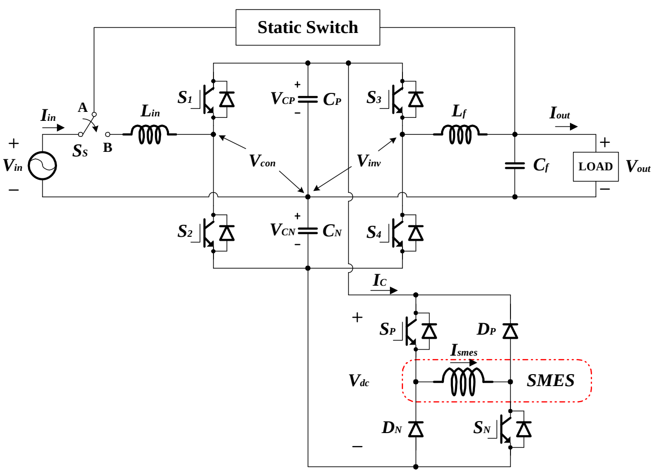


Figure 1. Proposed single-phase SMES-based UPS system.

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 Figure 1. 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

$$E_{smes} = \frac{1}{2} \cdot L_{smes} \cdot I_{smes}{}^{2} \tag{1}$$

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.

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

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

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

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

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).

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

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

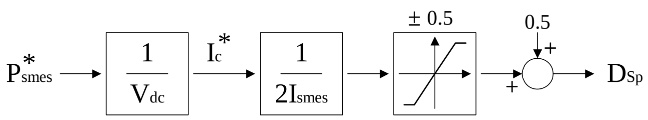


Figure 2. SMES controller.

Figure 2 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

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

Here I_C means the supplied current from the input source.

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 to a stored-energy mode. When some faults such as power outage, voltage fluctuations, under-and over-voltage, surge, occasional frequency fluctuations, and voltage harmonics are occurred, the input switch disconnects the UPS system from the grid. During this mode, the switches of ac-to-dc converter (S_1 and S_2) are not working. During this 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). 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.

3 RESULTS AND DISCUSSIONS

The performance of the proposed SMES-based UPS system was verified by experiments using a laboratory prototype.

Table 1. Specifications of the proposed UPS system

Item	Symbol	Feature
Switch	S_1-S_4, S_P, S_N	IGBT CM100DY-24A I_C=100A / V_{CES}=1200V
Diode	D_P, D_N	IGBT CM100DY-24A Internal body-diode
Input boost inductor	L_{in}	1 mH
Output filter inductor	L_f	0.5 mH
Output filter capacitor	C_f	47 μF
Switching frequency	f_s	2 kHz
Rated dc-link voltage	V_{dc}	385 V
Input voltage	V_{in}	110 V / 60 Hz
Output voltage	V_{out}	0 ~ 110 V

Table 1 lists the specification of the proposed UPS system. A digital controller equipped with a TMS320C240 was designed to ensure the stability and dynamic response of the proposed UPS system. It also provides programmability and immunity to noise.

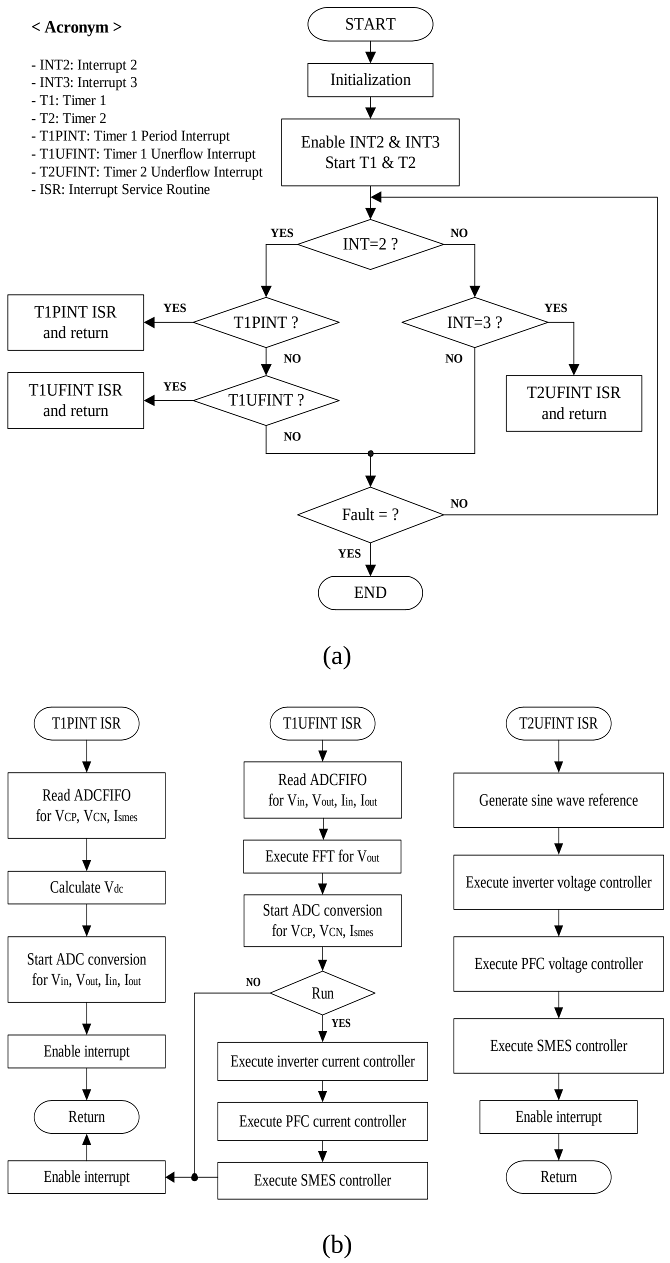


Figure 3. Software flowchart, (a) main program, (b) interrupt service routines.

Figure 3 shows the flowchart for the main program. 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 Figure 3(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 SMES unit such as electrical and magnetic parameters and dimensions of the magnet.

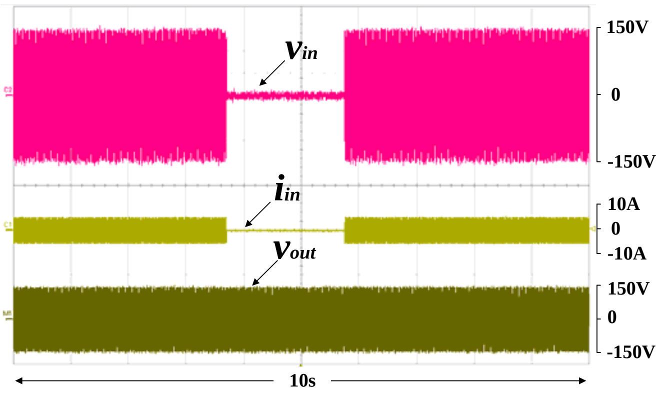
Table 2. Specification of the equipped SMES

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

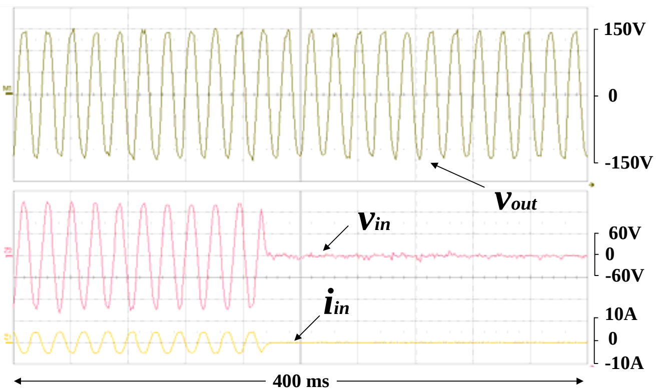
The command power of the SMES unit (P_{smes}*) is internally preset as 10 [kW]; thus, the current flowing through the SMES coil is regulated by the dc-link voltage (V_{dc}), and the relationship is given as

$$I_{smes} = \frac{P_{smes}^{*}}{V_{dc}} = \frac{10 \times 10^{3}}{385} \approx 25.974 \quad \text{[A]} \tag{6}$$

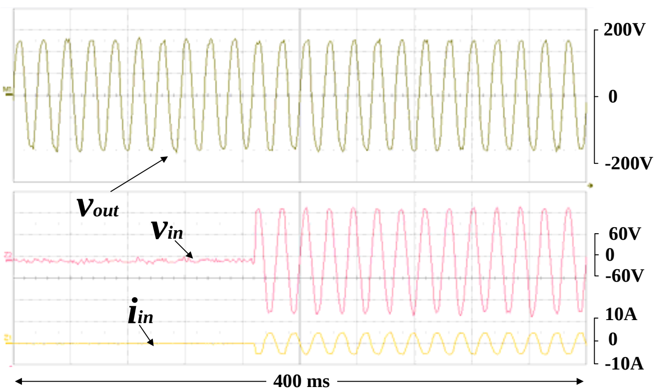
Figure 4 shows experimental result waveforms of input voltage (V_{in}), input current (I_{in}), and output voltage (V_{out}), respectively. During the outage of 2 [sec], the proposed SMES-based UPS system maintains the output voltage constant as shown in Figure 4(a). Its magnified waveforms before and 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. Figure 5 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.



(a)



(b)



(c)

Figure 4. 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.

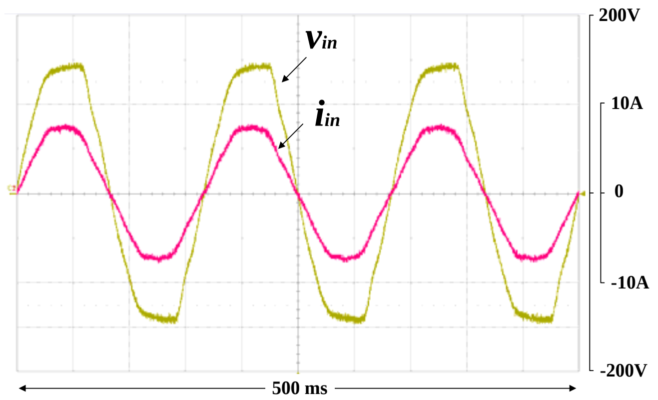
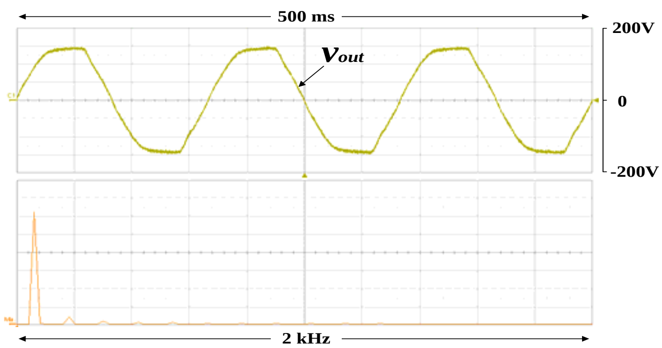
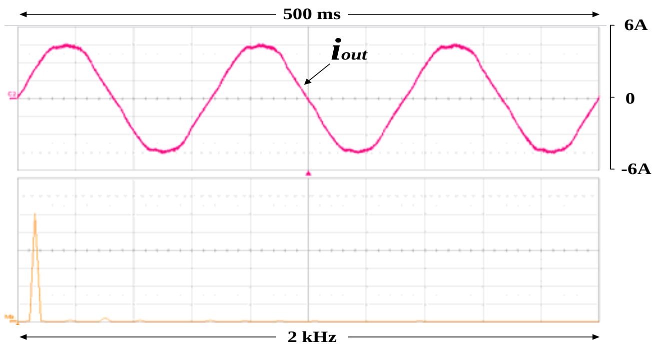


Figure 5. Input voltage and input inductor current at normal mode operation.



(a)



(b)

Figure 6. Output voltage, load current, and FFT results, (a) output voltage, (b) load current.

Figure 6 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.

4 CONCLUSION

An uninterruptible power supply employing a SMES as an energy storage unit is proposed to achieve a simple circuit configuration with higher system reliability. Valuable merits of the proposed system are summarized as:

(1) Simple circuit configuration,
(2) Fast response to outage,
(3) Long-term lifecycle due to SMES unit,
(4) 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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