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# 초전도 에너지 저장 시스템을 위한 단상 무정전 전원공급장치

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## A Single-phase Uninterruptible Power Supply for a Superconducting Magnetic Energy Storage Unit

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### 요 약

본 논문에서는 초전도에너지저장 시스템에 적합한 간략한 회로 구성과 높은 신뢰성을 가지는 단상 무정전 전원공급장치를 제안한다. 제안된 시스템은 공통암 방식을 적용하여 스위칭 소자수를 저감한다. Normal, Stored-energy, Bypass의 세 가지 동작 모드에 대하여 상세히 설명한다. 사용되는 스위칭 소자수를 저감시키거나 수동소자로 대체시킬 경우 제어가 복잡해지고 자유도를 감소키는 문제점이 있지만 고성능의 디지털 제어기를 통해 추가적인 부담 없이 해결할 수 있다. 제안된 시스템의 타당성 검증을 위해 시뮬레이션 결과를 제시한다.

### ABSTRACT

A single-phase uninterruptible power supply system suitable for a SMES unit 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. Operational principles to normal, stored-energy, and bypass mode are discussed in detail. Eliminating some of the switches or substituting passive components for active switches generally increases the sophistication and reduces degree of freedom in control strategy. However, the high-performance digital controller can execute the complicated control task with no additional cost. The validity of the proposed UPS system will be verified by a computer-aided simulation.

### 키워드

Power factor correction, superconducting magnet energy storage, uninterruptible power supply.

### 1. Introduction

Uninterruptible power supply (UPS) systems have been used to maintain a continuous supply of electric power to certain critical loads with high quality power protecting them against unexpected power outages as well as over and under voltage conditions. Energy storage units in UPS system must supply power to the load when the ac line fails. If they are not capable to carry out this important role, then the whole UPS system fails even though it employs high-performance

controller and well-designed power electronics circuits [1]-[2].

In recent years, a SMES (superconducting magnet energy storage) has been received a great attraction as the energy storage unit instead of the conventional batteries owing to the dynamic capabilities of a SMES and a long-term life cycle. Various UPS systems employing a SMES unit have been reported and developed [2]-[4]. 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 employed in a power conversion system. Reducing the number of switching devices and other elements in UPS systems saves the cost of the whole system, and it has several other merits such as superb compactness and higher reliability as well [2]-[4].

In this paper, a single-phase uninterruptible power supply system for a 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 reduces the number of switching devices by applying a common arm scheme. Operational principles are illustrated with useful discussions, and then the validity of the proposed UPS system is verified by computer-aided simulation.

## II. The proposed UPS system

Generally, conventional UPS system is divided into several parts according to their functional purposes: an ac-to-dc converter, an energy storage unit, a dc-to-ac inverter, and a static switch for bypassing as given in Fig. 1. The UPS system based on full-bridge converters has useful merits over the one based on half-bridge converters, such as better utilization of the dc link voltage, two fold-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 [1,3].

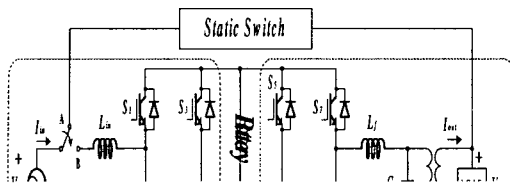


Fig. 4. Configuration of a typical single-phase UPS system using full-bridge structure

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 two fold-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 [2]-[4].

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. 2. 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  $D_N$ ).

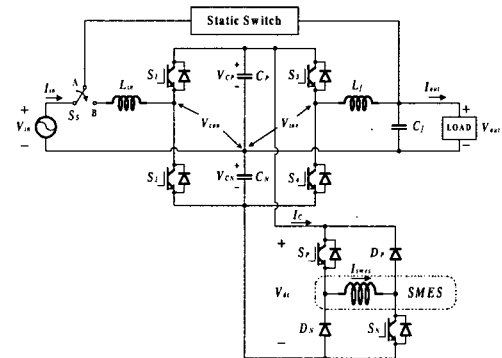


Fig. 2. Proposed single-phase UPS system for a SMES unit

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

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

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 a 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 a positive or negative voltage across the superconducting coil.

## 2.1. Operational principle

### 2.1.1. Normal mode operation

A case where the input ac voltage is within the allowable tolerance range, the proposed 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. The SMES control switches keep the SMES at 100 % state of charge. The selection switch (S<sub>s</sub>) in the input stage is lying at position B.

#### 2.1.1.1. Ac-to-dc converter

During the positive cycle of the input ac voltage, S<sub>2</sub> is conducting; thus, voltage across the input boost inductor yields

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

The inductor current will increase with the slope of (V<sub>Lin</sub>/L<sub>in</sub>) following the current path of V<sub>in</sub> Lin S<sub>2</sub> CN V<sub>in</sub>. When S<sub>2</sub> stops conducting, the upper capacitor (CP) 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<sub>CP</sub> is higher than that of V<sub>in</sub>, 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<sub>2</sub>). On the other hands, during the negative cycle, the input power factor and the dc voltage of the lower capacitor are controlled by the duty ratio of upper switch (S<sub>1</sub>).

#### 2.1.1.2. SMES controller

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

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



Fig. 3. SMES controller

Fig. 3 shows the principle of determination of duty ratio. It controls the duty ratio of SP, whereas SN is continuous conducting. The duty ratio is given as

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

Here IC 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<sub>3</sub> and S<sub>4</sub>), and two identical dc capacitors CP and CN, connected in series. By controlling of S<sub>3</sub> and S<sub>4</sub>, the voltage across the load becomes + V<sub>dc</sub>/2 or V<sub>dc</sub>/2. Because these switches operate alternately, there is always a dead time to avoid arm-short through faults.

### 2.1.2. Stored-energy mode operation

A case where 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-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 the ac-to-dc converter (S<sub>1</sub> and S<sub>2</sub>) are not working.

#### 2.1.2.2. SMES controller

During the stored-energy mode, the SMES controller should supply energy to the output load instead of the grid. The switches of SP and SN work at the same time. When these switches are turned off, the SMES current flowing through DP

and DN charging CP and CN, 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.

3. Simulation results and discussions

In the simulation, 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 (Vdc), and the relationship is given as

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

Fig. 4 shows experimental result waveform of input voltage ( $V_{in}$ ), input current ( $I_{in}$ ), and output voltage ( $V_{out}$ ), respectively. During the outage of 2.8 seconds, the proposed SMES-based UPS system maintains the output voltage constant. The output voltage is regulated sufficiently well within 10 % regardless of the variation of input voltage.

At normal mode operation, the input power factor is measured over 0.98, and the input current THD (total harmonic distortion) is less than 2.2 % regardless of the power rating. The overall system efficiency at normal mode operation was about 96.6 %, and 97 % at stored-energy mode operation.

4. Conclusion

A single-phase uninterruptible power supply system for 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) A simple circuit configuration,
- (2) Dynamic response to outage,

- (3) Long-term life cycle by means of applying SMES system,
- (4) High input power factor: over 0.98,
- (5) Good harmonic characteristics: less than 2.5 %,
- (6) High efficiency: over 96.6 %.

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

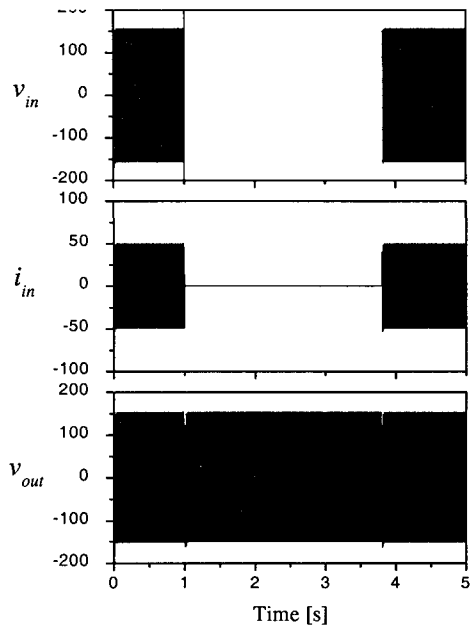


Fig. 4. Operational waveform with the outage of 2.8 s, input voltage, current and output voltage

참고문헌

- [1] Divan D.M. A new topology for single-phase UPS systems. IEEE IAS Conf. 1989; 931-936.
- [2] Andoh I, et al., Development of a high efficiency flywheel UPS using three arms inverter/converter inverter/converter. IEE Trans. Japan 1996; 116-D(11):1153-1158.
- [3] Noriyuki Hirao, Tetsuichi Satonaga, Takeshi Uematsu, Teruhiko Johama, Tamotsu Ninomiya, Masahito Shoyama. Analytical considerations on power loss in a three-arm-type uninterruptible power supply. IEEE Power Electronics Special Conf. 1998;1886-1890.
- [4] Park HW, Park SJ, Park JG, Kim CU. A novel high-performance voltage regulator for single-phase ac sources. IEEE Trans. Industrial Electronics 2001; 48(3):554-562.