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Energy Management Strategy and Adaptive Control for SMES in Power System with a Photovoltaic Farm

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Abstract – This paper proposes an energy management strategy and adaptive control for superconducting magnetic energy storage (SMES) in a distribution power system with a grid-connected photovoltaic (PV) farm. Application of the SMES system can decrease the output power fluctuations of PV system effectively. Also, it can control the real and reactive powers corresponding to the scheduled reference values with adequate converter capacity, which are required at a steady-state operating point. Therefore, the adaptive control strategy for SMES plays a key role in improving the system stability when the PV generation causes uncertain variations due to weather conditions. The performance of proposed energy management strategy and control method for the SMES is then evaluated with several case studies based on the PSCAD/ EMTDC® simulation.

Keywords: Energy manage strategy, Distribution system, Photovoltaic, Power converter, Superconducting magnet energy storage (SMES)

1. Introduction

The superconductingmagnetic energy storage (SMES), which is a large superconducting coil (SC) capable of storing electric energy in the magnetic field generated by a circulating current, is known as a good candidate for energy storage device. Because there is no conversion of energy to other forms such as mechanical or chemical, its efficiency can be very high [1]. In addition, the SMES has various prominent merits, including a high power density, a fast response charge and discharge, and a long periodic life [2]. Consequently, this system is suitable for the smoothing control of output power fluctuations and can improve the quality of the power supply in dispersed power compared with those of other storage equipment [3].

On the other hand, the recent trends in power system planning and operation are being toward maximum utilization of existing electricity infrastructure with tight operating margins due to new constraints placed by economic, political, and environmental issues. The photovoltaic (PV) system is being considered worldwide as an alternative solution to deal with the problem. However, the output power from PV system varies with weather conditions such as solar irradiation and atmospheric temperature. Therefore, if a large number of PV power generators are connected to a power system like a PV farm, their outputs can have the serious effects on its operation such as frequency and voltage fluctuations on a grid. In order to solve these problems, it is important to control the output power fluctuations. The SMES is a key technology in overcoming these fluctuations [2, 3]. Also, several SMESs in the range from KWh to MWh scale have been implemented for the compensation of load and generation fluctuations [4].

The conventional control method is insufficient for the use in various operating ranges due to the limit of the converter capacity by the fixed voltage of SMES. This paper proposes the new energy management strategy and adaptive control for SMES in a distribution power system with a grid-connected PV farm. The performance of the proposed control method for SMES is then evaluated with several case studies using the PSCAD/EMTDC® simulation.

2. Distribution Power System Modeling

The structure of a distribution power system with a PV farm and SMES is shown in Fig. 1. In general, the PV generation system consists of a PV array, DC/DC converter with a maximum power point tracking (MPPT) controller, and DC/AC converter to connect the commercial grid. The PV farm is formed by the combination of many solar cells connected in series and/or parallel, which generates power corresponding to the insolation and module temperature fluctuations [5]. In order to improve the efficiency of PV system, the maximum power point varying with irradiation and module temperature must be tracked. In this paper, the grid-connected PV farm system of 4 MW is modeled, and the perturbation & observation method is used to achieve the MPPT.

As mentioned before, the SMES stores electric energy by the DC current flowing through it. To control the power from SMES, it is necessary to convert the DC current mode

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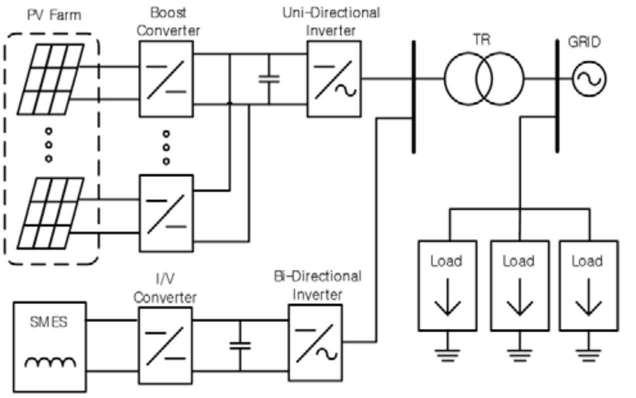


Fig. 1. Structure of the distribution power system with a photovoltaic farm and SMES

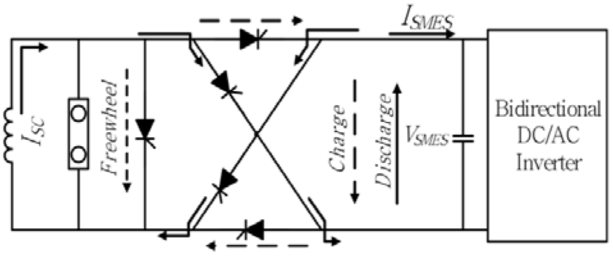


Fig. 2. I/V converter topology for SMES operation

to the DC voltage mode by the current/voltage (I/V) converter, and an I/V converter topology is used for the SMES which is shown in Fig. 2. The primary function of converter is to keep the terminal voltage of DC capacitor constant. When the V_{SMES} is over (under) the setting range, V_{SMES} is controlled by charging conduction modes of GTOs so that current of SMES flows through DC capacitor in same (opposite) direction as expressed by the arrow of discharging mode [6, 7].

The SMES system is designed such that it has the maximum current and voltage of 10 kA and 2.5 kV, respectively. To suppress the fluctuation of 4 MW system output power, the proper size of SMES is considered with the series connection of high-temperature superconductor (HTS) based SMES of 0.55 MWh [8].

When the SMES is charged from the utility system in the absence of insolation or at a low required load condition, the bi-directional DC/AC converter receives power from the utility in the form of the reverse power flow. The total output power of this distribution power system is determined by the DC/AC converter, which is a voltage source/full bridge type, and it is controlled in the pulse width modulation (PWM) mode.

3. Energy Management Strategy and Control

3.1 Proposed control of I/V converter

In a distribution power system, the SMES operates to suppress any output power fluctuations, while the PV output experiences sudden change due to the environmental condition. In this case, the speed of the PV power fluctuation compensation depends on the capacity of the I/V converter, and thus its capacity must be larger than the desired compensation capacity of the system. The capacity of the I/V converter is given by the simple relationship described in (1).

$$P_{SMES} = V_{SMES} I_{SMES} \tag{1}$$

where P_{SMES} is the charge/discharge power of the I/V converter, V_{SMES} is the output voltage of the I/V converter, and I_{SMES} is equal to the current of the SMES coil I_{SC}.

For example, if the required minimum compensation capacity is 3.5 MW due to the 4 MW PV system capacity, when the charged SMES current drops below 4 kA and the I/V converter voltage is 0.5 kV, the charge/discharge capacity is lower than 3.5 MW. In this case, the SMES loses its ability to smoothly control the output power fluctuations in severe cases, such that the PV breaks down. When the I/V converter voltage is 2.5 kV for 3.5 MW compensation capacity at 1.4 kA SMES current, the converter capacity is excessively large to 25 MW at 10 kA SMES current. The unreasonably large capacity makes selection problem of capacitor volume because stability of the SMES voltage. The safe operating area (SOA) which is defined as the voltage and current conditions over which the device has usually higher voltage limit at low current than the voltage limit at high current due to power limit. Therefore, to satisfy the minimum compensation capacity and proper maximum converter capacity, the adaptive control is required.

When the SMES charge level exceeds 49 % (I_{SMES} > 7 kA), the SMES operates in a constant voltage mode that is appropriate for the size of the distribution power system and that is based on the DC link voltage. If the SMES charge level is between 1.96 % and 49 % (1.4 kA < I_{SMES} < 7 kA), the output voltage of the I/V converter is changed to provide additional converter capacity. When the SMES charge level is less than 1.96 % (I_{SMES} < 1.4 kA), the output voltage of the I/V converter is limited to 2.5 kV because the electrical insulation level is low around 3 kV in the applied superconducting apparatus [9]. The control strategy is illustrated in Fig. 3 and is explained in (2).

$$V_{SMES} = \begin{cases} 0.5\ \text{kV} & I_{SC} \geq 7\ \text{kA} \\ \dfrac{3.5\ \text{MW}}{I_{SC}}, & 1.4\ \text{kA} \leq I_{SC} < 7\ \text{kA} \\ 2.5\ \text{kV} & I_{SC} < 1.4\ \text{kA} \end{cases} \tag{2}$$

The I/V converter control strategy should regulate its voltage or power as amounts of SMES current, and the SMES system must stably operate in 6 system operating modes to compensate for the output power fluctuations.

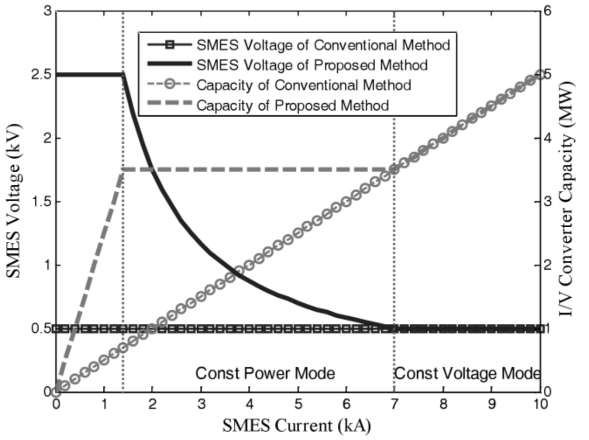
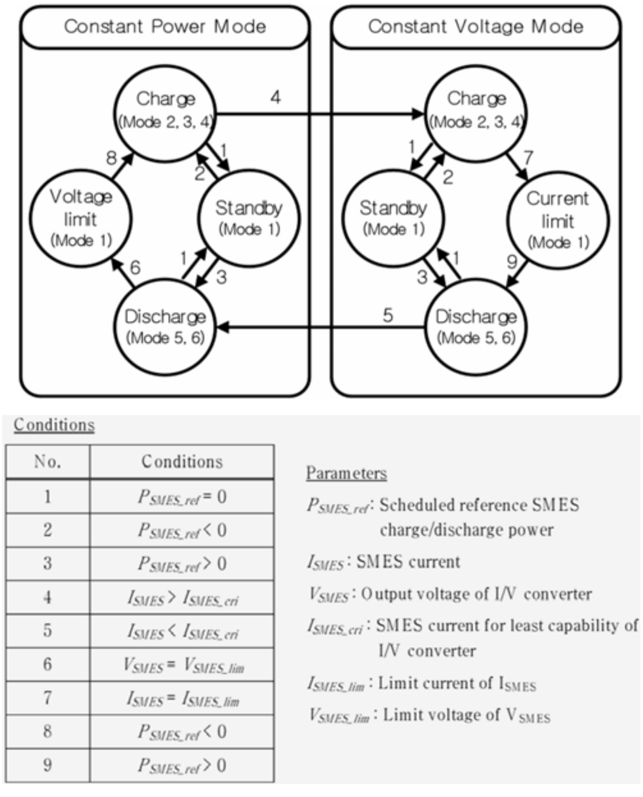


Fig. 3. SMES voltage & I/V converter capacity versus SMES current



Conditions

No.	Conditions
1	$P_{SMES\_ref} = 0$
2	$P_{SMES\_ref} < 0$
3	$P_{SMES\_ref} > 0$
4	$I_{SMES} > I_{SMES\_cri}$
5	$I_{SMES} < I_{SMES\_cri}$
6	$V_{SMES} = V_{SMES\_lim}$
7	$I_{SMES} = I_{SMES\_lim}$
8	$P_{SMES\_ref} < 0$
9	$P_{SMES\_ref} > 0$

Parameters

P_{SMES_ref}: Scheduled reference SMES charge/discharge power
I_{SMES}: SMES current
V_{SMES}: Output voltage of I/V converter
I_{SMES_cri}: SMES current for least capability of I/V converter
I_{SMES_lim}: Limit current of I_{SMES}
V_{SMES_lim}: Limit voltage of V_{SMES}

Fig. 4. State machine representation for the adaptive control strategy of SMES in distribution power system with PV farm.

Fig. 4 shows the proposed adaptive control strategy for the SMES in distribution power system with PV farm. The circles represent the SMES state of the system. The arrows indicate events changed from one SMES state to another, and each event happens under a corresponding condition that is unique to the present SMES state [10]. When the SMES is in standby anywhere in constant power mode (CPM) or constant voltage mode (CVM), the charge /discharge mode can be changed freely in accordance with the scheduled reference SMES power (conditions 1~3). On the other hand, the mode change between CPM and CVM for I/V converter control strategy is presented in specific state. The mode change from CPM to CVM occurs in charge mode, and the change from CVM to CPM occurs in discharge mode only based on the direction of the SMES current change (conditions 4 and 5). If the discharge continues to the low state of charge under the limit current of I_{SMES} in CPM mode, the I/V converter and SMES suffer from limited electrical insulation voltage. Then, the SMES control mode remains as SMES ideal mode 1 until that control mode is replaced by a charge mode (conditions 6 and 8). Similarly, when the SMES is fully charged, the mode changes to SMES current limit mode and then waits for discharge control (conditions 7 and 9). The conditions of transitions state are summarized in the table of Fig. 4.

3.2 System operating modes

In order to suppress the output power fluctuations, the SMES must have the ability to completely control charge and discharge under various system conditions. When the SMES is fully charged or fully discharged (I_{SC} < 1.4 kA), the SMES operates in ideal mode to maintain the charged energy. The charge modes are divided into 3 sub-modes. First, when there is sufficient larger irradiation than required power, the portion of the PV generation energy is used to charge the SMES. Second, when the PV system is turn off and the electricity consumption is also relatively low, the SMES is charged from the grid power. Third, when the electricity consumption is relatively low and the PV generation power is not zero, the SMES is charged from the PV and the grid power.

The discharge modes are separated into 2 sub-modes according to the system power flow. First, when the PV system is turn off but the electricity is required, the SMES discharges the energy. Second, when it is impossible to be adequate to the required power only PV power, the energy is adequate to the PV and the SMES. The specific SMES control modes and associated system power flows are presented in Table 1.

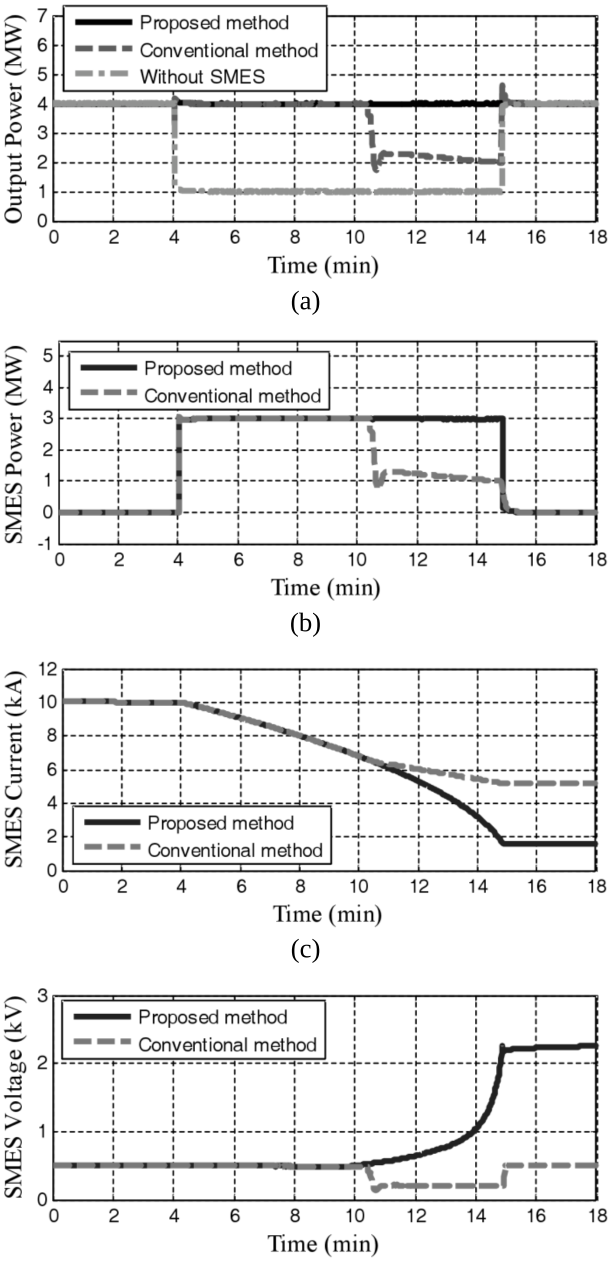
Table 1. System operating modes

Mode	System Control	Condition
1	PV Only	1) SMES fully charged 2) SMES fully discharged
2	SMES Charge Mode I	PV Farm → SMES
3	SMES Charge Mode II	Grid → SMES
4	SMES Charge Mode III	PV Farm + Grid → SMES
5	SMES Discharge Mode I	SMES → Grid
6	SMES Discharge Mode II	SMES + PV Farm → Grid

4. Case Studies and Analysis

4.1 Constant output power compensation test

The control strategy of the I/V converter for fast SMES



(a)

(b)

(c)

(d)

Fig. 5. Comparison of the proposed and conventional control strategies during SMES discharge CPM; (a) discharging power, (b) remaining SMES energy, (c) voltage across SMES, (d) current across SMES.

response is evaluated by a time-domain simulation based on the PSCAD/EMTDC® software. During the simulation from 4 min to 14.9 min, the power of PV generation drops to 75 % of its rated power 4 MW. The initial charged SMES energy is about 0.55 MWh, and the calculated full discharge time is about 11 minutes.

Fig. 5 (a) shows the output power of PV system without SMES, and the output power responses applied conventional fixed voltage control method and proposed control method. When the PV power drops, the SMES discharge reference is constant at 3.0 MW as Fig. 5 (b). When using the proposed method, the proposed I/V converter control strategy provides a constant discharge power according to the reference values for the required output power in full operation time. Because the SMES voltage increases with CPM as Fig. 5 (c), the SMES energy decreases linearly, and it is possible to use up to the last energy as Fig. 5 (d). Then, the SMES compensates adequately the output power fluctuation.

However, when using the conventional case, the SMES cannot supply a constant power at a low current condition of SC. When the current across SMES is lower than 1.4 kA, the capacity of I/V converter is insufficient to compensate PV power fluctuation 3.0 MW. Therefore, the voltage across the SMES cannot stay at a constant 0.5 kV, and the output power of the whole system is not possible to maintain a constant power. The SMES energy is remained as show in Fig. 5 (d).

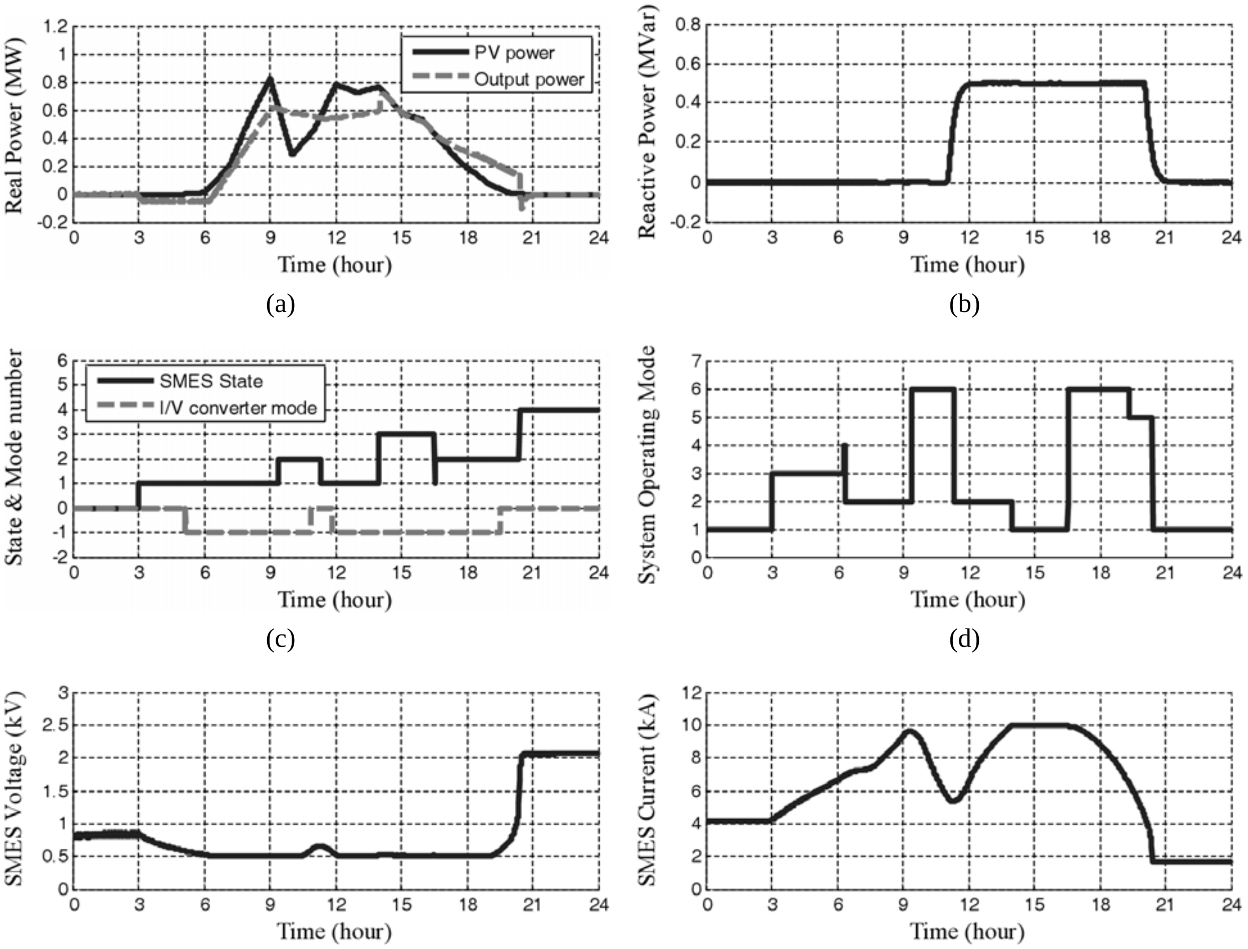
The above results show that the proposed control strategy has the high capability of power compensation even at a low current condition.

4.2 PV generation power compensation test

The test results under arbitrary weather conditions and the real and reactive power requirements are shown in Fig. 6. The PV irradiation and temperature use experimental data on a cloudy day from June 4, 2011 in Boryeong, Chungcheongnam-do, South Korea. The reference values for the required output real power are selected arbitrarily, the operating point of the reactive power remains at 0.5 MVar between 11 a.m. and 8 p.m. The capacity of SMES is 0.55 MWh, and the initial charged SMES energy is about 0.098 MWh with 4.2 kA SMES current.

The system is controlled so that the variability in the actual system output power is small compared to the PV generated power, and the reactive power is provided at the reference value, as shown in Figs. 6 (a) and (b). The state of the SMES and the I/V converter mode by the proposed adaptive control strategy are shown in Fig. 6 (c). The values of the state of the SMES present 0 as ‘Standby,’ 1 as ‘Charge mode,’ 2 as ‘Discharge mode,’ 3 as ‘Current limit mode’ and 4 as ‘Voltage limit mode.’ The values of the I/V converter mode for the SMES are 0 for CVM and -1 for CPM. The SMES is fully charged at 14 hour, and is fully discharged at 20.4 hour, the SMES operates with current limit mode and voltage limit mode. System operating modes revealed system power flows among the SMES, the PV farm and the grid are identified in Fig. 6 (d). The meaning of system operating mode numbers is indicated in Table 1. Fig. 6 (e) shows that the voltage of the SMES is controlled by the I/V converter control strategy, and Fig. 6 (f) shows that the current of the SMES is changed by the SMES charge/discharge operations.

The results confirm that compensation for the output power fluctuations of the PV system is successful when the



(a) (b)

(c) (d)

(e) (f)

Fig. 6. Simulation results of a distribution power system with a PV farm and SMES: (a) PV and actual system output power; (b) reactive system output power; (c) SMES state and I/V converter mode; (d) system operating mode; (e) voltage across SMES; (f) current across SMES.

proposed adaptive control strategy is used.

5. Conclusion

This paper proposed the new energy management strategy and adaptive control strategy for the application of super conducting magnetic energy storage (SMES) to a power system with a photovoltaic (PV) farm. The proposed control strategy could adjust the operation of system effectively according to the SMES state of charge and the voltage of current/voltage (I/V) converter.

The proposed method was implemented by using the PSCAD/EMTDC$^{®}$ software, and several case studies were carried out based on various weather conditions to evaluate the real and reactive power requirements. The simulation results showed that the proposed adaptive control strategy can adjust the SMES output power to improve the stability of power system.

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