Standby Mode Operation of Series Type SMES for Voltage Sag Compensation

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In this paper, the novel standby mode operation of series type SMES (Superconducting Magnetic Energy Storage) for voltage sag compensation is presented. In the proposed control scheme for standby mode, the power losses are minimized and voltage drop is mitigated. The series type SMES is bypassed during the normal weather. During the adverse weather, the series type SMES can compensate voltage sags instantaneously. Simulations of standby mode operation and voltage sag compensation demonstrated the validation of the proposed control scheme.

Keywords: standby mode operation, series type SMES, loss minimization, voltage sag compensation, adverse weather criteria

1. Introduction

Voltage sags are considered as the most important power quality problem concerning by both utilities and industrial consumers. Series voltage sag compensator is recognized as the most effective voltage sag mitigation equipment (1)-(4). As the compensator has to supply active power as well as reactive power, a kind of energy storage is needed. In this study, a superconducting magnetic energy storage (SMES) is used as an energy storage device because of its instantaneous power availability, high cycle lifetime and environment friendly. A series voltage sag compensator with SMES as energy source is called as a series type SMES. The configuration of the series type SMES with charging circuit is shown in Fig. 1.

Since voltage sags generally only occur a few times each year at any particular location, a series voltage sag compensator will generally spend most of its time in standby mode waiting for a voltage sag to occur. Ideally, it would be advantageous if the series voltage sag compensator could disappear then there will be no energy loss during the standby mode, and it could be inserted instantaneously for voltage sag compensation. Mostly, the series voltage sag compensator is short-circuited at the low voltage side of series transformer by the inverter switch or bypass switch (5), in order to be ready to compensate voltage sags. Unfortunately, it will still introduce an extra impedance to the line, primarily due to the leakage inductance in series transformer; and cause a small voltage drop and power losses to the load. This problem can be mitigated by bypassing the series compensator; however, when voltage sags occur, the bypass switches must be completely turned off before the inverter injects the compensation voltage through the series transformer. The system power quality performance will be decreased by this delay.

During the standby mode, the SMES current continually circulates through the closed switch of the dc chopper or an additional semiconductor bypass switch and back to SMES coil. However, the power supply still provides a small trickle charge to replace the power loss in the non-superconducting part of the circuit. If the mechanical bypass switch is used for standby loss minimization, the delay time for opening the bypass switch will decrease the power quality performance.

The authors proposed the new standby mode control scheme for loss minimization and voltage drop mitigation is proposed. The adverse weather condition is used as the voltage sag risk criteria. The series type SMES will be bypassed during the good weather condition. During the adverse weather condition, the series compensator will be ready for voltage sag compensation. The performance of the proposed control scheme is verified by computer simulation results.

The following section describes the voltage sags frequency and adverse weather effect on voltage sags. In Section 3, we propose the new standby mode for series type SMES. In
Section 4, the control scheme of standby mode operation of series type SMES for voltage sag compensation is described. Finally, we show the simulation results in Section 5.

2. Voltage Sags Frequency and Adverse Weather Effect on Voltage Sags

2.1 Voltage Sags Frequency From the average presumed result of an annual voltage sag occurring situation (5), the relation between voltage sag duration and the event per year is shown in Fig. 2. The voltage sags only occur a few times each year at any particular location. As a result, the series voltage sag compensator will spend most of its time in standby mode.

2.2 Adverse Weather Effect on Voltage Sags Voltage sags are mostly caused by faults on the transmission system as reported in Ref. (6). These faults are mostly due to adverse weather, such as lightning, rain, snow, etc. Although the adverse weather conditions can be warned, voltage sags from these causes are still impossible to be eliminated. Fig. 3 illustrates the failure rate as a function of time (7). The failure rate is low most of the year, but high during a number of short periods of adverse weather. Other causes of voltage sags are such as equipment failure, animals, human errors, starting major loads and etc., where they can be eliminated by proper protection and design. The voltage sags monitoring report from 6 locations in Japan (8) shows that most of voltage sag occurrences are due to the adverse weather condition. The weather during voltage sags and the rainy weather classification during voltage sags are shown in Figs. 4 and 5, respectively. The voltage sags occurrence during cloudy and rainy weather are more than 80% of the total events, and most of the events were occurred under thunder storm and typhoon conditions. Therefore, voltage sags are likely to occur during the adverse weather conditions and voltage sags mitigating device is essential for the critical loads under such weather conditions.

3. Proposed Standby Mode for Series Type SMES

Series type SMES is connected with high-speed mechanical switches that needs only 1–2 ms to turn off (9), for bypassing the series compensator and SMES coil. The proposed standby mode has 2 operation modes with adverse weather criteria as follows:

3.1 Standby Mode I The proposed standby mode I, which operates during normal voltage and normal weather is shown in Fig. 6. The series voltage sag compensator and SMES coil are bypassed by the high-speed mechanical switches BS1 and BS2, respectively. The power losses at the series compensator impedance and SMES are minimized and the voltage drop during standby mode operation is mitigated. The switch BS2 will be opened periodically during the trickle charge from power supply to replace the power loss in the non-superconducting part. The frequency of the trickle charge can be calculated from the dissipated energy in SMES which can be expressed by

\[ E_{\text{Loss}}(t) = \int_0^t P_{\text{loss}} dt = \frac{1}{2} L_{\text{SMES}} I_o^2 \left( 1 - e^{-2Rt/L_{\text{SMES}}} \right) \]

where \( I_o \) is the desired SMES current after the charging process, \( R \) is the resistance of the non-superconducting parts and \( L_{\text{SMES}} \) is the SMES inductance. With the use of the mechanical switch, the stored energy will dissipate slower and the trickle charge will become less frequent. For example, with assumption of SMES inductance = 1 H, total circuit resistance = 10 \( \mu \)Ω and 150,000 cycles operation of a circuit breaker, the replacing period is estimated as more than 10 years.
3.2 Standby Mode II The proposed standby mode II, which operates during normal voltage and adverse weather is shown in Fig. 7. After the adverse weather warning, the bypass switches BS1 and BS2 are opened. The load current flows through the high voltage side of series transformer where the current circulates at the inverter, and the SMES current circulates through the dc chopper. The series type SMES now can compensate voltage sags instantaneously. The series voltage sag compensator has 2 possible options to operate as follows:

[Standby Mode II-a] The series voltage sag compensator is short-circuited by turning the lower switches of inverters on. Since the leakage impedance of transformer is connected in series with the load, the leakage impedance of series transformer must be designed to be small enough, for example about 0.01–0.03 pu, then the voltage drop and power losses are within the acceptable level. The load power factor should be considered in order to estimate the voltage drop during standby mode.

[Standby Mode II-b] Fig. 8 shows the equivalent circuit of the series voltage sag compensator when it is not bypassed. The inverters are controlled to operate in short circuit mode during standby. The transfer function of output voltage across injected transformer terminal can be expressed by

\[
V_{Co}(s) = P(s)V_{Ci}(s) - D(s)P(s)I_L(s) = V_{Cop}(s) - V_{Csc}(s)
\]  

where,

\[
P(s) = \frac{(R_D/L_1)s + 1/(C_P L_1)}{s^2 + ((R_D + R_1 + R_e)/L_1)s + 1/(L_1 C_P)},
\]

\[
D(s) = (R_1 + R_e) + L_1 s,
\]

\[
V_{Cop}: \text{output voltage when } I_L = 0,
\]

\[
V_{Csc}: \text{output voltage when } V_{Ci} = 0.
\]

\[
V_{Csc} \text{is the voltage drop on the series impedance of the compensator. If the series compensator operates for canceling this voltage drop, the output voltage across injected transformer will be zero. The solution for voltage drop mitigation without injecting energy to load can be done by solving Eq. (2). The injecting inverter output voltage } (V_{Ci}) \text{ for voltage drop cancellation at the internal impedance } (R_1, L_1 \text{ and } R_e) \text{ can be expressed by}
\]

\[
V_{Ci}(s) = I_L(R_1 + R_e + L_1 s) \rightarrow \frac{V_{Ci}(s)}{I_L(s)} = \frac{1}{R_1 + R_e + L_1 s}\]

However, the drawbacks are the switching power losses at the inverter and power loss for keeping the dc bus voltage constant.

The standby mode II-a will increase the initial cost due to the small leakage impedance of series transformer. In contrast, the standby mode II-b will increase the operating cost due to power losses from voltage drop cancellation. The consideration for choosing the proper standby mode II of the series voltage sag compensator is the duration of voltage sag risk in the area of critical loads location. If the voltage sag risk is high, the standby mode II will operate often and standby mode II-a should be used for minimizing the operating cost. While the standby mode II-b should be used if the voltage sag risk is low.

For SMES circuit, SMES current circulates through the 2-quadrant dc chopper by closing switch S_{chp2} as shown in Fig. 9. The switches S_{chp1} and S_{chp2} close periodically during the trickle charge for the SMES. Since the load current circulates at the inverter, and the SMES current circulates through the dc chopper during the standby modes II-a and II-b, the voltage sag compensation can be instantaneously started.
4. Control Scheme for Proposed Standby Mode

4.1 Operation Modes

Fig. 10 illustrates the flowchart of control algorithm of the series type SMES. There are 3 operation modes, that is, standby mode I, standby mode II and voltage sag compensation mode. Generally, the series type SMES operates in standby mode I because the power losses are minimized and no voltage drop occurs. After the adverse weather warning is occurred, the bypass switches are opened and the series type SMES enters the standby mode II and is ready to mitigate voltage sags. The adverse weather condition warning can be acquired from the meteorological center or from the meteorological monitoring system of the electric power company. These severe weather information that might affect the power system network can be used to determine the risk of voltage sags to the system. If a voltage sag occurs, voltage sag compensation at load can be started instantaneously. The voltage sag detection method is based on the rms of the error vector voltage, which is given in the Eqs. (4) and (5) as follows:

\[
V_{\text{error}}_{dq} > V_{\text{Threshold}} \tag{4}
\]

where the rms of the error is

\[
V_{\text{error}}_{dq} = \sqrt{(V_{\text{ref}}_{d} - V_{Td})^2 + (V_{\text{ref}}_{q} - V_{Tq})^2} \tag{5}
\]

The voltage sag will be detected if the error voltage is higher than 10% of the rated voltage, which is set as \(V_{\text{Threshold}}\).

The method for fast detection of fundamental positive sequence voltage has been proposed, and the positive sequence voltages on the \(d\) and \(q\) axes reach steady state within one cycle, with a settling time of 3/4 cycle.

For voltage sag compensation mode, the inverters inject the missing voltage to the load and dc bus voltage is kept constant with the energy from SMES by controlling the switches \(S_{\text{chp1}}\) and \(S_{\text{chp2}}\). The effective minimum energy injection algorithm for voltage sag compensation has been presented in Ref. (11). In the worst case, if a voltage sag occurs during standby mode I, the voltage sag compensation at load can be operated after the bypass switches open, which takes about 2 ms. After the voltage recovery occurs, the series type SMES will enter the standby mode II again until the risk of voltage sag is over then it enters the stand-by mode I.

4.2 Control Scheme of Switches

The high-speed mechanical switch used as a bypass switch for series type SMES has the opening time less than 1∼2 ms and closing time about 10 ms. The delay time during the opening/closing of the bypass switch could occur due to the use of mechanical switches in standby mode I. The switch sequence procedures according to the operation of series type SMES are as follows:

[Changing from Standby Mode I] The series type SMES normally operates in standby mode I until the adverse weather is warned or voltage sag is detected, then the bypass switches are commanded to be turned off. When an open operation is required, it needs time less than 1~2 ms for the mechanical switch to be completely turned off. The inverters are in short-circuited (S/C) mode (the inverter’s lower switches or upper switches are turned on) and the switch \(S_{\text{chp1}}\) or \(S_{\text{chp2}}\) is turned on instantaneously, in order to have the continuous current path for the load current and SMES current. The inverters cannot operate for voltage drop mitigation or voltage sag compensation until the bypass switch at the series transformer is completely turned off. As the bypass switches are completely turned off, the load current will flow through the high voltage winding of the series transformer, and the SMES current will flow through the switch \(S_{\text{chp2}}\) and lower diode in dc chopper. Then, the series type SMES can enter the standby mode II or voltage sag compensation mode.

[Entering Standby Mode I] After the risk of voltage sag is over, the series type SMES will change from standby mode II to standby mode I by closing the bypass switches.

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Fig. 10. Flowchart of control algorithm

Fig. 11. Time chart of the switch operation
The turn-on signal is commanded and it needs about 10 ms for the closing operation. The inverters are in short-circuited (S/C) mode where the SMES current circulates at dc chopper. After bypass switches are closed, the inverters’ switches and switch Schp2 are turned off in 1 ms.

[Trickle Charge during Standby Mode I] The switch BS2 must be opened before the trickle charge operation at SMES coil. A small trickle charge can be done by controlling the switches Schp1 and Schp2 where the power supplies from the incoming line through the charging circuit. After a trickle charge is finished, the switch BS2 is closed again. The procedures to open and close the bypass switch in the SMES circuit are the same as in Changing from Standby Mode I and Entering Standby Mode I.

Fig. 11 illustrates the time chart of the switch operation due to the use of mechanical bypass switches in standby mode I.

5. Simulation Results

The computer simulation of standby mode operation and voltage sag compensation was carried out with the transmission system model as shown in Fig. 12 by using PSCAD/EMTDC. The parameters in the model are based on the real transmission system and using 1000 MVA per unit base. An R-L linear load is assumed as the the load connected to the protected line by SMES in this study. The parameters of series type SMES are given in Table 1. The SMES capacity is designed from the voltage compensation capability. From the system model, the energy for 100% voltage compensation at load for 0.1 s is 0.4 MJ. The $I_0 = 1$ kA, $L_{SMES} = 1$ H are arbitrarily chosen for the 0.5 MJ SMES capacity.

5.1 Standby Mode Operation The series compensator operated in the standby mode I and changed into standby mode II at 0.4 s as the adverse weather was alarmed. The simulation results for proposed standby modes I, II-a and II-b, were carried out for comparison purpose. The steady-state rms value of the load voltage in standby modes I, II-a and II-b are 100%, 97.5% and 100%, respectively as shown in Fig. 13. The waveform of the voltage across series transformer and load voltage during changing of standby mode is shown in Figs. 14 and 15, respectively. The voltage across series transformer is zero in standby mode I and the overshoot is occurred during 2 ms turn-off period, where the load voltage has a transient voltage drop occurred. Due to the transient voltage observed in Fig. 14, the load voltage is dropped as shown in Fig. 15. According to the effectiveness of voltage sag on electrical loads \(^\text{5}\), this 4% voltage drop will not affect the normal operation of electrical loads. The voltage across the series transformer is about 110 Vrms in the mode II-a where it is almost zero but contains high frequency ripple in the mode II-b. The active power and reactive power of the supply side (measured at 6.6 kV bus) and load side are shown in Figs. 16 and 17, respectively. The load consumed active power almost the same as the supply active power in standby mode I. The difference is the power losses in step-down transformer in the charging circuit. In standby mode II-a, the active power at load is reduced because the reactive power consumed at series transformer causes the voltage drop at load. In standby mode II-b, the active power at load is the same active power at load as in mode I; however, the losses from voltage drop cancellation increased
Fig. 14. Comparison of the voltage across series transformer

Fig. 15. Comparison of the load voltage

Fig. 16. Comparison of the supply and load side active power

Fig. 17. Comparison of the supply and load side reactive power

Fig. 18. Current in SMES circuit

the supply side active power. Note that, the voltage drop effect in standby mode II-a is caused by the 0.8 lagging load power factor and the use of 3% leakage impedance in series transformer. The load power factor and leakage impedance of series transformer will not be the concern in standby mode II-b, but the power losses in the power converter will occur.

The SMES current, bypass switch (BS2) current and dc chopper switch (Schp2) current are shown in Fig. 18. The SMES current circulated through bypass switch in standby mode I and through semiconductor switch in standby mode II. The decrease of SMES current (or stored energy in SMES) in mode I was very slow due to the very low resistance of mechanical switch (5 mΩ) and became higher in mode II because of higher resistance of semiconductor switch (20 mΩ). In practical, the resistance of mechanical switch is much smaller (about 5 µΩ); however, the 5 mΩ-resistance is used due to the limitation of the simulation.

5.2 Voltage Sag Compensation during Standby Mode II
Because most faults are caused by adverse weather condition, the series compensator will mostly operate voltage sags in standby modes II-a or II-b. Standby mode II-b is chosen to demonstrate that voltage sags can be instantaneously compensated during standby mode II. A 0.1-second two-phase fault was applied at load B at 0.2 second after simulation started in order to cause a voltage sag where the series type SMES already operated in standby mode II-b. The simulation results for voltage sag compensation during standby mode II-b are shown in Fig. 19. The compensator instantaneously compensated for a voltage sag after a voltage sag was detected. The DC link voltage is kept constant by the injected energy from SMES resulting the decrease of SMES current. The series compensator instantaneously compensated for voltage sag after voltage sag detection. The load voltage during the voltage sag compensation is well maintained, balanced and exhibits neither transient overvoltage nor oscillations. After the voltage recovery, the series type SMES entered standby mode II and trickle charge for SMES started.

5.3 Voltage Sag Compensation during Standby Mode I
In the worst-case scenario, the series compensator may have to compensate voltage sags during standby mode I. A 0.1-second two-phase fault was applied at load B at 0.2 second after the simulation started where the series type SMES operated in standby mode I. The simulation results for voltage sag compensation during standby mode I are shown in
Fig. 19. Voltage sag compensation during Standby Mode II

Fig. 20. Voltage sag compensation during Standby Mode I

Fig. 20. After voltage sag detection, the 2 ms turn-off period was occurred for bypass switches’ turn-off procedure and then the series type SMES started the voltage sag compensation. The load voltage during the voltage sag compensation is well compensated. The transient voltage sag at load will occur from the 2 ms turn-off period in standby mode I where it will not occur in standby mode II.

6. Conclusion

The novel control scheme for standby mode operation of the series type SMES with bypass mechanical switch have been presented for reduction of power losses and voltage drop at load during standby mode. The weather condition is used to determine the proper standby operation. The proposed standby mode can minimize the power losses, mitigate the voltage drop during standby mode and compensate the voltage sags instantaneously. The simulation results validate the proposed method. Although the R-L load was assumed in this study, the standby mode operation shown in this paper can be applied to other loads such as motor or capacitor as well because the load characteristics will not affect on the transient voltage by the operation of shorting switches for standby mode.

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References


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