Transient Enhancement in a Distribution Power System with SMES-Based SFCL and DVR

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ABSTRACT
In this proposed paper we recommend an inductive SFCL and DVR to beautify the energy quality, normally the energy great troubles like voltage sag and swells are compensated through DVR however in our proposed approach we are using SMES and SFCL to beautify the transient stability. The simulations have confirmed that the proposed voltage sag compensation scheme is in a position to hold the stabilizations of root mean-square voltages, and mitigate the unfavorable consequences of voltage sag on touchy load. Furthermore, the compensated energy injected to touchy load through DVR is diminished owing to the extra voltage enhancement supplied by using SFCL, thereby lowering the complete capital charges of DVR.

1.INTRODUCTION

IN RECENT years, a promising voltage sag compensation scheme based on the dynamic voltage restorer (DVR) equipped with superconducting magnetic energy storage (SMES) has been investigated and technically demonstrated in [1]–[6]. For instances, a 1.85- H/0.3-MJ Notti magnet and its matched 150 KVA current source converter (CSC) were developed in[2] for protecting an 110-kVA critical load from voltage sags. In terms of HTS SMES magnets used in mitigating volt- age sag disturbances, two typical devices are a 7.87-H/1-MJ/ 0.5-MVA BSCCO magnet in Japan [5] and a 6.28-H/1-MJ/ 0.5-MVA BSCCO magnet in China [7]. However, the SMES-based DVR systems is uneconomical compared to those equipped with conventional Battery Energy Storage (BES) de- vices, owing to the expensive capital costs from SMES coils [8]. Thus, a promising concept of hybrid energy storage (HES) integrated a high-power low-capacity SMES device and a medium power high-capacity BES device could be a more suitable option in practice [9], [10]. In our previous works in [11], a kW-class HES-based DVR has been demonstrated to integrate the fast-response feature from the SMES and the high-capacity feature from the BES. Subsequently, a MW-class SMES-based DVR is also proposed and evaluated. Nevertheless, all of these SMES-based DVR schemes have a high power or energy storage requirement for SMES, especially for compensating severe voltage sag.

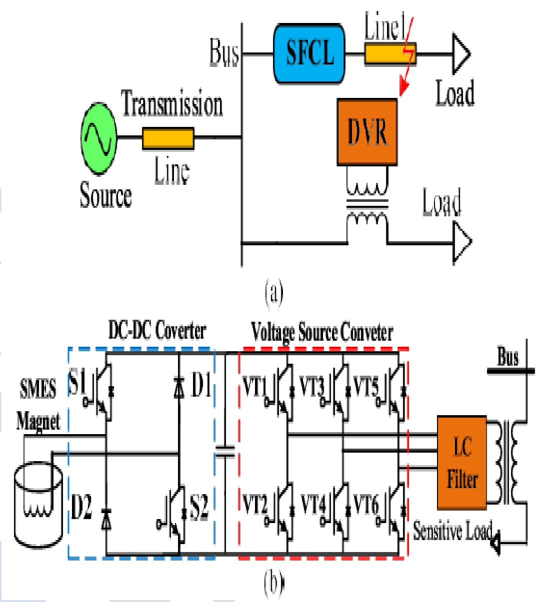

Fig. 1. (a) The system topology of the SMES-based DVR and SFCL. (b) The detailed topology of SMES-based DVR.

In addition, the super conducting fault current limiter (SFCL) is validated to be conducive to compensating voltage sag in distribution power system. Also, a resistive-type SFCL with self-starting and self-recovery for enhancing fault ride through of Double Fed Induction Generator (DFIG) has been proposed and investigated in our previous work. Therefore, a MW-class SMES-based DVR system integrated with a resistive-type SFCL will be introduced to mitigate the adverse effects of voltage sag on sensitive load.

The basic topology and technical principle of this system, parameters evaluation of SMES's magnet and SFCL, control strategy of DVR and simulation verification are described in detail. Furthermore, the comprehensive performance evaluation of the proposed com pensation scheme is also interpreted from the viewpoint of voltage sag compensation, DVR's output power under distribution line fault.

I. SYSTEM PRINCIPLE AND CONTROL STRATEGY A. **Basic Topology and Principle**

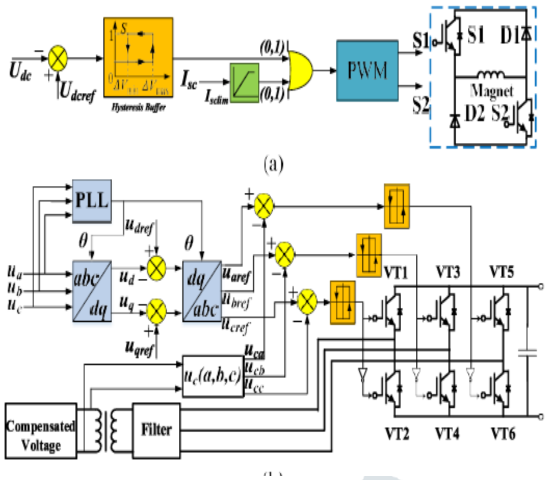

Fig. 2. **(a) The dc voltage control strategy of DC-DC converter. (b)The pre-sag compensation strategy of VSC**.

sensitive load side mainly consists of a bidirectional voltage source converter (VSC), a LC filter, an in-grid transformer, a DC-link capacitor and a SMES device formed by one SMES magnet and its equipped chopper, as shown in Fig. 1(b).In addition, a SFCL device is connected in series with other feeders. The suppressions of voltage sag for sensitive load come mainly from the cooperative operation of the SFCL and the fast-response SMES device. When a three-phase fault occurs in one feeder by which the sensitive load is not supplied, the SFCL will limit the fault current, and slightly increase the common bus voltage. Subsequently, the SMES-based DVR is activated to provide a compensated voltage after the voltage sag is detected, thereby maintaining the constant terminal voltage of sensitive load.

B. Control Strategy of SMES-Based DVR

The control strategy of SMES-based DVR is shown in Fig. 2, including the control of both DC-DC converter and Voltage t1 < t Rm Source Converter (VSC). For the DC-DC converter, the dc voltage control strategy is utilized to maintain the constant dc voltage. The error between the dc voltage reference and the actual value is transferred to a hysteresis buffer to generate a PWM control signal to drive the two switches (S1, S2). By controlling the on-off state of two switches to achieve repeats witch between charge-mode (S1 ON,S2 ON) and discharge-mode (S1 OFF,S2 OFF) for SMES, the dc voltage can be stabilized. It is important to emphasize that the excessive magnet's current is not allowed to guarantee the SMES's normal operation. Thus, a comprehensive control scheme integrated with the dc voltage control and SMES magnet's current limit is presented in Fig. 2(a). In addition, a pre-sag compensation strategy with dq transform is adopted for controlling the VSC [11], as shown in Fig. 2(b). Both the real-time voltage magnitude and phase angle of sensitive load voltage are locked and stored independently, and subsequently used to compensate the voltage quality disturbance accurately based on the instantaneous re active power theory and hysteretic voltage control method. As compared to other strategies like in-phase or optimized-energy Compensation the pre-sag one result sin lowest transient voltage waveform distortion.

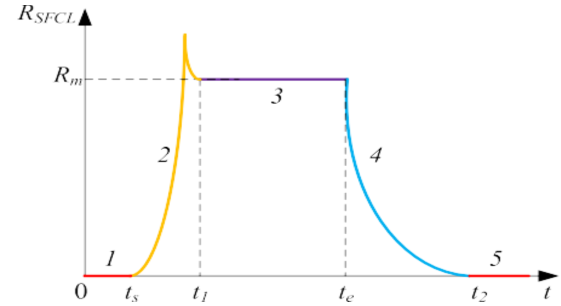

Fig. 3.The equivalent resistance of SFCL under different operation condition.

C. Equivalent Resistance Modelling of SFCL

In our previous work, the resistive-type SFCL's resistance characteristic has been investigated which indicates that the SFCL will perform a different physical state and resistance characteristic under different current flowing through itself. Also, the SFCL resistance value can be divided into five operational segments under different operation conditions, as shown in Fig. 3. The mathematical expression of the resistance curve shown in Fig. 3 can be expressed by (1), and all parameters are described in.

$$R_{sfcl} = \begin{cases} 0 & t < t_s \\ SE_c I_r^{n-1}/I_c^n & t_s < t < t_1 \\ R_m & t_1 < t < t_e \\ R_m e^{-(t-t_e)/\tau_2} & t_e < t < t_2 \\ 0 & t > t_2 \end{cases} \qquad (1)$$

II. PARAMETERS ESTIMATION OF SMES AND SFCL

A. Magnet Design of SMES

Considering that the requirement of short-time high-power energy exchange operations for SMES when it is integrated with a resistive SFCL device, the SMES magnet with very high critical current should be designed. In this work, a step-shaped SMES magnet with the inductance of 1.2 H and critical current of 880 A is adopted [20]. The step-shaped SMES magnet has nine step-shaped pancake assemblies from one end to the other end. The middle assembly is made up often serial pancakes, and each pancake is wound by fifty coil turns. Its inner and outer radii are 250 mm and 285 mm. Four symmetrical assemblies at two sides is formed by five serial pancakes from each coil end to the middle part, in order to construct a step-shaped cross-sectional shape. Their inner radii are 278 mm, 271 mm, 264 mm and 257 mm, respectively. To meet the current-enhanced requirements from the SMES in this work, four step-shaped units are connected by series-parallel connection. The total tape usage of this combined SMES magnet is about 21 km.

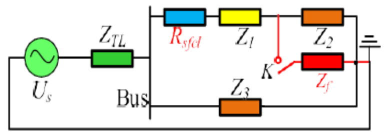

Fig. 4. The equivalent circuit of distribution system.

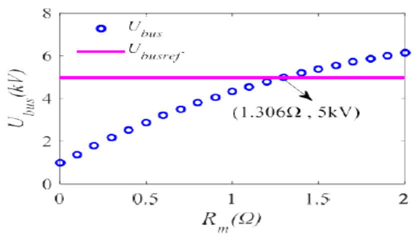

Fig. 5. The relation curve between Rm and Ubus

B. Resistance Estimation of SFCL

The equivalent circuit of distribution system shown in Fig. 1(a) is presented in Fig. 4. When a three-phase fault occurs in one feeder, the switch K is closed, and the bus voltage can be expressed by Where Ztl is the total impedance of transmission line; Rm is the steady SFCL resistance; Z1 is the initial point of line to fault location; Z2 is the sum of load

$$U_{\rm bus} = \frac{Z_I}{Z_{tl}(Z_I + Z_3) + Z_I Z_3} U_s \qquad (2)$$

where,

$$Z_I = R_m + Z_1 + \frac{Z_2 + Z_f}{Z_2 Z_f} \qquad (3)$$

impedance and equivalent impedance from end point of line to fault location and; Z3 is the impedance of sensitive load. Equations (2) shows that the bus voltage (U bus) depends on the SFCL resistance Rm. Thus, the SFCL resistance can be estimated to satisfy the specified bus voltage requirement based on (2). The relation curve between Rm and U bus can be obtained, as shown in Fig. 5. It illustrates that the SFCL resistance is set to 1.306Ωto increase the common bus voltage to 5 kV (0.5 pu).

III. SIMULATION RESULTS AND ANALYSES

To prove the feasibility and practicality of proposed voltage sag compensation scheme, a three-phase 10 kV simple power distribution system shown in Fig. 1(a) is simulated under distribution line1 fault condition where a three-phase fault occurs in distribution line1 at t = 2 s and lasts for 100ms, resulting in a 90% drop of common bus. The main parameters of 10 kV distribution systems are listed in Table I. The parameters of the SFCL and SMES are listed in Table II. Furthermore, the simulation of single SMES-based DVR compensation scheme is also Conducted for comparison.

TABLE I
PARAMETERS OF 10 KV DISTRIBUTION SYSTEM

Parameter	Value	Unit
Rated voltage of AC source	10.77	kV
Rated voltage of common bus	10	kV
L, R of transmission line impedance	4.76, 1.188	mH, Ω
L, R of distribution line 1	0.4, 0.0998	mH, Ω
Ordinary Load	1	MW
Sensitive load	5	MW

TABLE II
PARAMETERS OF SFCL AND SMES

Parameter	Value	Unit
SFCL resistance	1.306	Ω
SC inductance	1.2	H
SC initial current	1500	A
SC critical current	1760	A

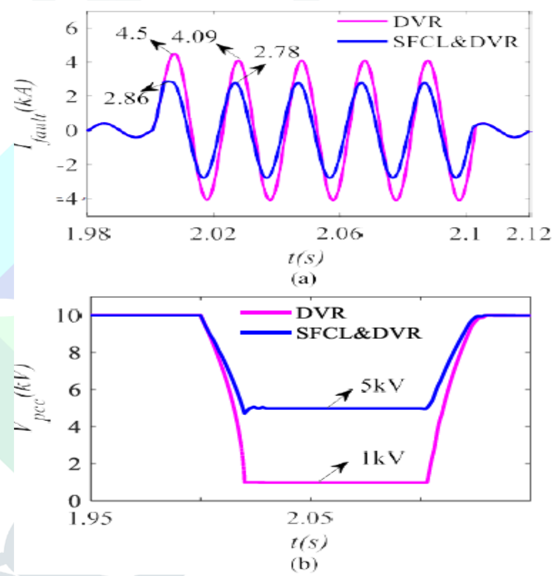

Fig. 6. (a) The fault current on distribution line1 with single DVR and the proposed SFCL&DVR. (b) The common bus RMS voltage with single DVR and the proposed SFCL&DVR.

A. Voltage Compensation Performance

Fig. 6 shows the fault current on distribution line1 with two voltage compensation schemes. With the proposed cooperative scheme integrating SFCL and DVR (SFCL&DVR), the initial peak value of fault current is decreased to 2.86 kA that is less than that in the single DVR scheme (4.50 kA). Similarly, the steady fault current is also limited from 4.09 kA (with single DVR) to 2.78 kA (with SFCL&DVR). Furthermore, the bus voltage will be increased from 1.0 kV (with single DVR) to

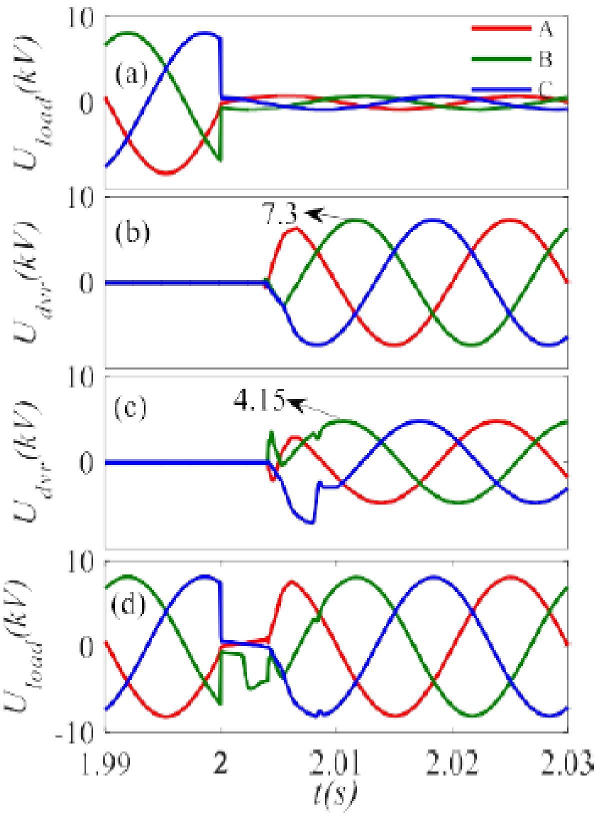

Fig. 7. (a) The sensitive load voltage without compensation. (b) The DVR output voltage with single DVR. (c) The DVR output voltage with proposed SFCL&DVR. (d) The sensitive load voltage with compensation.

5.0 kV (with SFCL&DVR), as shown in Fig. 6(b). Because the voltage loss of transmission line is reduced owing to the suppression of fault current. Therefore, it is concluded that the SFCL not only effectively suppresses the fault current but also increases the common bus voltage due to its high resistance during distribution line fault. The terminal voltage of sensitive load and DVR output voltage with different voltage compensation schemes are shown in Fig. 7. Compared Fig. 7(a) with Fig. 7(d), it is obviously seen that both of single DV Rand proposed SFCL&DVR scheme can completely increase the sensitive load voltage to pre-fault value within about 8ms, thereby effectively eliminating the adverse effect of voltage sag on sensitive load. Furthermore, owing to the additional voltage-enhancement of common bus by SFCL, the DV Rout put voltage is only about to 4.15 kV in the proposed SFCL&DVR scheme, while it will be increased to 7.3 kV in the single DVR scheme. Thus, the proposed SFCL&DVR scheme can also reduce the compensated voltage requirement for DVR and further reduce the DVR's capacity, while completely compensating the sensitive load voltage to pre-fault value.

B. Performance Evaluation and Comparison of DVR

Fig. 8 shows the output compensated power of DVR with two compensation schemes. The output compensated power of DVR with the proposed SFCL&DVR scheme is decreased to 0.54 MW that is 1.63 times less than that in single DVR scheme (0.88 MW). This is because the additional SFCL can reduce the voltage sag depth of common bus owing to its voltage enhancement effect for common bus, thereby effectively reducing the compensated power requirement for DVR, which will lead to lower capital costs. Specifically, if a single DVR is applied to compensate 100% voltage sag across the 5-MW sensitive load in Fig. 1, the compensating power is as high

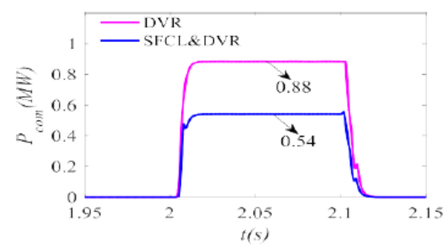

Fig. 8**.** The output compensated power of DVR with single DVR and proposed SFCL&DVR

as 5 MW, which is about 9.2 times of that in the proposed SFCL&DVR scheme (0.54 MW). This means that the total usage of DI-BSCCO tapes manufactured by Sumitomo [20] is increased from about 20.9 km to 188.1 km for designing this full-scale SMES magnet. In contrast, if a resistive-type SFCL [19] is applied to cooperate with the SMES, the total usage of SF12100-type Re BCO tapes manufactured by Super Power is only about 540 m.

IV. CONCLUSION

A voltage sag compensation scheme based totally on the MW-class SMES-based DVR device built-in with SFCL is proposed and demonstrated. The conceptual design, compensation principle, manage strategy, parameters evaluation, simulation outcomes and overall performance assessment are introduced and mentioned in detail. The proposed SMES-based DVR gadget with pre-sag compensation method is capable to precisely keep the touchy load voltage to prefault price in the course of frequent bus voltage sag. In addition, the extra SFCL now not solely correctly suppresses the fault cutting-edge however will increase the frequent bus voltage due to its excessive resistance. More importantly, in contrast to the single DVR scheme, the capability requirement for DVR with the proposed scheme can be needless to say reduced due to the SFCL's voltage enhancement impact for frequent bus, which can similarly limit the complete capital expenses of DVR. Therefore, the MW-class SMES primarily based DVR gadget built-in with SFCL can be predicted to make use of to decorate the transient voltage first-class in modern-day distribution electricity system.

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