SMES Based Dynamic Voltage Restorer for Voltage Fluctuations Compensation

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***Abstract*—This paper presents a superconducting magnetic energy storage (SMES) based dynamic voltage restorer (DVR) to protect consumers from the grid voltage fluctuations. Due to the characteristic of high energy density and quick response, a superconducting magnet is selected as the energy storage unit to improve the compensation capability of DVR. This paper analyses the operation principle of the SMES based DVR, and designs the DVR output voltage control method. The control system mainly consists of two parts, the PWM converter controller and the DC/DC chopper controller. The PWM converter controller adopts double-loop control strategy, with an inner current regulator and an outer voltage controller. Combining the coordinated control of DC/DC chopper, the DVR can regulate output voltage accurately and quickly to compensate the system voltage fluctuations. Using MATLAB SIMULINK, the models of the SMES based DVR is established, and the simulation tests are performed to evaluate the system performance.**

***Index Terms*—DVR, series PWM converter, SMES, voltage fluctuation compensation.**

I. Introduction

SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES), characterized by its highly efficient energy storage, quick response, and power controllability, is expected to contribute to high-quality power of the power systems. The researches on SMES for power quality improvement mainly have two methods. One is utilizing SMES as an uninterruptible power supply (UPS) to protect sensitive loads [1], [2]. The SMES-UPS needs to compensate full power for the load, which requires large capacity converters and energy storage units. The other method is connecting SMES in parallel with the system and compensates system voltage fluctuation [3]. The parallel compensation method controls the system voltage indirectly through regulating the injecting current of SMES. The compensation capability is influenced by the system short circuit capacity and the location of SMES.

For the dynamic voltage fluctuation compensation, the dynamic voltage restorer (DVR) which uses a series-connected topology is a more cost-effective solution. The basic operating principle of a DVR is to insert a voltage of required magnitude and phase in series with a distribution feeder to maintain the desired amplitude and waveform for the load voltage. Moreover, the compensation capability is sensitive to the load level, and is independent of the system short circuit capacity and the installation position. To improve the compensation capability of DVR, such as the large amplitude or long duration voltage fluctuation, the energy storage unit is essential to supply the power transfer during the voltage compensation [4]. In this paper, a superconducting magnet is introduced as the energy storage unit of the DVR. Firstly, the operation principle of the SMES based DVR is analysed. Secondly, the voltage compensation control method is designed. Then, the dynamic response of the SMES based DVR is evaluated using MATLAB simulation.

II. Topology and Model of the DVR

The basic topology of SMES based DVR is shown in Fig. 1. The DVR consists of three single-phase series transformers, a PWM converter, a DC chopper and a superconducting magnet (SC). Generally, the PWM converter adopts controllable switching device, which can control the active and reactive power transfer in four quadrants quickly and independently. The output of the converter is filtered by LC-filters in order to reduce the influence from the high switching frequency. Due to the inherent current source characteristic of the magnet, a DC/DC chopper is adopted to regulate the voltage across the magnet to satisfy the required power transfer. The DC chopper significantly decouples the superconducting magnet from the power system and protects the magnet from the disturbances of the power system.

A. Series PWM Converter

The mathematical model of the series PWM converter in synchronous rotating coordinates is given by (1):

$$\begin{cases} L\frac{di_{td}}{dt} = -Ri_{td} + \omega L i_{tq} + u_{12d} - u_{td} \\ L\frac{di_{tq}}{dt} = -Ri_{tq} - \omega L i_{td} + u_{12q} - u_{tq} \\ C_1\frac{du_{12d}}{dt} = i_d - i_{td} + \omega C_1 u_{12q} \\ C_1\frac{du_{12q}}{dt} = i_q - i_{tq} - \omega C_1 u_{12d} \end{cases} \tag{1}$$

where ω is the angular frequency of source voltage at AC side and it is also the synchronous rotating frequency of d-q axis. In the synchronous rotating d-q frame, the d axis is directed in line with the source voltage vector. The current components in d axis

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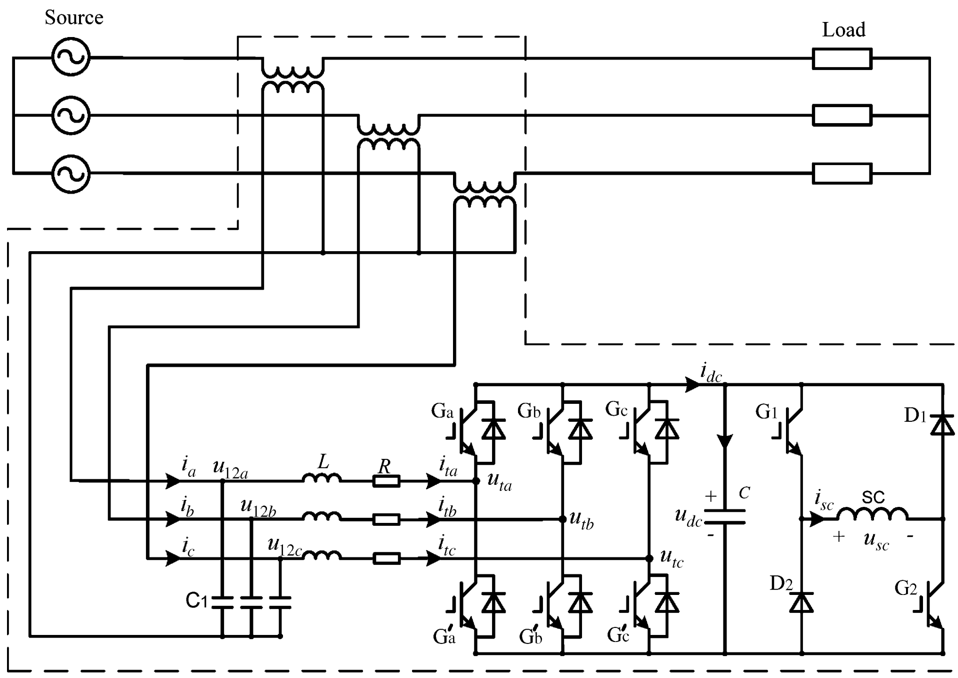

Fig. 1. Basic topology of the SMES based DVR.

and q axis (i_d and i_q) can be defined as the active component and reactive component of the current, respectively.

To improve the dynamics of controller, the active power balance between AC side and DC side must be considered in the power control. The dynamic active power balance can be expressed as:

$$p_{ac} = p_{dc} \pm p_{loss} \tag{2}$$

where p_{loss} includes the switching and conduction loss in the converter and the chopper. The power loss becomes positive when the power is transferred from the AC system to the superconducting magnet, otherwise, the power loss is negative. Then, (2) can be rearranged as:

$$Cu_{dc}\frac{du_{dc}}{dt} = \frac{3}{2}u_{sd}i_d + \frac{3}{2}u_{sq}i_q - p_{chopper} \mp p_{loss} \tag{3}$$

where $p_{chopper}$ is the power transfer between the magnet and the series converter.

B. DC Chopper

In the process of voltage compensation, the DC chopper is utilized to control energy transfer of the superconducting magnet. The DC chopper has two basic operation modes.

1) Charging mode. The DC chopper absorbs active power from AC side and charge the superconducting magnet. In this mode, G1 is on at all times, and G2 is alternately on and off during each chopper cycle. When G2 is on for D (duty cycle) per unit time, the magnet is charged from the DC link through G1 and G2 in series. When G2 is off, the magnet current is bypassed through G1 and D1.

2) Discharge mode. The DC chopper delivers active power to AC side and discharge the superconducting magnet. In this mode, G1 is off at all times, and G2 is alternately on and off during each chopper cycle. When G2 is on for D per unit time, the magnet current is bypassed through G2 and D2. When G2 is off, the magnet discharges to the DC link through D1 and D2 in series.

Adopting the state space averaging method, the mathematical model of the DC chopper can be described as:

$$\begin{cases} C\frac{du_{dc}}{dt} = -Di_{sc} + i_{dc} & \text{charge state} \\ C\frac{du_{dc}}{dt} = (1-D)i_{sc} + i_{dc} & \text{discharge state} \end{cases} \tag{4}$$

According to the dynamic active power balance of the converter represented by (3), the model of DC chopper can be deduced as:

$$\begin{cases} p_{chopper} = Du_{dc}i_{sc} & \text{charge state} \\ p_{chopper} = (1-D)u_{dc}i_{sc} & \text{discharge state} \end{cases} \tag{5}$$

III. Control System

The control system of SMES based DVR has three parts: (1) voltage compensation control, which detects the voltage fluctuation and generates the reference voltage for compensation; (2) series converter control, which controls its output voltage according to the reference voltage for compensation; (3) DC chopper control, which regulates the power transfer of the superconducting magnet in coordinated with the voltage control of the PWM converter.

A. Voltage Compensation Control

For dynamic voltage compensation, the accuracy and promptitude of voltage fluctuation detection is the important premise. To achieve this, the instantaneous power theory is adopted. As to the generation of the reference voltage for compensation, different control methods have been proposed, such as pre-sag compensation, in-phase compensation, minimum energy compensation, and optimized energy compensation [5], [6]. The pre-sag compensation can reestablish the exact voltage before fluctuation, which maintains the amplitude and phase of load voltage. The other methods mentioned above will lead to a certain phase jump at the load side and the possible tripping of sensitive load. So, the pre-sag compensation is adopted to design the control system of the SMES based DVR.

B. Series Converter Control

The series converter is a typical second-order system, which adopts the AC output current of converter as the intermediate control variable. So, the series converter model can be regarded as two cascaded first-order systems. One first-order system shows the dynamics between the source voltage and the AC side input capacitors, which can be denoted as system1. The other first-order system shows the dynamics between the AC side input capacitors and the AC side output of the converter, which can be denoted as system2. Using the discretization-based decoupled state-feedback control method [7], the control equation of series converter can be designed in the form:

System 1,

$$\begin{bmatrix} i_{td}(\mathbf{k}) \\ i_{tq}(\mathbf{k}) \end{bmatrix} = \begin{bmatrix} i_d(\mathbf{k}) \\ i_q(\mathbf{k}) \end{bmatrix} - \frac{C_1}{T_{s1}} \begin{bmatrix} u_{12d}(\mathbf{k+1}) \\ u_{12q}(\mathbf{k+1}) \end{bmatrix} + \frac{C_1}{T_{s1}} \begin{bmatrix} \mathbf{1} & \omega T_{s1} \\ -\omega T_{s1} & \mathbf{1} \end{bmatrix} \begin{bmatrix} u_{12d}(\mathbf{k}) \\ u_{12q}(\mathbf{k}) \end{bmatrix} \tag{6}$$

where (k) is sample time point of the control system, and $(\mathrm{k}+1)$ is the next sample time point. T_{s1} is the discretization time constant of system 1.

System 2,

$$\begin{bmatrix} u_{td}(\mathbf{k+1}) \\ u_{tq}(\mathbf{k+1}) \end{bmatrix} = -\frac{L}{T_{s2}} \begin{bmatrix} i_d(\mathbf{k+2}) \\ i_q(\mathbf{k+2}) \end{bmatrix} \begin{bmatrix} R - \frac{L}{T_{s2}} & -\omega L \\ \omega L & R - \frac{L}{T_{s2}} \end{bmatrix} \times \begin{bmatrix} i_{td}(\mathbf{k+1}) \\ i_{tq}(\mathbf{k+1}) \end{bmatrix} + \begin{bmatrix} u_{12d}(\mathbf{k+1}) \\ u_{12q}(\mathbf{k+1}) \end{bmatrix} \tag{7}$$

where T_{s2} is the discretization time constant of system 2. As the second stage of the two cascaded system, the sample time point of its control system is delayed by one sample period. So, the sample time points of the control system 2 are denoted as $(\mathrm{k}+1)$ and $(\mathrm{k}+2)$.

C. DC Chopper Control

According to the mathematical model of DC chopper, the dynamic active power balance based control equation can be expressed as:

$$\begin{aligned} Cu_{dc}(\mathbf{k+1})\frac{u_{dc}(\mathbf{k+1}) - u_{dc}(\mathbf{k+1})}{T_s} &= \frac{3}{2}u_{sd}(\mathbf{k})i_d(\mathbf{k}) + \frac{3}{2}u_{sq}(\mathbf{k})i_q(\mathbf{k}) \\ &\quad - p_{chopper}(\mathbf{k}) \mp p_{loss}(\mathbf{k}) \end{aligned} \tag{8}$$

$$\begin{cases} p_{chopper}(k) = D(\mathbf{k})u_{dc}(\mathbf{k})i_{sc}(\mathbf{k}) & \text{charge state} \\ p_{chopper}(\mathbf{k}) = (1 - D(\mathbf{k}))\,u_{dc}(\mathbf{k})i_{sc}(\mathbf{k}) & \text{discharge state} \end{cases} \tag{9}$$

According to above analysis, the control system is designed, as shown in Fig. 2. The voltage compensation section detects the voltage fluctuation and generates the reference voltage for compensation (u_{12d}^* and u_{12q}^*). Based on the control equations of the two cascaded system represented by (6) and (7), the control system follows the reference voltage, and generates the converter AC output voltage (u_{td} and u_{tq}). With the Sinusoidal Pulse Width Modulation (SPWM) algorithm, the SPWM signals can be obtained to control the operation of converter, and the compensation voltage in series with the distribution feeder can be controlled to comply with the power quality requirement. The DC chopper control is accomplished base on (8) and (9), and the active power balance between the superconducting magnet and the AC system can be maintained, which ensures the dynamic response of the voltage regulation.

IV. Parameter Design

The energy storage unit is relatively expensive, but for certain voltage fluctuation, it may be necessary. This refers especially to the cases when terminal supply voltage fluctuation exceeds $\pm 40\%$. On defining the variation factor of the terminal-supply voltage as

$$k = \frac{U_{rated} - U_S}{U_{rated}} \tag{10}$$

where U_{rated} is the rated load voltage in normal state, U_S is the terminal supply voltage. Supposing the duration of the voltage fluctuation is T. The energy variation during the compensation of DVR is given by

$$E = k \cdot U_{rated} \cdot I_L \cdot T = P_L \cdot k \cdot T \tag{11}$$

where I_L is the rated load current and P_L is the rated load power.

To illustrate the relationship between the energy variation during compensation and the scope of the voltage fluctuation, a numerical example is adopted. Supposing a 380 V distribution system has a maximum load of 15 kVA. The DVR is designed to protect loads from a $\pm 50\%$ voltage fluctuation with maximal duration of 500 ms. According to (11), the energy variation can

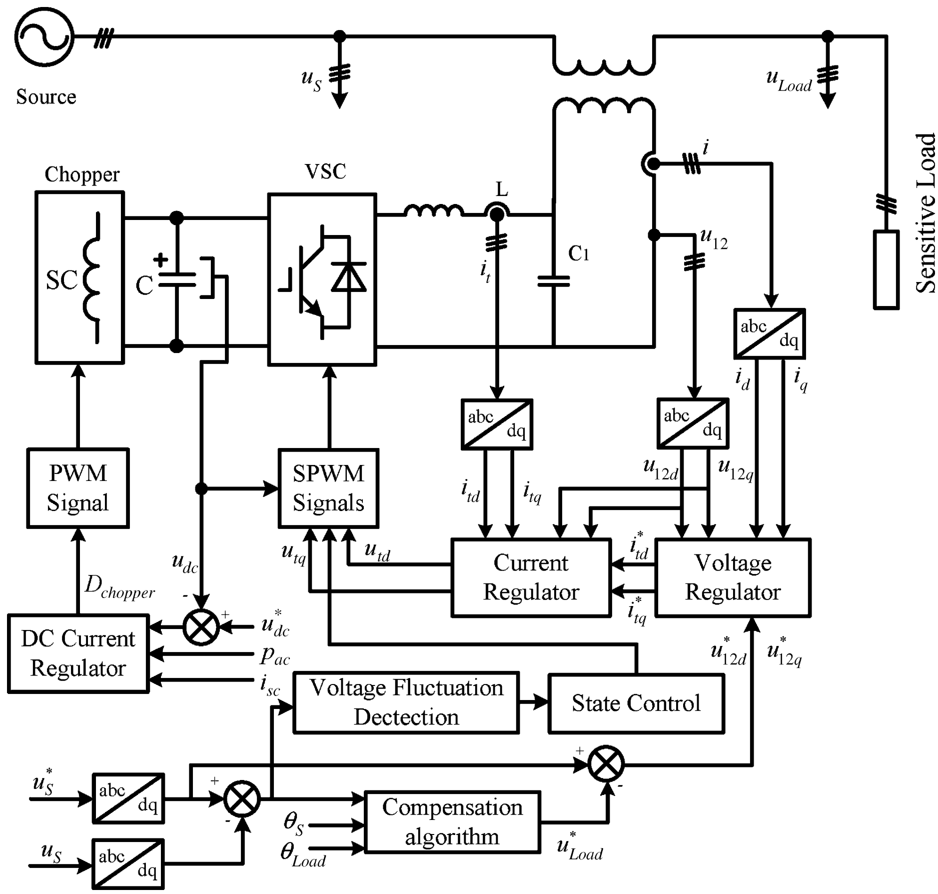

Fig. 2. Block diagram of the DVR controller.

TABLE I
DESIGN PARAMETERS

Item	Parameters
Source voltage	380 V, 50 Hz
Converter rating power	8 kVA
Switching frequency of converter	5 kHz
Filter inductor L	6 mH
Filter capacitor C_1	4 μ F
DC link capacitor	9400 μ F
DC rating voltage	400 V
Switching frequency of chopper	10 kHz
SC rating energy storage	12.5 kJ
SC inductor	2.5 H

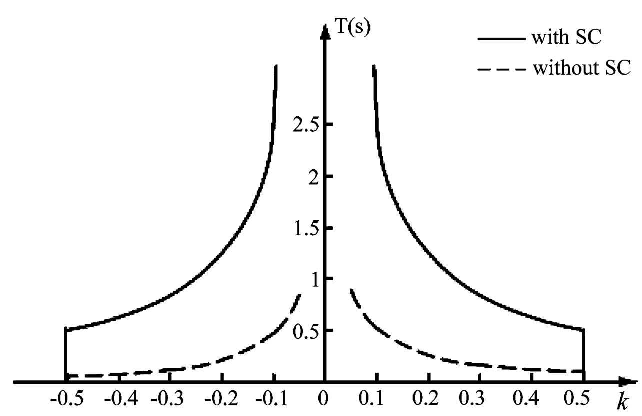

Fig. 3. The comparison of the compensation scope for a DVR with and without the superconducting magnet.

reach to ±5 kJ in the process of dynamic compensation. Considering the current carrying level of the high temperature superconducting tapes, the rating current of the magnet is selected as 100 A. According to the above condition, the rated energy storage capacity of the magnet is designed at 12 kJ, with an inductance of 2.5 H. When the DVR is in a standby state, the current of the superconducting magnet is maintained at 75 A, which ensures the magnet could absorb or release sufficient energy. The detail parameter of the SMES based DVR is shown in Table I.

Adopting the superconducting magnet as the energy storage unit and the compensation scope of the DVR is shown in Fig. 3. The abscissa denotes the amplitude of voltage fluctuation and the ordinate denotes the maximum duration of compensation. It can be seen that the compensation time can reach 2.5 s in the condition of ±10% system voltage fluctuation.

If the voltage fluctuation is short lived, it is usually enough to apply a DVR arrangement without energy storage unit, for which a variable DC voltage is characteristic. The relationship

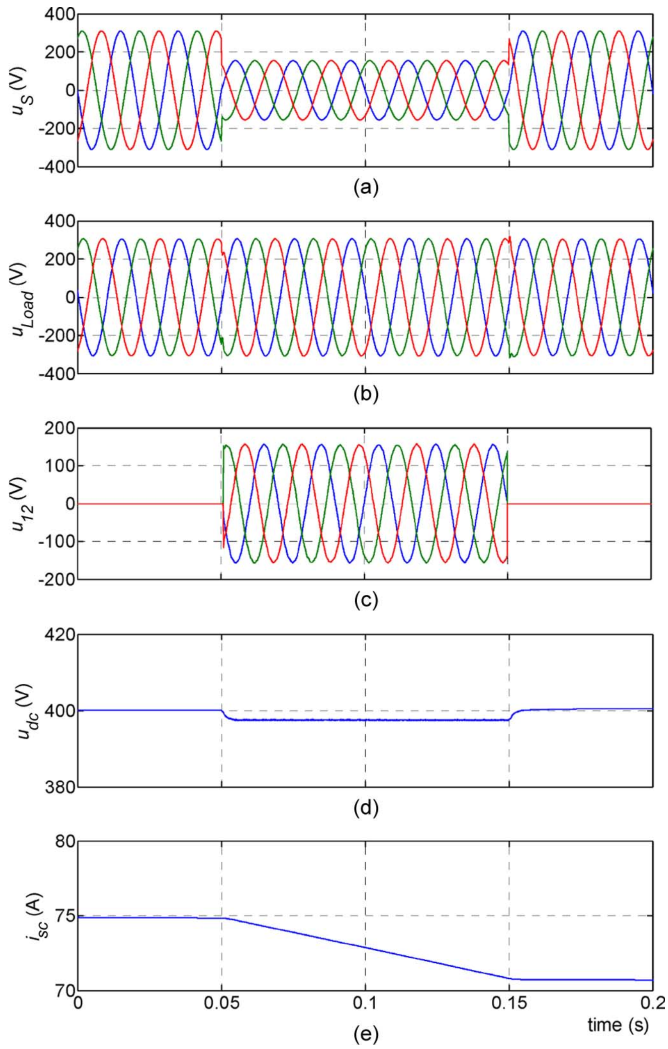

Fig. 4. Dynamic compensation for voltage sag.

between the DC voltage and the AC output voltage of converter can be presented as

$$U_{12} = kU_{rated} = \frac{u_{dc}}{2\sqrt{2}} \tag{12}$$

For example, to compensate voltage sag of -50%, the DC voltage must be higher than 310 V. Otherwise, the voltage sag can not be compensated completely. For voltage swell, the compensating ability is restricted by the voltage-proof level of the DC capacitor. If the maximum voltage of the DC capacitor is set at 600 V, the compensation scope is represented as dashed line in Fig. 3. Adopting the superconducting magnet as the energy storage unit, the compensation capability of the DVR can be improved considerably.

V. Simulation Results

To evaluate the performance of the SMES based DVR, a series of simulation is carried out using MATLAB. The system parameters are derived from Table I.

During the simulation, a three-phase voltage sag is simulated. The grid voltage drops to 50% of its nominal value at 0.1 s, and the DVR starts to operate (Fig. 4). Fig. 4(b) is the load voltage after compensation. It can be seen that the load voltage can be compensated within 4 ms. Fig. 4(c) is the output voltage of the DVR in series with the system, the harmonic component of is very low and the total harmonic distortion is within 5%. To compensate the voltage sag, the superconducting magnet is in discharging state, and the voltage across the magnet is negative. The DC side capacitor voltage can be maintained about 400 V, as shown in Fig. 4(d). The duration of voltage sag is 0.1 s, and the magnet delivers about 750 J of energy. The magnet current drops from 75 A to about 71 A, as shown in Fig. 4(e).

To compensate the voltage swells, the superconducting magnet is in charging state, and the voltage across the magnet is positive. The active power is transferred from the AC system to the magnet, and the system voltage swell can be limit to ensure the constant load voltage.

VI. Conclusion

This paper presents the SMES based DVR to compensate voltage fluctuations. It can compensate long term voltage fluctuation. Based on the mathematical model of the DVR system, the control topology and algorithm are designed. Simulation results illustrate that the superconducting magnet can effectively increase the compensation capability of DVR, compared to the compensation performance by a DC capacitor.

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