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Research on Voltage Stability on the DC Side of Static Synchronous Compensator Based on Supercapacitor

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Abstract. In order to achieve the purpose of simultaneously compensating for active power and reactive power during voltage sags in the distribution network, a Buck/Boost bidirectional converter is used to connect the supercapacitor energy storage device and the static synchronous compensator. The system adopts voltage and current double closed-loop control method. According to Matlab/Simulink, the relevant simulation experiments show that the supercapacitor has constant voltage on the DC bus side whether it absorbs electric energy or releases.

1. Introduction

In recent years, the issue of power quality has attracted more and more attention. Households are increasingly demanding more stable power supply. Abnormal power quality were often presented as abnormality of amplitude or waveform such as voltage sags, three-phase imbalances, voltage fluctuations and flicker, harmonics and frequency fluctuations[1, 2].

The decline of power quality will bring various hazards to the power system, which will directly threaten personal safety and reduce economic efficiency. Therefore, power quality problems are eager to be solved.

Voltage sag is a sudden drop in voltage, but it returns to normal in a very short period of time. The grid voltage sag that occurs during power grid fault, power system oscillation and HVDC transmission block, will lead to the auxiliary variable-frequency drive trip and then cause the generator unit off-grid, which will further impact the power grid in the transient process, deteriorate the stability conditions. This issue has attracted the high attention from power grid corporation [3-5]. Generally, a short circuit fault in the line often causes the momentary large current. When a short-circuit fault occurs in a certain part of the line, the current will increase drastically and the voltage will suddenly decrease. However, the protection device in the fault circuit immediately begins to isolate the fault point, then the voltage returns to normal, which results in a voltage sag. In addition, sudden power connections to the grid can also lead to voltage sags.

STATCOM is the most advanced device in reactive power compensation currently. It can continuously compensate reactive power in both directions and quickly track changes in reactive power in the system. However, the voltage-type inverters of STATCOM mainly exchange reactive power with the system .STATCOM will be useless when it comes to problems such as terminal voltage sag and active oscillation of power system, which needs to be solved by energy storage technology [6].

At present, the research on energy storage technology is still in its infancy, but preliminary results show that its effect is good. There are many demonstration projects for the research of electrochemical (battery) energy storage system (BESS) technology, but they are mainly applied in renewable power integration and adjusting system frequency. The main disadvantage is that the power density of BESS is not high enough, and the supercapacitor can precisely make up for this shortcoming.

If supercapacitor energy storage system (SCESS) is introduced into the DC side of STATCOM, it will become a new parallel compensation device. STATCOM/SCESS not only can quickly compensate for reactive power of system, but also can compensate for active current, which can provide more flexible and diverse power regulation functions. If the energy storage unit is large enough, the load can be provided with the necessary power to ensure continuity of power supply and avoid economic losses caused by interrupted power supply.

2. Scheme design

2.1. Basic principle

The system comprises a STATCOM with a SCESS. The SCESS consists of a bank of supercapacitors which is interfaced to the DC link of the STATCOM by a bidirectional DC to DC converter, which controls the charge and discharge of the supercapacitors [7]. The text below will expand technical details step by step.

2.1.1. Supercapacitor energy storage system. Compared with current energy storage technology such as lithium batteries, flywheel energy storage and superconducting energy storage, there are many advantages of supercapacitor: rapid charge and discharge rates, high efficiency, large charge and discharge currents, and long cycle life [8].

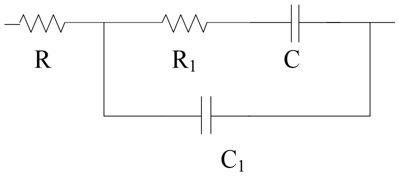

Figure 1. The equivalent model of supercapacitor

The circuit of the *RC* model is relatively simple. In the figure 1 above, *R* is the separation resistance. The surface area and conductivity of the electrolyte electrode determine the size of the resistance; R_1 is the charge transfer resistance, and its size depends on its own material; *C* is the adsorption capacity. It has different capacitance in different operating temperatures. The parameters in the circuit model are determined by the supercapacitor's material, the internal composition, and the working state of the supercapacitor.

The rated working voltage of the super capacitor is set to U_W, and the minimum working voltage is U_{min}. The stored energy of supercapacitor can be expressed as:

$$W_o = \frac{1}{2} C\left(U^2{}_w - U^2{}_{\min}\right)$$

The energy storage unit consists of *m* supercapacitors which connected in series and *n* supercapacitors which connected in parallel. The stored energy of each supercapacitor is w_o. The energy stored by the energy storage unit satisfies the following formula:

$$W_s = \frac{1}{2} mnC\left(U^2{}_w - U^2{}_{\min}\right)$$

According to above, we can ascertain the quantity of needed supercapacitor:

$$mn = \frac{2W_s}{C\left(U^2{}_w - U^2{}_{\min}\right)}$$

2.1.2. Overall system block diagram and control. The overall block diagram of system is shown in figure 2. Supercapacitor DC energy storage unit usually adopts the half-bridge structure with positive and negative current flowing, which is also called Buck-Boost bi-directional DC converter. With only two power semiconductor devices, its structure is simple and compact .When the supercapacitor stores energy, the bidirectional DC/DC converter operates in the mode of Buck and charges the supercapacitor to a predetermined voltage. When the supercapacitor releases energy, the bi-directional DC/DC converter operates in the mode of Boost to maintain the stability of the DC bus voltage of the grid-connected converter, so that the grid-connected converter can deliver constant power to the grid [9].

The control scheme of bi-directional DC/DC converter is figure 3.

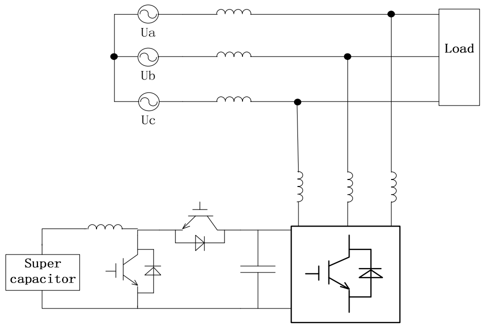

Figure 2. Overall block diagram of system

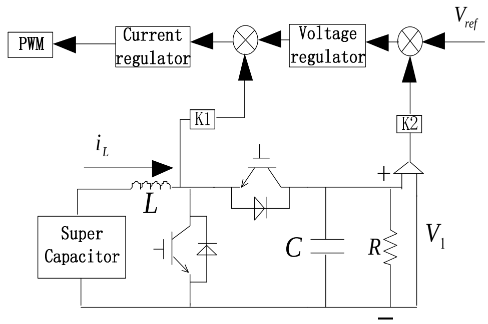

Figure 3. DC/DC control scheme

In order to be able to perform power and energy management on the supercapacitor, a bi-directional DC/DC converter for the supercapacitor energy storage system must be controlled by closed-loop, so that the charging and discharging processes of the supercapacitor energy storage system can be controlled [10]. In this part, the bi-directional DC/DC converter of the supercapacitor energy storage system is designed by closed-loop to store energy and release energy respectively, and the bi-directional DC/DC converter are controlled by the inner loop of the inductor current and the outer loop of the instantaneous voltage value. The current loop adopts an inner loop of inductor current. When the supercapacitor is charged, the closed-loop control of the inner loop of the inductor current controls the charging current of the super capacitor and protects the power device. When the supercapacitor releases energy, the inductor current inner loop can improve the system's performance of rapid response [11, 12].

2.2. Mathematical analysis of voltage sags for STATCOM

In the moment of a voltage sag or outage of power, the supercapacitor supplies energy to the load and provides active compensation to ensure normal operation of the load [13].

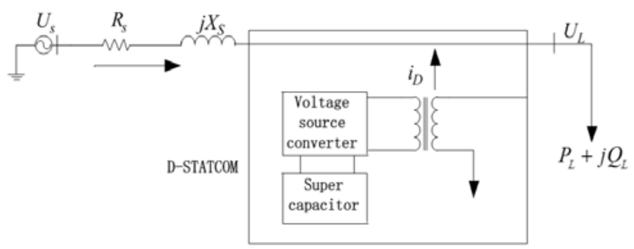

Figure 4. Wiring diagram of system

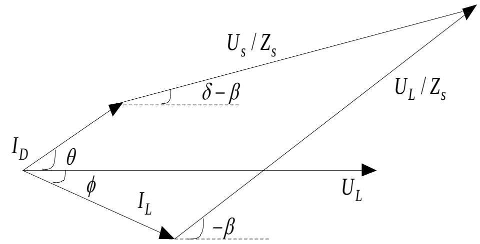

Figure 5. Vector illustration

As shown in figure 4, we know:

$$I_D = I_L - I_S = I_L - \frac{U_S - U_L}{Z_S} \tag{1}$$

Set U_L as the benchmark, we expand formula (1):

$$I_D \angle \theta = \left(I_L \angle -\varphi\right) - \frac{U_S}{Z_S} \angle\left(\delta - \beta\right) + \frac{U_L}{Z_S} \angle -\beta \tag{2}$$

In formula (2), θ β δ is the angle of amplitude of I_D Z_s U_s respectively; $\varphi = \arctan(Q_L / P_L)$.
Then we can get the capacity of STATCOM:

$$S_D = U_L I_D^{\,*} \tag{3}$$

According to above formula, vector illustration can be drawn as figure 5.
The amplitude of current injected by STATCOM is:

$$I_D^{\,2} = I_L^{\,2} + \frac{U^2{}_S}{Z^2{}_S} + \frac{U^2{}_L}{Z^2{}_S} + 2\frac{U_L I_L}{Z_S}\cos\left(\varphi + \beta\right) - 2\frac{U_S I_L}{Z_S}\cos\left(\delta - \beta + \varphi\right) - 2\frac{U_S I_L}{Z^2{}_S}\cos\delta \tag{4}$$

STATCOM needs to obtain the minimum current for minimum capacity, so:

$$\partial I_D^{\,2} / \partial \delta = 0 \tag{5}$$

Solving formula (5), we get:

$$\delta = \arctan\left[\frac{Z_S I_L \sin\left(\beta - \varphi\right)}{U_L + Z_S I_L \cos\left(\left(\beta - \varphi\right)\right)}\right] \tag{6}$$

According to the known conditions, δ can be calculated, and then δ is assumed to be formula (2) and the formula (3) respectively .We will obtain the minimum injection current and the minimum capacity of the STATCOM.

Without supercapacitor energy storage unit, STATCOM only compensates reactive power. In this situation, active power P_L of the load is provided by the infinite system, then:

$$P_L = \frac{U_S U_L}{Z_S}\cos\left(\beta - \delta\right) - \frac{U_L^{\,2}}{Z_S}\cos\beta \tag{7}$$

From formula (7), we can get:

$$\delta = \beta - \arccos\left(\frac{U_L}{U_S}\cos\beta + \frac{Z_S P_L}{U_S U_L}\right) \tag{8}$$

To satisfy the above equation, you must satisfy the below:

$$U_S \geq U_L \cos\beta + Z_S P_L / U_L \tag{9}$$

It can be concluded that voltage sag cannot always be achieved only by means of reactive power compensation, so it is necessary to increase the use of supercapacitor as energy storage units.

3. Build a mathematical model

Based on mathematical methods, state-space averaging method is complex on the calculation and not intuitive [14, 15]. If we can get the AC small-signal model by circuit transformation, the circuit will be more intuitive and easier to use. This is the starting point of the average switch model method. The average switching model can be applied not only to PWM DC/DC converters but also to resonant converters and three-phase PWM converters.

Any DC/DC converter can be divided into two sub-circuits. One sub-circuit is a fixed-length linear sub-circuit and the other is a switching network. Figure 6 is the AC small-signal average switch model of the switch network of Buck-Boost converter .The left side is the switch network, the right side is the fixed-length linear sub-circuit.

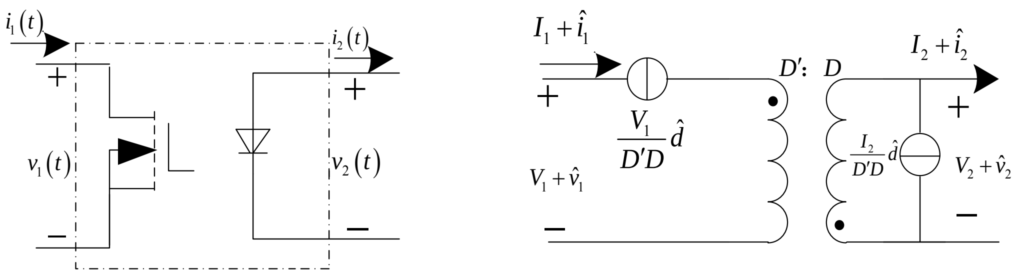

Figure 6. AC small-signal average switch model of Buck-Boost converter

Get the transfer function from input to output and transfer function from control to output:

$$G_1 = \left.\frac{v_0(s)}{v_g(s)}\right|_{d(s)=0} = -\frac{DD'}{LCs^2 + \frac{L}{R}s + D'^2}$$

$$G_2 = \left.\frac{v_0(s)}{d(s)}\right|_{v_g(s)=0} = \frac{V\left(\frac{D'}{D} - \frac{sL}{D'R}\right)}{LCs^2 + \frac{L}{R}s + D'^2}$$

4. Simulation model

According to the transfer function, we select the appropriate parameters and build a simulation circuit as below:

Table 1. Simulation parameters

Filter inductor	DC side capacitor	DC voltage command value	Load resistance	Grid frequency	Super capacitor
0.3mH	6000μF	400V	10Ω	50Hz	27F

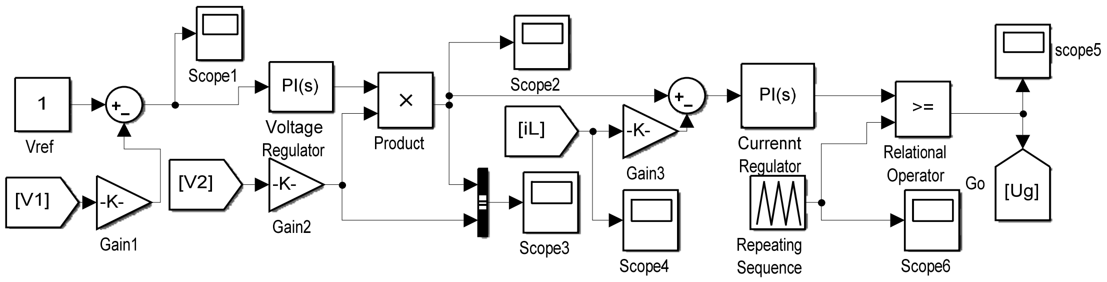

Figure 7. Dual closed loop simulation model

As is shown in figure 8, inductive load is put into system to simulate the model in 0.2s-0.4s. The system generate a current to compensate reactive and active power losses when the load is applied at 0.2 s. During this period, the slight grid voltage fluctuations and the short time going into a steady-state can verify the superiority of its stability and dynamic performance.

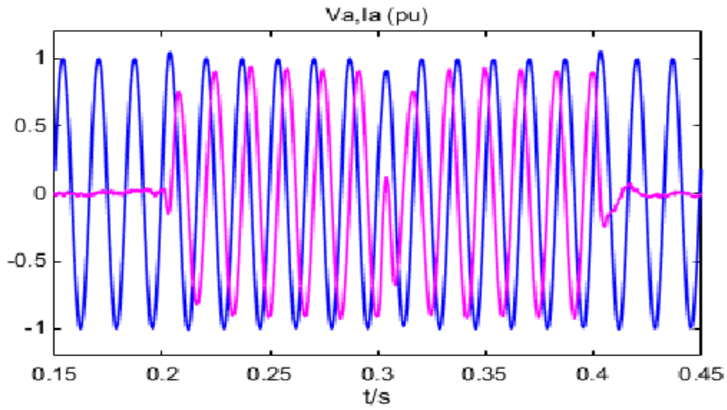

Figure 8. The voltage and current waveforms of the STATCOM

It can be seen from the figure 9 that the DC side voltage, which reaches steady state in a short time when the load suddenly changes, is always constant at about 400V.

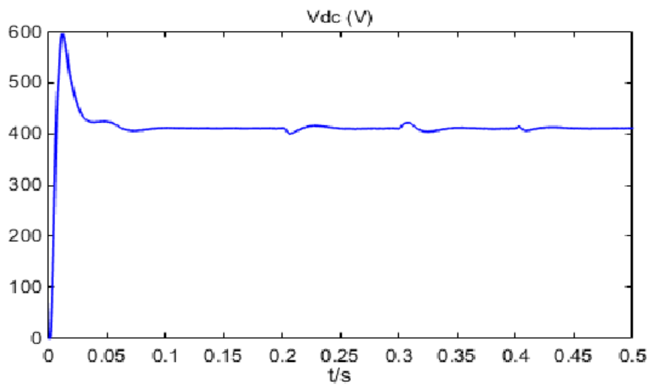

Figure 9. The simulation waveform of DC-side voltage

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In summary, the dual-closed-loop PI controller in this paper has the characteristics of fast response speed and strong adaptability, which will control the voltage stability of the DC side of the STATCOM and ensure stable operation of the entire power system.

5. Conclusions

This paper introduces the Buck/Boost type bidirectional DC converter which is used to connect the supercapacitor energy storage device and the static synchronous compensator. The dual closed-loop PI control method was analyzed, and the simulation analysis of its effectiveness was performed by Matlab/Simulink.

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