Power System Stabilization Control by HVDC with SMES
Using Virtual Synchronous Generator

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(Manuscript received Nov. 30, 2011, revised March 27, 2012)

This paper describes power system stabilization with a VSG (virtual synchronous generator) control scheme by using VSC (voltage source converter) type HVDC (high-voltage DC transmission) with SMES (superconducting magnetic energy storage). Power system stabilization schemes that prevent instability due to the disturbance in grids that are connected to renewable power sources were studied. This paper further discusses the effect of SMES connected to the DC link of the VSC-HVDC system for the compensation of power fluctuation caused by distributed generators in one AC newtork of HVDC for eliminating the influence on the network on the other side to which the HVDC is connected. Simulations using PSCAD/EMTDC were carried out to evaluate the performance of the applied control system.

Keywords: VSG, SMES, VSC-HVDC, synchronous generator, power fluctuation

1. Introduction

The number of renewable power sources connected to electrical power grids, such as photovoltaics (PV) and wind turbines is rapidly increasing. For example, the expected accumulated power of wind turbines and PV to the Japanese power grid will be 4.9 GW and 14.3 GW by 2020, and 6.6 GW and 56 GW by 2030, respectively. With the rapid increase in the capacity of distributed generators, maintenance of grid stability is becoming important because their extensive use in interconnected power grids tend to result in instability issues. Fluctuations in renewable energy can lead to system power oscillation which in turn results in instability and frequency deviation problems in power systems. Conventional power plants are equipped with synchronous generators and such power plants can realize frequency control. However wind turbines and PV are not equipped with a frequency control mechanism, but they maintain power system frequency by using PLL (phase locked loop).

To preserve the positive effect of inertia on stability of power systems, methods that allow for an inertial response need to be developed. There are many methods and devices that revert the frequency to its nominal value. In this paper, a VSC type HVDC system is applied to do so. In most grid-connected VSC systems, a PLL method based on power synchronization control is used. Ref. (1) describes a power synchronization control similar to a synchronous machine; however, it does not describe power system stabilization control. Similarly, this paper discusses a VSC-HVDC connected with a weak AC system.

Recently, a novel concept VSG (virtual synchronous generator) was proposed as a control strategy to tackle stability issues in a power system with distributed generators (2). VSG is a control scheme of inverters that behave as SGs (synchronous generators). In the literature on VSG includes its application to grid stabilization with inverter-connected-type distributed generators (3)(4), especially in microgrid systems. However, using VSG in the stabilization of large-scale power systems has not been studied thus far.

In the case of large-scale power systems, many generators including distributed generators are connected to the power system. Therefore, it would be difficult to connect the VSG controller to all the distributed generators in the system for higher stability. In this paper, a method to enhance the stability of power systems by using the HVDC system equipped with VSG control is proposed. Moreover, conventional speed deviation control (5) is described for comparison with the VSG method.

Installing SMES (superconducting magnetic energy storage) in the DC link of HVDC is more effective than on the AC side because power fluctuation in both the systems with DC inertia can be compensated for by a common SMES. In Refs. (6) and (7), an SMES coil is directly connected in series with power converters. However, this configuration causes changing of the current flowing through AC/DC converters of HVDC due to charging and discharging of SMES. Therefore, a DC-DC converter is used as an interface between HVDC and SMES in order to reduce the rating of AC/DC converters of HVDC. In this research, SMES is connected at the DC link of VSC-HVDC in order to make independent stabilization of two AC systems. The purpose of using SMES is to smooth out fluctuating power and to maintain constant power flow in one terminal side of HVDC by absorbing and providing power according to the system requirement while power fluctuations exist at the another terminal as shown in Fig. 1.

The effectiveness of the proposed VSG control scheme and SMES for power system stabilization is investigated by
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2. Control Schemes

Figure 2 shows the configuration of proposed control system. In this VSC-HVDC model, SG (Synchronous Generator) and disturbance source exist in AC1 network. SG represents the power grid and disturbance source represents as distributed generator of renewable energy source. There are two six pulse voltage source converters in each sending and receiving side, and four SMESs which are attached in shunt in each VSC in DC link.

To avoid the influence of the disturbance source in SG side, grid stabilization is considered. The output of SG side is stabilized by rectifier side converters. To maintain constant power flow into receiving terminal AC2 network, SMES system compensates power fluctuation of AC1 terminal by realizing required power ($\Delta P_1$) to be compensated. Therefore, $\Delta P_1$ is applied to control of SMES. In inverter side converters, dc voltage control is applied to keep rated dc line voltage constant.

2.1 Control Scheme of SMES

The SMES is composed of a DC-DC chopper and a superconducting coil as shown in Fig. 3. The function of SMES in the proposed system shown in Fig. 1 is to absorb power fluctuation of ac system (AC1) while keeping constant power flow to another ac system (AC2). According to the system circuit configuration, receiving side power ($P_2$) is

$$P_2 = P_1^* + \Delta P_1 - P_{SMES}$$  \hspace{1cm} (1)

where $P_1^*$ and $P_2^*$ are reference power of $P_1$ and $P_2$ in Fig. 2, $\Delta P_1$ is power variation of rectifier ac bus ($\Delta P_1 = P_1 - P_1^*$) and $P_{SMES}$ is power from SMES.

To obtain stable power flow of $P_2$, SMES power ($P_{SMES}$) and disturbance power amount ($\Delta P_1$) should be the same as shown in Fig.4. Therefore, $\Delta P_1$ is added to SMES control system to compensate required power of the system. Moreover, SMES current needs to be kept constant so that stored energy in the SMES coil can be maintained constant by $P_{SMES, avg}$, which means a constant power to supply losses of SMES.

The stored energy ($E_{SMES}$) and rated power ($P_{SMES}$) in the coil can be expressed as,

$$E_{SMES} = \frac{1}{2}L_{SMES}I_{SMES}^2 \hspace{1cm} (2)$$

and

$$P_{SMES} = \frac{dE_{SMES}}{dt} \hspace{1cm} (3)$$

where $L_{SMES}$ is the inductance of the coil and $I_{SMES}$ is the current flowing through the coil.

With above consideration and equations (2) and (3), the feedback block diagram of SMES energy control loop is shown in Fig.5. The input of PI controller is the error of SMES stored energy, and the output is the average constant power of SMES. The reference instantaneous power of SMES to compensate power requirement of the system is determined by $P_{SMES, avg} + \Delta P_1 = P_{SMES}$. Equation (4) shows

$$P_{SMES} = \frac{dE_{SMES}}{dt} \hspace{1cm} (3)$$
2.2 Power System Stabilization Control by HVDC using VSG

The relation of the control scheme shown in Fig. 5. In equation (4) of SMES transfer function, $\Delta P_1$ represents a disturbance in the SMES energy control loop. The first term of equation (4) is not so important for dynamic characteristics as $E_{SMES}^*$ is constant. Assuming the frequency of fluctuating power ($\Delta P_1$) is larger than 1 Hz, the second term of equation (4) should be integral for the frequency region larger than 1 Hz in order to absorb the fluctuating power $\Delta P_1$ by SMES. Considering these points, $K_2 = 1$ and $T_2 = 10$ were chosen.

The bode diagram of the transfer function of equation (4) is shown in Fig. 6 and the complete control block of SMES is shown in Fig. 7.

$$E_{SMES} = \frac{T_2 s + 1}{K_2 s^2 + T_2 s + 1} E_{SMES}^* + \frac{s}{s^2 + K_2 s + K_2^2 \frac{T_2}{T_2}} \Delta P_1$$

(4)

2.2 Control Scheme of Grid Stabilization

In the grid stabilization scheme, two methods are studied. One is conventional speed deviation control and the other is VSG (virtual synchronous generator) control.

2.2.1 Conventional Speed Deviation Control

Figure 8 shows the control block of conventional frequency control for grid stabilization. Frequency of grid is controlled to bring back to its nominal value closely. In this conventional speed deviation control (Δω), $\Delta \omega = \omega - \omega_0$, where $\omega_0 = 2\pi \cdot 60 \text{rad/s}$ is the speed deviation of SG. In this control case, AC1 grid power is stabilized by realizing power variation amount ($\Delta P_g$) which is determined by speed deviation ($\Delta \omega$) with constant gain ($K$). Figure 9 shows the control block for rectifier side converter (VSC1). Constant initial value of SG power ($P_{g0}$) is added to $\Delta P_g$ to determine the reference value of grid power. Then, grid power is controlled by using PI controller to maintain its average value. From the output of PI controller of $P_g$, reference value of ac input power ($P_{g1}^*$) to rectifier converter (VSC1) is given to apply for internal current control part. After converting reference three phase sinusoidal voltage of converter, third harmonic is injected to improve dc voltage utilization in generation of PWM. The same control block as VSC1 is applied for VSC2.

2.2.2 Virtual Synchronous Generator Control

The model of synchronous generator used in this research is a cylindrical-rotor type. In the concept of VSG control, rectifier side converters are controlled to behave like a synchronous generator. The control scheme of VSG is based on the swing equation of synchronous generator. VSG has virtual inertia which is realized by Equation (5).

$$M = J \omega_m^2 \frac{P_{base}}{F_{base}}$$

(5)

In equation (5), $M$ is the inertia constant, $J$ is the inertia moment of rotor, $\omega_m$ is the speed of the rotor, and $P_{base}$ is based power of the system. Kinetic energy of VSG ($E_{VSG}$) can be described as

$$E_{VSG} = \frac{1}{2} J \omega_m^2$$

(6)

From this energy equation, power swing equation of generator can be expressed as equation (7). As there are damper windings on the rotor of the synchronous generator, the damping term is added to swing equation.

$$\Delta P_g = \frac{1}{2} J \omega_m^2$$

(7)
\[ P_{g0} - P_g = M \frac{d}{dt} \omega_m + D \Delta \omega_m \tag{7} \]

\[ \Delta \omega_m = \omega_m - \omega_{m0}. \]

where \( P_{g0} \) and \( P_g \) are the input and output power of SG respectively, \( D \) is the damping coefficient, \( \omega_m \) is the virtual rotating frequency and \( \omega_{m0} \) is synchronous rotating frequency.

For SG, the governor function as shown in Fig. 10 is used to provide the input mechanical torque signal to the machine. In governor function, \( \delta \) is the speed regulation which is typically 5%. Figure 11 shows the diagram of VSG control block.

The swing equation (7) is applied to the VSG control in rectifier side converters. Virtual mechanical phase, \( \omega_m \) is calculated in swing equation by substituting \( P_{g0} \) and \( P_g \) in VSG control. Then, virtual mechanical phase (\( \theta_m \)) is calculated by integrating \( \omega_m \).

\( \theta_m \) is controlled as a phase reference to generate three phase sinewave for rectifier ac voltage. In this VSG control based on generator swing equation, the change of \( \omega_m \) over a time step \( \Delta t \) can be calculated by the application of the forth-order Runge-kutta approximation as shown in Fig. 12 of the flow chart of applied VSG control.

### 3. Simulations

To verify the proposed control methods, simulations were carried out by PSCAD/EMTDC. Two cases of simulations for grid stabilization by using conventional speed deviation control and VSG control are presented. The parameters of synchronous generator and SMES are shown in Table 1 and Table 2, respectively. VSC-HVDC system links AC system with a short circuit ratio (SCR) of 3. Disturbance source is a current disturbance source.

#### 3.1 Simulation with Conventional Speed Deviation Control of Grid Stabilization

Figure 13 shows the configuration of simulated system. This simulation system consists of one disturbance source in sending terminal which represents distributed generators, one synchronous generator which represents as the power grid and VSC-HVDC transmission with SMES connection in the DC link. This simulation was performed to evaluate the effectiveness of SMES for compensation of power fluctuation to maintain constant power flow in receiving side and to verify the grid.

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Table 1. Circuit parameters of synchronous generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>235 MW</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>275 kV</td>
</tr>
<tr>
<td>Per-unit inertia constant, ( Mf )</td>
<td>4 s</td>
</tr>
<tr>
<td>( X_s )</td>
<td>1.70 pu</td>
</tr>
<tr>
<td>( X_q )</td>
<td>1.70 pu</td>
</tr>
<tr>
<td>( X_{sd} )</td>
<td>0.38 pu</td>
</tr>
<tr>
<td>( X_{qd} )</td>
<td>0.228 pu</td>
</tr>
<tr>
<td>( T_{do} )</td>
<td>0.15 s</td>
</tr>
<tr>
<td>( T_{qo} )</td>
<td>0.85 s</td>
</tr>
<tr>
<td>( X_{sd}'' )</td>
<td>0.28 pu</td>
</tr>
<tr>
<td>( X_{qd}'' )</td>
<td>0.28 pu</td>
</tr>
<tr>
<td>( T_{do}'' )</td>
<td>0.03 s</td>
</tr>
<tr>
<td>( T_{qo}'' )</td>
<td>0.03 s</td>
</tr>
</tbody>
</table>
stabilization control by rectifier side converters with conventional frequency control. For inverter side converters, DC voltage control is used to keep the rated DC line voltage constant.

3.2 Simulation by Using VSG Control for Grid Stabilization

In this case, AC1 grid is stabilized by using VSG control based on the swing equation of synchronous generator as shown in Fig. 14. In this simulation, \( M = 200 \text{ s} \), \( D = 119 \text{ W/rad} \) and \( P_{\text{base}} = 320 \text{ MW} \) where the capacity of rectifier is taken as \( P_{\text{base}} \), are used. For choosing the appropriate values of \( M \) and \( D \), firstly the value of \( D \) is set at the fixed value. Then, the value of \( M \) is chosen according to the simulation results of grid power stability. The detailed graph of setting of parameters \( M \) and \( D \) is described in section 4.

3.3 Simulation Results

3.3.1 Effect of Proposed Grid Stabilization Control

In this simulation case, disturbance of distributed generator source starts at 4 s of simulation time as shown in Fig. 15 of waveform of disturbance power \( (P_d) \). Figure 16 shows the simulation results of active power of AC1 grid \( (P_g) \) without stabilization control and with conventional speed deviation and VSG control, respectively.

Investigating the results of simulation, power oscillation at AC1 grid was occurred when disturbance happens at the distributed generator side if there is no stabilization control for the grid. Disturbance of the distributed generator affects on grid frequency deviation. Therefore, output frequency of the grid cannot keep to its nominal value. However, the grid frequency can be restored to its rated value by VSG control as well as speed deviation control as shown in Fig. 17. Therefore, the grid power \( (P_g) \) is maintained stable by the proposed stabilization controls as shown in Fig. 16.

Although both VSG and speed deviation control can stabilize grid power to avoid the influence of disturbance, VSG control is more convenient because VSG can keep the grid frequency to its nominal value without speed information \( (\Delta \omega) \) from a generator.

3.3.2 Effect of SMES for Stabilization of Power Flow

As the disturbance contributes to rectifier side converters, sending power of HVDC \( (P_1) \) is fluctuated. However, there is no influence of power fluctuation in inverter side because of the effectiveness of SMES control system. Therefore, power flow \( (P_2) \) is maintained constant in the receiving side AC2 network. The effectiveness of SMES for compensation of power fluctuation can be seen in Fig. 18. SMES coil current \( (I_{\text{SMES}}) \) is shown in Fig. 19. The waveform of current flowing through SMES coil shows that the average of SMES coil current is stable. Therefore, the stored energy in the coil is also kept constant.

4. Effect of \( D \) and \( M \) of VSG on System Stability

In the proposed control of VSG for grid stabilization, the sending side of the system can be drawn as two machines

<table>
<thead>
<tr>
<th>Table 2. Parameters of control system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SG</strong></td>
</tr>
<tr>
<td>Disturbance source</td>
</tr>
<tr>
<td>DC voltage</td>
</tr>
<tr>
<td>SMES1</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Fig. 16. Effect of stabilization control on active power $P_g$ of AC1 grid

Fig. 17. Effect of stabilization control on mechanical angular frequency $\omega_m$ and electrical angular frequency $\omega_g$ of the SG

Fig. 18. Simulation result of sending and receiving terminal power of HVDC

Fig. 19. Current of SMES coil

Fig. 20. Diagram of two machines SG and VSG

Power swing equations for two machines in Fig. 20 can be written as

$$M_1 \frac{d^2}{dt^2} \delta_1 + D_1 \frac{d}{dt} \delta_1 = P_{m1} - P_{e1} \tag{8}$$

$$M_2 \frac{d^2}{dt^2} \delta_2 + D_2 \frac{d}{dt} \delta_2 = P_{m2} - P_{e2} \tag{9}$$

where $M_1, D_1, \delta_1, P_{m1}$ and $P_{e1}$ are the inertia constant, the damping coefficient, rotor angle, mechanical and electrical power of SG, and $M_2, D_2, \delta_2, P_{m2}$ and $P_{e2}$ are those of VSG respectively.

Multiplying both sides of equation (8) by $M_2$ and equation (9) by $M_1$ and subtracting, the following equation (10) is obtained.

$$M_1 M_2 \frac{d^2}{dt^2} (\delta_1 - \delta_2) + \left( D_1 M_2 - D_2 M_1 \right) \frac{d}{dt} (\delta_1 - \delta_2) = (M_2 P_{m1} - M_1 P_{m2}) - (M_2 P_{e1} - M_1 P_{e2}) \tag{10}$$

Neglecting losses in transmission line between two machines, the expressions for $P_{e1}$ and $P_{e2}$ are given by

$$P_{e1} = -P_{e2} = \frac{E_1}{X_1} \sin(\delta_1 - \delta_2) = P_{\text{max}} \sin(\delta_1 - \delta_2) \tag{11}$$

where $\delta_1$, $\delta_2$, $P_{e1}$, $P_{e2}$ and $P_{\text{max}}$ are defined as above.

Let $\delta_1 - \delta_1 = \delta_{12}$

Swing equation (10) can be linearized around the operating point that is characterized by $\delta_{120}$. Variation signal $\Delta$ around the operating point is defined by

$$\Delta = (\delta_1 - \delta_{120})$$
\[ \delta_{12} = \delta_{120} + \Delta \delta \]  
(12)

Linearization of \( \sin \delta_{12} \) around \( \delta_{120} \) gives:

\[ \sin(\delta_{12}) = \sin(\delta_{120} + \Delta \delta_{12}) = \sin(\delta_{120}) + \Delta \delta_{12} \cos(\delta_{120}) \]  
(13)

Substituting the relation of rotor angle \( \delta_{12} \) and angular velocity \( \omega_{12} \) \( \frac{d}{dt} \delta_{12} = \omega_{12} \) and taking \( P_s = P_{\text{max}} \cos(\delta_{120}) \), equation (14) is obtained.

\[
\Delta \omega_{12} = -\frac{(M_1 + M_2)}{M_1 M_2} P_s (\Delta \delta_{12}) - \frac{(D_1 M_2 - D_2 M_1)}{M_1 M_2} (\Delta \omega_{12})
\]  
(14)

Linear approximation for the swing equations of SG and VSG is obtained as shown in equation (15).

\[
\begin{bmatrix}
\Delta \delta_{12} \\
\Delta \omega_{12}
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
-\frac{(M_1 + M_2)}{M_1 M_2} P_s & -\frac{(D_1 M_2 - D_2 M_1)}{M_1 M_2}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_{12} \\
\Delta \omega_{12}
\end{bmatrix}
\]  
(15)

The solution of this linear set of equations can be characterized by eigenvalues shown in equation (16).

\[
\lambda_{1,2} = \frac{-(D_1 M_2 - D_2 M_1)}{2 M_1 M_2} \\
\pm \sqrt{\frac{1}{4} \left( \frac{(D_1 M_2 - D_2 M_1)}{M_1 M_2} \right)^2 - \frac{(M_1 + M_2)}{M_1 M_2} P_s}
\]  
(16)

Stability of the system can be discussed by the eigenvalues. \( P_s \) in equation (16) can be calculated as follow:

\[ P_s = P_{\text{max}} \cos(\delta_{120}) = P_{\text{max}} \sqrt{1 - \sin^2(\delta_{120})} \]  
(17)

Reference power of the system of Fig. 20 can be expressed as

\[ P_{\text{ref}} = P_{\text{max}} \sin(\delta_{120}) = \frac{(E_1 E_2)}{X_1} \sin(\delta_{120}) \]  
(18)

Then, the value of \( P_s \) is as

\[ P_s = \sqrt{\left( \frac{E_1 E_2}{X_1} \right)^2 - \left( P_{\text{ref}} \right)^2} \]  
(19)

Since the value of \( P_s \) is very large \( (P_s = 905 \times 10^6 \text{ W with } P_{\text{ref}} = 320 \text{ MW}) \), the value in the square root of the equation (16) is usually negative, hence the second term of equation (16) is the imaginary part of the eigenvalues. When the first term of equation (16) is divided by \( M_2 \), it becomes as

\[ D_1 - \frac{D_2}{M_2} M_1 \]  

As the parameters \( D_1 \) and \( M_1 \) are known values from the power system, the value of \( \frac{D_2}{M_2} \) is important. Performance of the system was evaluated by setting various values of \( D_2 \) and \( M_2 \) when \( D_1 = 4.5 \text{ W/rad, } M_1 = 4 \text{ s} \). Figure 21 shows the set points of \( M_2 \) versus \( D_2 \) at which the grid power is maintained stable according to simulation results.

The eigenvalues corresponding to the power swing modes of Fig. 21 in stable and unstable condition are shown in Fig. 22. As shown in Fig. 22, the pole locations exist on right side plane in unstable modes and on left side plane in stable modes of the system. Figure 23 shows the simulation result of system power in unstable mode. The system power has very large oscillation and it can not maintain constant in the unstable area. The rectifier side power shown in Fig. 14 in stable mode with various values of \( D_2 \) and \( M_2 \) is shown in Fig. 24.
5. Conclusions

VSG control based on the swing equation of a synchronous generator for stabilization of SG grid was proposed in the application of VSC-HVDC with SMES in DC link. Conventional speed deviation control is also presented for grid stabilization. Investigating the simulation results, the grid is stable and there is no influence of disturbance when the rectifier side converters are controlled with both VSG to behave like a synchronous generator and conventional speed deviation control. Comparing these two methods, VSG control is more convenient because VSG can keep the grid frequency to its nominal value without speed information from a generator. Since there is virtual inertia which can restore the frequency to be back to nominal value in VSG, it can contribute to increase the natural inertia response of the system. The stability of the system can be explained by eigenvalues analysis.

SMES connected in the DC link of VSC-HVDC system was described for compensation of power fluctuation caused by the distributed generators. Simulation results show the effectiveness of SMES in stabilization of power flow in one terminal side of HVDC while another terminal side power is fluctuated.

References


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