2005년도 대한전기학회 하계학술대회 논문집 2005. 7. 18 - 20

계통안정도 개선을 위한 SMES 제어모델에 관한 연구

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Superconducting Magnetic Energy Storage (SMES) Control Models for the Improvement of Power System Stability

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Abstract - Superconducting Magnetic Energy Storage (SMES) can inject or absorb real and reactive power to or from a power system at a very fast rate on a repetitive basis. These characteristics make the application of SMES ideal for transmission grid control and stability enhancement.

The purpose of this paper is to introduce the SMES model and scheme to control the active and reactive power through the power electronic device.

1. 서 론

Transient stability is an important part of power system design and operation. Superconducting Magnetic Energy Storage (SMES) may be an effective means of suppressing system instabilities in electric power networks because of its fast response rate in exchanging electric power. It has good properties such as high efficiency, quick response, and lagging and leading phase control by means of Gate Turn-Off (GTO) thyristors.

A SMES device is characterized as consisting of both internal and external control modules that guide its application in a power systems application.

Active and reactive powers demanded by the power system are modified into feasible active and reactive power by means of the internal controller. The demanded active and reactive powers are the input values of the internal controller. The firing angles of the power converters that control the SMES active and reactive power outputs to produce the feasible active and reactive power are the output values of internal control.

SMES has been widely applicated into the several transmission systems. American Transmission Company (ATC) has purchased six Distributed Superconductor Magnetic Energy Storage (D-SMES) systems that provide voltage stabilization to the Rhinelander Loop transmission grid in USA. BC Hydro installed a D-VAR (Dynamic Volt-Ampere-Reactive) system to mitigate significant voltage problems in Fort St. James, British Columbia, Canada. Fort St. James is located at the end of a radial transmission line where it is susceptible to voltage problems during peak load, faults, and the presence of large motors. D-VAR transmission grid reliability system provides critical voltage support to the electric power grid for Scotland's Orkney Islands. Canada's largest wind farm developer, Vision Quest Windelectric purchases a D-VAR system to provide reactive power support, regulating voltage at the Summerview wind farm, which is located approximately 100 miles south of Calgary, Alberta Canada.

2. 본 론

A SMES Device

As shown in Figure 1, a SMES device has a magnetic inductor, power converters, and transformers.

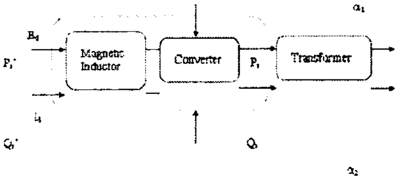


Figure 1. A SMES Device

Components of a SMES System

As shown in Figure 2, a SMES system includes external control, internal control, and a SMES device.

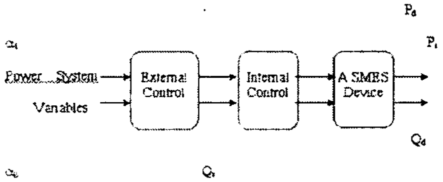


Figure 2. Components of A SMES System

By external control, the SMES system uses the input variables of voltage, frequency, and current to determine the demanded active and reactive power from the power system. By internal control, the SMES system modifies the demanded active and reactive power into feasible active and reactive power and uses those feasible values to control the power converter firing angles that determine outputs. A SMES device receives the signals from the firing angles determined by internal control and then produces the active and reactive power outputs.

SMES Internal Control

The active and reactive powers through two converters are

$Pr = Ed \cdot Id = Edo \cdot Id\ (\cos\theta_1 + \cos\theta_2)$,
$Qr = Edo \cdot Id\ (\sin\theta_1 + \sin\theta_2)$, [2],

where Pr, Qr are the SMES active and reactive power. From two equations, α_1 and α_2 are derived as follows.

$$\cos\alpha_1 = \frac{1}{2E_{do} \cdot I_d}[P_r + \frac{6}{\pi}X_{Ls}I_d^2 + Q_r\sqrt{\frac{4E_{do}^2 \cdot I_d^2 - (P_r^2 + Q_r^2)}{P_r^2 + Q_r^2}}].$$

$$\cos\alpha_2 = \frac{1}{2E_{do} \cdot I_d}[P_r + \frac{6}{\pi}X_{Ls}I_d^2 - Q_r\sqrt{\frac{4E_{do}^2 \cdot I_d^2 - (P_r^2 + Q_r^2)}{P_r^2 + Q_r^2}}].$$

To get the control domain of P, and Q, two sets of GTO converters are applied. GTO's can be turned on by a gate current pulse. In the on-state, the GTO may stay on without any further gate current. GTO'scan be turned off by applying a gate pulse. Therefore, the firing angle can be controlled between 0 and 360. GTO converter can absorb not only lagging but also leading phase active and reactive powers with a full range of SMES size.

Two priority schemes are previously applied for contoling the SMES outputs within the controllable powers: active power priority scheme and reactive power priority scheme [4]. Optimal priority scheme is developed to improve the internal control scheme. As shown in Figure 3, the optimal priority scheme uses the active and reactive power deviations between the demanded powers and the SMES size.

This is a least scheme of active and reactive power deviations.

$$\text{Min}\ (\Delta P^2 + \Delta Q^2),$$

which is subjected to $P_{sm}^2 + Q_{sm}^2 = S_{sm}^2$,

where

$\Delta P = P_{sm} - P_{dam}$,

$\Delta Q = Q_{sm} - Q_{dam}$,

S_{sm} is a SMES size, P_{sm}, Q_{sm} are SMES powers,

P_{dam}, Q_{dam} are demanded powers,

$S_{dam}^2 = P_{dam}^2 + Q_{dam}^2$.

As a result,

$$P_{sm} = \frac{S_{sm}}{S_{dam}}P_{dam},\ Q_{sm} = \frac{S_{sm}}{S_{dam}}Q_{dam}.$$

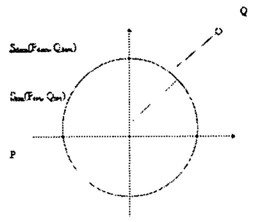


Figure 3. Optimal Scheme for Feasible Powers

SMES External Control Modeling for Power System Stability

Thesecond order time delay nonlinear model for active and reactive power with independent frequency and voltage deviations is applied into the SMES external model.

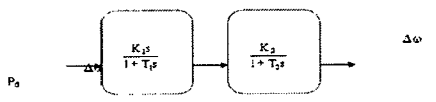


Figure 4. SMES External Model for the Demanded Active Power

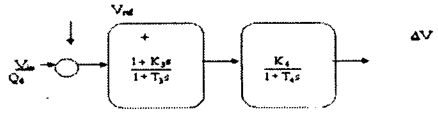


Figure 5. SMES External Model for the Demanded Reactive Power Application of SMES Models for Transient Stability Improvement

As shown in Figure 6, the dynamic model consists of the SMES external and internal models.

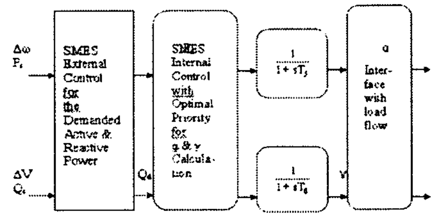
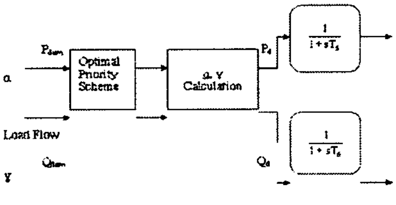


Figure 6. SMES Application with Dynamic Models

The following equations are used to calculate α and γ

$$\alpha = \tan^{-1}\left(\frac{P}{Q + \frac{V_{base}^2 V^2}{X_c S_{base}}}\right),$$

$$\gamma = \frac{X_c S_{base}}{V_d V_t}\sqrt{P^2 + (Q + \frac{V_{base}^2 V^2}{X_c S_{base}})^2}$$



where T5, T6 are time delays.

Figure 7. SMES Internal Control for α, γ

Transient Stability Analysis with SMES Models

1) Example System without SMES Application

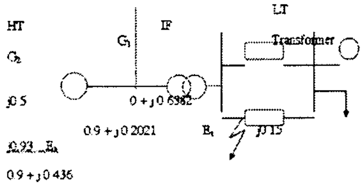


Figure 8. The Infinite Bus System for Studying Transient Stability

A thermal generating station consists of one 555 MVA, 24 kV, 60 Hz unit supplying power to an infinite bus (IF). The infinite bus has a swing generator as a slack bus. Resistances are negligible and the bases for the per unit (p.u.) are 555 MVA, 24 kV.

The initial condition is P = 0.9 p.u., Q = 0.2021 p.u., Et = 1.025.32, EB = 1.00. The G1 generator is modeled as a single equivalent generator represented by the classical model. Xd' = 0.3 p.u., H = 3.5 MWs/MVA, [3].

Figure9 shows the stability simulation result for the example system with a 15 cycle normal clearing time for the three-phase to ground fault.

Power Angle (tc = 0.25s)

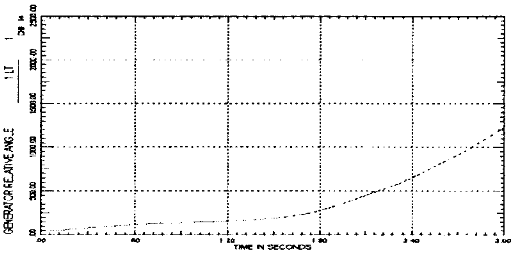


Figure 9. Power Angle for Example System with tc = 0.25s

A three-phase to ground fault was applied to HT bus for 15 cycles, and the fault was cleared by opening the HT-IF line with 0.93 p.u. reactance. The result shows the power angle is unstable with the 15 cycle three-phase to ground fault.

2) Example System with SMES Application

Figure 10 shows the same example system with the SMES connected.

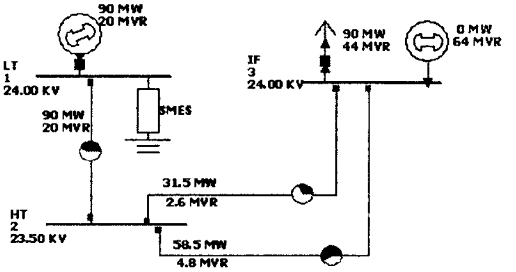


Figure 10. Example System 1 with SMES Application

The 100 MVA SMES is installed at the generator bus to stabilize the power angle. SMES internal and external control models use the following parameters.

$$K_1 = \frac{1}{360},\ K_2 = -\frac{50}{60},\ K_3 = 0.2,\ K_4 = 20.$$

$$T_1 = 0.02,\ T_2 = 0.025,\ T_3 = 2.0,\ T_4 = 0.025,\ T_5 = T_6 = 0.001.$$

After the SMES load flow and dynamic models with the external and internal models using optimal priority scheme are applied to the SMES, the generator power angle shows a stable response with the same fault applied to the system as shown in Figure 11.

Power Angle (tc = 0.25s)

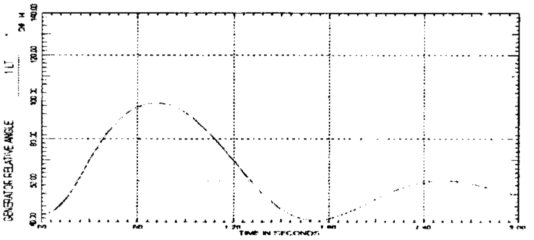


Figure 11. Power Angle for Example System 1 with SMES

The following diagrams as shown in Figure 12, and Figure 13 show how the SMES active power is responded to the frequency deviation, and the SMES reactive power is responded to the voltage deviation.

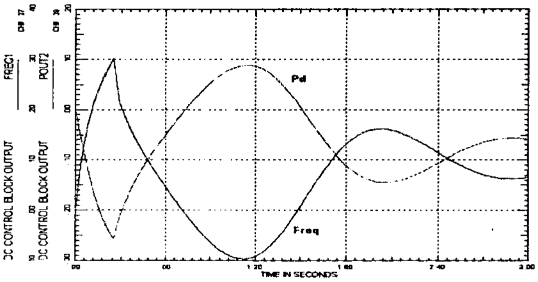


Figure 11. The Active Power Responded to Frequency Deviation

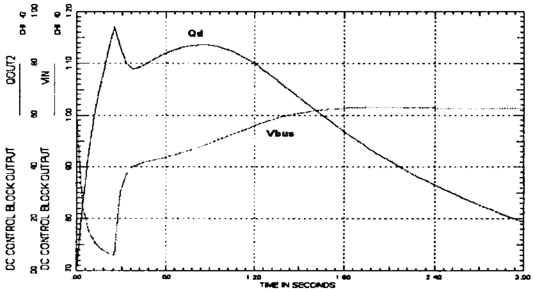


Figure 12. The Reactive Power Responded to Voltage Deviation

3. 결론

SMES application through the internal and external control modules into power system is contributed to improve the transient stability in addition to the contribution of voltage stability, which the SMES was widely applied in the world. Through the optimal priority scheme into the internal control model, and the external model with the second order time delay nonlinear model with independent frequency and voltage deviations, this paper shows that the SMES can be an effective means of stabilizing power transient oscillations to increase power transfer capabilities of transmission system.

감사의 글

본 연구는 2005년도 산업자원부 전력산업연구개발사업 전력선행기술연구에 의하여 이루어진 연구로서, 관계부처에 감사드립니다.

[참 고 문 헌]

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