Active and Reactive Power Control Model of Superconducting Magnetic Energy Storage (SMES) for the Improvement of Power System Stability

Wan Kyun Ham*, Sung Wook Hwang[†] and Jung Hoon Kim**

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. Furthermore, an optimal priority scheme is proposed for the combination of active and reactive power control to be able to stabilize power transient swings.

Keywords: priority scheme, stability, Superconducting Magnetic Energy Storage (SMES)

1. Introduction

Power system stability problems have attracted the attention of power system engineers for several decades. Considerable progress has been made on excitation control, governor control, control by static var compensator, etc. Modern power systems, which are growing in size and complexity, are characterized by long distance bulk power transmissions and wide area interconnections. In such power systems, undamped power swings of low frequency can occur. This can be a serious problem since the instability often decreases the power transmission capacity. As a result, the power that can be transmitted in steady state and transient situations is limited. If the limit is exceeded, the generator loses synchronous operation and system instabilities occur. SMES may be an effective means of preventing these instabilities, thereby maximizing power transfer to meet increased load demand. Recently, several SMES applications were installed in the USA transmission system to control dynamic voltages during a contingency. Many transmission system engineers keep exploring the possibility of expanding the applications to the area of the transient stability.

In general, the reactive power compensation could be achieved by the adjacent reactive power resources such as generator var support, synchronous condenser, STATCOM, SVC, etc. for dynamic controls. For the active power compensation, generators or load reductions could be used under the frequency control. Therefore, the simultaneous P-f and Q-V controls are essential to stabilize power

systems. SMES can provide both active power and reactive power spontaneously to control power system stability.

A SMES system can be represented in dynamic simulations as a continuous controllable real and reactive power source. In steady-state simulations, SMES can be represented as a continuous controllable reactive power source since it can continuously operate throughout its range of reactive power. Through the continuous reactive power control during a contingency, the SMES can be an effective FACT device to manage system dynamic voltages. However, the output of real power from a SMES device is limited to the amount of energy stored in the coil. The effective active power control of the magnitude and duration based on the amount of energy stored provides a meaningful capability to stabilize the power system swings.

To determine the control domains of the active and reactive power from converter firing angles, formulas for the relationship between firing angles and active and reactive power must be used. Many researches describe the equations for control domains using the firing angles and provide the schematic diagrams to show the control domains [1, 2, 4, 8, 10, 11, 12, 14, 15, 18]. Also, the transformer tap [1, 3] and the duty cycle in the pulse-width-modulation (PWM) mode [2, 6, 7, 10, 11, 17, 18] can change the size of the control domains of active and reactive power. In Korea, methodologies for determination of the optimal size have been studied. In this study, application technology of the superconducting machine and device to the power system has also been developed [23].

Many researches use the active power priority scheme to calculate firing angles because transient stability is affected more by active power than by reactive power, and because transient stability is more often a problem than other stabilities. In this scheme, maximum active power is limited by setting an upper limit [3, 13]. In active power

priority, reactive power is dependent on the SMES size; that is, the reactive power comes from the difference between complex power and active power when active power is within the control domain. Reactive power priority is used to support and maintain voltage stability during fault and is also applied to supporting voltage in the steady state. A priority scheme strategy is chosen based on system state. In steady state, for example, the reactive power priority scheme can be used because the system needs to support voltage. In transient state, the active power priority scheme is more appropriate because power angle stability is of greater significance than voltage support.

The combination of the active and reactive power control can be achieved by the following objectives: The first objective is to determine the optimal internal control scheme needed to decide the controllable active and reactive power based on the active and reactive power demanded by the power system. The second objective is to design and simulate SMES external control models that are dependent on the network configuration. The third objective is to resolve how the optimal size of a SMES device varies for a given transient stability disturbance when alternative internal control models and external control models are used.

2. A SMES System

As shown in Fig. 1, a SMES device has a magnetic inductor, power converters (I-C units), and transformers. Voltage and current depend on the capacity of the magnetic inductor. Converters use the firing angles set by internal control to produce feasible active and reactive power outputs determined by priority schemes. The transformers reduce the harmonic components by using the Δ-Y and Δ-Δ parallel connections.

By external control, the SMES system uses the input variables of voltage, frequency, and current to establish 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 decide outputs. A SMES device receives the signals from the firing angles determined by internal control and then produces the active and reactive power outputs.
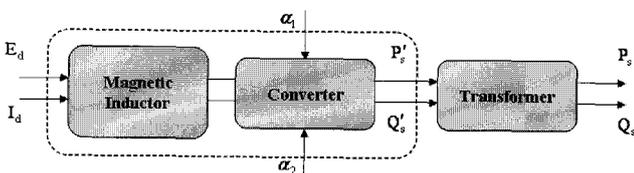

Fig. 1. A SMES Device

where E_d and I_d are the SMES voltage and current, α_1 and α_2 are the firing angles, $P_s{'}$ and $Q_s{'}$ are the active and reactive power which contain the harmonics, and P_s and Q_s are the SMES active and reactive power.
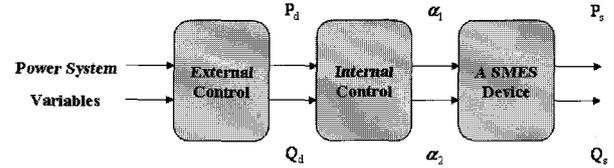

Fig. 2. Components of A SMES System

where power system variables are the deviation of voltage, frequency, and current, P_d and Q_d are the demanded active and reactive power, α_1 and α_2 are the firing angles of power converters, and P_s and Q_s are the SMES active and reactive power outputs.

3. SMES Control Models

3.1 Optimal Priority Schemes for the Control Domains

Two priority schemes are previously applied for controlling the SMES outputs within the controllable powers: active power priority scheme and reactive power priority scheme [19]. Optimal priority scheme is developed to improve the internal control scheme. As shown in Fig. 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.

$$Min\ (\Delta P^2 + \Delta Q^2)$$

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

where

$$\Delta P = P_{sm} - P_{dem},$$
$$\Delta Q = Q_{sm} - Q_{dem},$$

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

As a result,

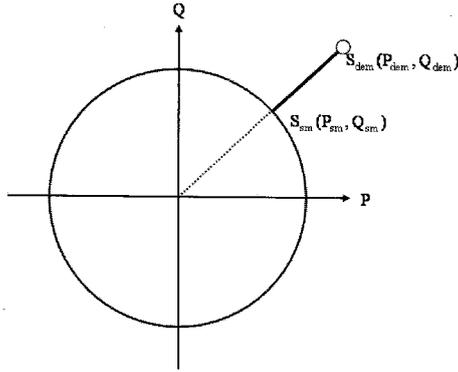$$P_{sm} = \frac{S_{sm}}{S_{dem}} P_{dem}, \qquad Q_{sm} = \frac{S_{sm}}{S_{dem}} Q_{dem}$$

Fig. 3. Optimal Scheme for Feasible Powers

The demanded reactive power for the external model as indicated in Fig. 5 uses the voltage deviation. The related block diagram is as follows.

Fig. 5. SMES External Model for the Demanded Reactive Power

3.2 SMES External Control for Power System Stability

The SMES external control models are mainly classified into two categories—decoupled and coupled models. Decoupled models show the demanded powers resulting from separate input signals; Coupled models show the demanded powers resulting from bound input signals. In decoupled control models, two classifications exist: linear and nonlinear [16]. In this study, to improve the transient stability, the second order time delay nonlinear model for active and reactive power with independent frequency and voltage deviations is applied into the SMES external model. The active and reactive powers are represented by the following equations.

$$\Delta P_{sm} = \frac{K_1 s}{1+T_1 s} \frac{K_2}{1+T_2 s} \Delta \alpha ,$$

$$\Delta Q_{sm} = \frac{1+K_3 s}{1+T_3 s} \frac{K_4}{1+T_4 s} (V_{ref} - V_{in})$$

where K_1, K_2, K_3, K_4 are the gains and T_1, T_2, T_3, T_4 are time response parameters, $\Delta \alpha$ is the angle deviation, V_{ref} is the reference voltage, and V_{in} is the controlled bus voltage.

The demanded active power for the external model as shown in Fig. 4 uses the power angle deviation. The related block diagram is as follows.
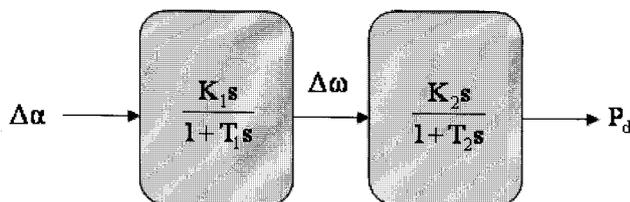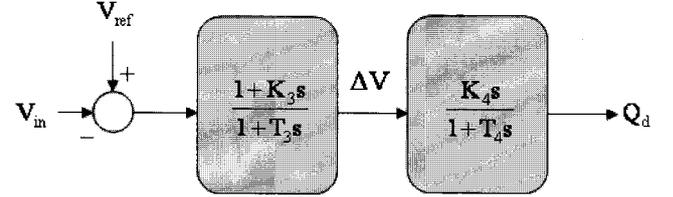

Fig. 4. SMES External Model for the Demanded Active Power

3.3 SMES Internal Control Modeling for Power System

To understand the concept of the internal control schemes, it is necessary to examine the idea that converter type effects control domains. The controllable domains of the SMES active and reactive power outputs are affected by the power converter units, either line commutated or Gate Turn Off (GTO) converter. Both line commutated and GTO converters can control active power. However, with the line commutated converter of the conventional Graetz bridge type, which has been used in prior research, the reactive power control domain has been constrained to the lagging phase [4, 5, 9, 12]. Even along with a capacitor inserted in parallel [9] into a SMES device to compensate the reactive power, the lagging reactive power of the line commutated converter could still not effectively support the voltage during voltage problems. Therefore, the GTO converter was introduced to control the wide range domain of SMES reactive power [1, 7, 10, 15, 18]. By using the GTO converter, both lagging and leading reactive power are achievable. Most research focuses on a GTO converter to control the lagging and leading phases of active and reactive power.

As presented in Fig. 6, the SMES internal control consists of the optimal priority scheme and α, γ calculation.

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

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

where

V_d =   DC voltage,

V =   terminal voltage magnitude,

V_c =   converter voltage,

X_c = converter reactance,

γ = modulation magnitude ratio,

$-1 \leq \gamma \leq 1$,

V_{base} = rated voltage

S_{base} = SMES size, MVA, and
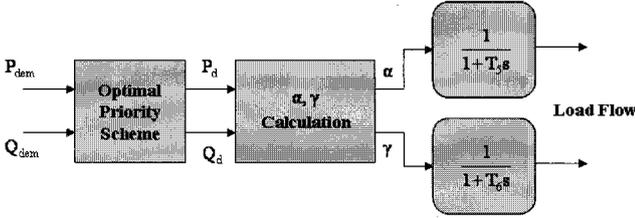
α = power angle, $-90° \leq \alpha \leq 90°$

Fig. 6. SMES Internal Control for α, γ

where T_5, T_6 are time delays

3.4 SMES Application with Load Flow Model

The load flow model interfaces the SMES output with the power system through the converters. The outputs from the load flow model are as follows.

$$P = \frac{V_d V_c \gamma \sin\alpha}{X_c S_{base}},$$

$$Q = \frac{V_d V_c \gamma \cos\alpha}{X_c S_{base}} - \frac{V_{base}^2 V^2}{X_c S_{base}},$$

where

$$V_c = \frac{K_c V_{base} V}{n_t a_t},$$

$X_c = X_t N_b$, converter reactance,

N_b = number of bridges,

S_{base} = rated MVA.

3.5 SMES Application with Dynamic Models

As presented in Fig. 7, the dynamic model consists of the SMES external and internal models.

Since the SMES external control model uses the second order time delay model for the active and reactive power with independent frequency and voltage deviations, four parameters are needed to obtain the demanded active power, and another four parameters are needed for the demanded reactive power, which consist of gains and time
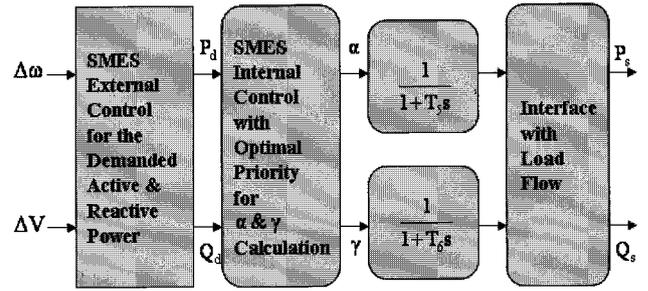

Fig. 7. SMES Application with Dynamic Models

responses as shown in Fig. 4 and Fig. 5. And the SMES internal control model uses the first order time delay for the active and reactive power to interface the outputs to the load flow model, which are the active and reactive power needed to improve the system stability.

4. Transient Stability Analysis with SMES Models

4.1 Example System without SMES Application

A 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 per unit (p.u.) are 555 MVA, 24 kV.

The initial condition is P = 0.9 p.u., Q = 0.2021 p.u., E_t = 1.025.32, E_B = 1.00. The G_1 generator is modeled as a single equivalent generator represented by the classical model. X_d' = 0.3 p.u., H = 3.5 MW· s/MVA, [3].
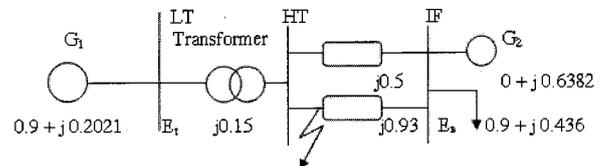

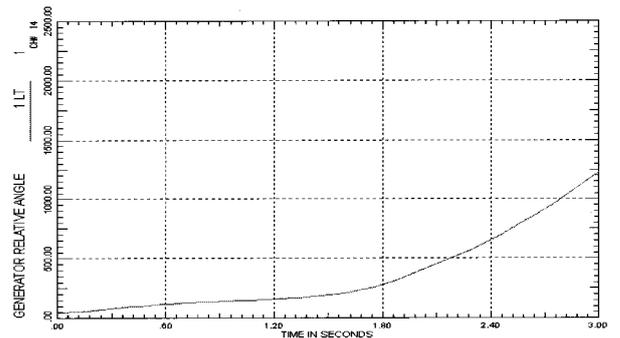**Fig. 8.** The Infinite Bus System for Studying Transient Stability

Fig. 9. Power Angle for Example System with t_c = 0.25s

Fig. 9 shows the stability simulation result for the example system with a 15 cycle normal clearing time for the three-phase to ground fault. A three-phase to ground fault was applied to an 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 that the power angle is unstable with the 15 cycle three-phase to ground fault.

4.2 Example System with SMES Application

Fig. 10 indicates the same example system with the SMES connected. 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.

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 seen in Fig. 11.

The following diagrams in Fig. 12 and Fig. 13 depict how the SMES active power responded to the frequency deviation, and how the SMES reactive power responded to the voltage deviation respectively.
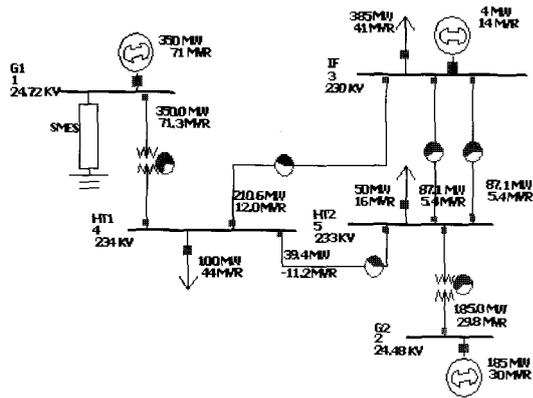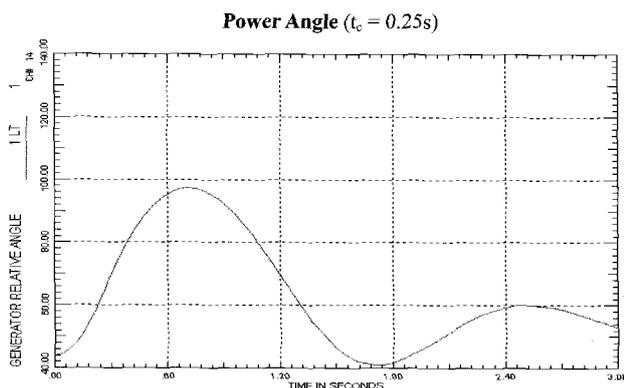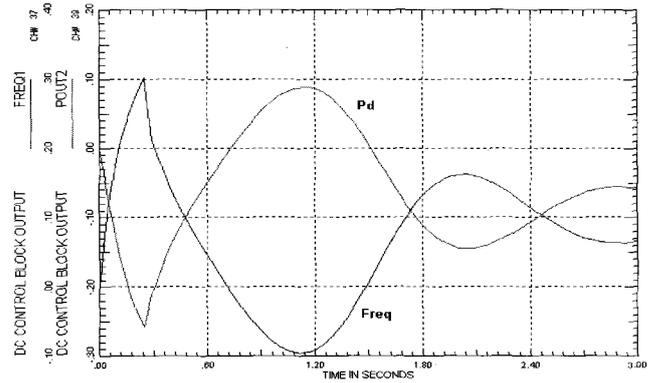

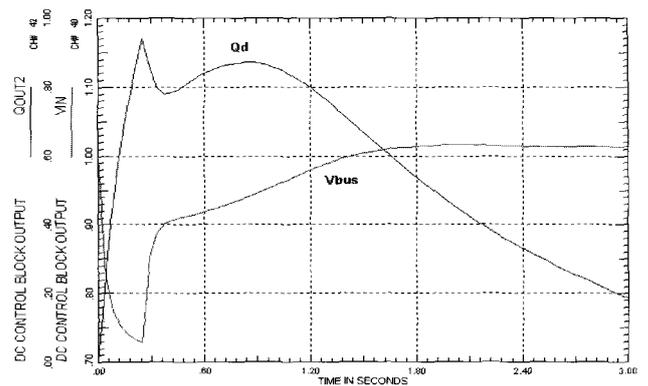**Fig. 12.** The Active Power Responded to Frequency Deviation

Fig. 13. The Reactive Power Responded to Voltage Deviation

5. Conclusion

SMES application through the internal and external control modules into a power system is contributed to improve the transient stability and the voltage stability, for which the SMES has been widely applied throughout the world. Through the optimal priority scheme into the internal control model, and the external control 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 a transmission system.

Acknowledgements

Fig. 10. Example System 1 with SMES Application

**Fig. 11.** Power Angle for Example System 1 with SMES

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Wan Kyun Ham
He received his B.S and M.S degrees in Electrical Engineering from Seoul National University and his Ph.D. in Electrical Engineering from the University of Texas at Austin. His research interests are utility regulatory affairs, power system modeling including superconducting magnetic energy storage (SMES), transmission planning and operation analysis, and power economics including transmission pricing and locational marginal pricing.
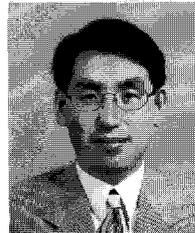
Jung Hoon Kim
He received his B.S, M.S and Ph.D. degrees in Electrical Engineering from Seoul National University in 1978, 1981, and 1985, respectively. He is currently a Professor in the School of Electrical Engineering at Hongik University, Seoul, Korea. He is also working for the President of PITA (Power IT Academy) in KESRI (Korea Electrical Engineering & Science Research Institute). His research interests are power system stability, power economics, load modeling, energy efficiency, demand response, new & renewable energy, and electrical railways.

Sung Wook Hwang
He received his B.S and M.S degrees in Electrical Engineering from Hongik University, Seoul, Korea, in 1997 and 1999. He was a Volunteer Professor at SENATI (Servicio Nacional de Adiestramiento en Trabajo Industrial), Zonal La Libertad, Peru from 2003 to 2005. He is currently working towards his Ph.D. at Hongik University. His research interests are energy efficiency, demand response, and new & renewable energy.