ON-LINE MEASUREMENT OF THE EIGENVALUES OF MULTI-MACHINE POWER SYSTEM BY USE OF SMES

Takenori Yonezu, Tanzo Nitta
The University of Tokyo
Tokyo, Japan
yonezu@asc.t.u-tokyo.ac.jp

Yasuyuki Shirai, Akihito Nakamaru
Kyoto University
Kyoto, Japan
shirai@pe.energy.kyoto-u.ac.jp

Katsuhiko Shibata
Kansai Electric Power Co., Inc.
Osaka, Japan
shibata.katsuhiko@d2.kepco.co.jp

Abstract - Small signal stability of power systems is evaluated by eigenvalues of state equations derived from system models. The values are given by off-line computer analyses. However, parameters of system models may not be obtained accurately. Direct obtaining of the eigenvalues of operating system makes power system more stable and more economical. On-line measurement of the eigenvalues of power system by use of Superconducting Magnetic Energy Storage(SMES) has been proposed. The imaginary part of the eigenvalues can be measured in any power system. However, the real parts of them can be measured only in one-machine infinite power system. The new method to measure the real part of the eigenvalues in multi-machine power system is proposed here. Simulations for measuring eigenvalues of the sample 5-machine longitudinal power system were carried out to verify the proposed method by use of analogue simulator. The factors corresponding to the real part of the eigenvalues are obtained as the results of simulation.

Keywords* - *Power System, Small Signal Stability, Superconducting Magnetic Energy Storage(SMES), On-line Measurement, Multi-Machine, Eigenvalue

1 INTRODUCTION

SMALL signal stability of power systems is evaluated by eigenvalues of state equations derived from system models. The eigenvalues are currently given by off-line computer analyses.

For the computation, a lot of parameters, such as impedance of transmission lines, transformers, generators, and so on, are necessary. However, the values of parameters may not be obtained accurately. They may change with operation conditions. Then the power system may be operated with a certain margin from the calculation results. If the eigenvalues can be measured directly from operating power systems, it will contribute to make power systems more stable and more economical than now. Therefore, on-line measurement of the eigenvalues by use of Superconducting Magnetic Energy Storage (SMES) has been proposed [1]-[11]. The eigenvalues of power systems can be measured by analyzing the output power of generators and transmission lines for small power changes generated by SMES. SMES can control its active and reactive powers quickly and simultaneously. It is a high impedance power source with little loss. Therefore, it can give small power changes without affecting operating conditions of the power systems.

For the waveforms of power changes from SMES, sinusoidal signals and chirp signals have been studied. In case of sinusoidal signals[1]-[7], the imaginary parts of the eigenvalues can be measured in any power systems. However, the real parts of them can be measured only in one-machine infinite bus system.

In case of chirp signals[8]-[10], both the real parts and the imaginary ones can be measured in any power system as computer simulation results show. However, measuring the eigenvalues by chirp signal doesn't work properly when measured active power responses contain noise. Parameter identification is used in chirp signal method. So it may be difficult to use chirp signal method in actual power systems.

A new method by use of power change of sinusoidal waveform for measurement of the real parts of the eigenvalues of multi-machine power system are described in the paper. Simulations of the sample 5-machine longitudinal power system are described. The simulations in order to examine the method were carried out by use of an analogue type power system simulator (APSA: Advanced Power System Analyzer in Kansai Electric Power Co., Inc., Japan).

2 CONCEPT OF MEASURING THE REAL PART OF THE EIGENVALUES BY USE OF SMES

2.1 *One-Machine Infinite Bus System*

LET us consider the method to measure the real part of the eigenvalues of one-machine infinite bus system shown in Figure 2.

The active power P_{sm} of SMES is set to be sinusoidal. The reactive power Q_{sm} is controlled to be zero.

$$P_{sm} = P_0 \sin(\omega_{sm} t) \tag{1}$$

P_0 : amplitude of active power
ω_{sm} : angular frequency of active power

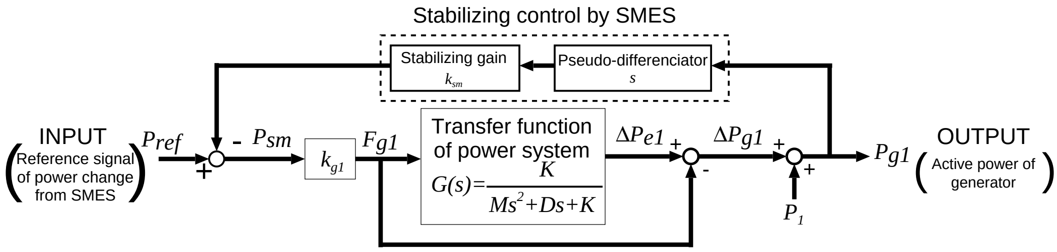
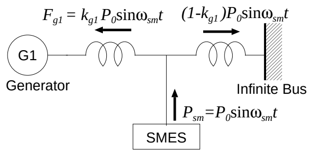
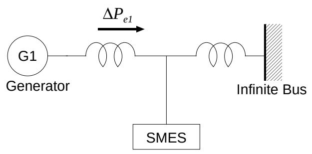


Figure 1: Concept of measuring the real part of the eigenvalues of one-machine infinite bus system



(a) Input to System



(b) Output from System

Figure 2: Power flow of one-machine infinite bus system with SMES

Some of the power change of SMES is delivered to generator and the other is to infinite bus (see Figure 2(a)).

Power change delivered to generator is denoted by F_{g1}. The ratio of F_{g1} to P_{sm} is denoted by k_{g1}. The value k_{g1} is given as eq. (2).

$$k_{g1} \equiv \frac{F_{g1}}{P_{sm}} \tag{2}$$

The value k_{g1} can be calculated by measuring the derivative power change of generator G1 generated by power change from SMES of angular frequency far from natural angular frequency.

The output power change ΔP_{e1} of system is excited by F_{g1} as shown in Figure 2(b).

Transfer function $G(s)$ between F_{g1} and ΔP_{e1} is given as eq. (3)[1].

$$\begin{aligned} G(s) &= \frac{\mathcal{L}[\Delta P_{e1}]}{\mathcal{L}[F_{g1}]} \\ &= \frac{K}{Ms^2 + Ds + K} \end{aligned} \tag{3}$$

M	:	$\frac{M_0}{\omega_n}$
		(M_0 : inertia constant of generator)
		(ω_n : rated angular velocity)
D	:	damping coefficient of generator
K	:	synchronizing torque of generator
$\mathcal{L}[\Delta P_{e1}]$	:	Laplace transformation of ΔP_{e1}

Eigenvalues λ of $G(s)$ are complex numbers as eq. (4).

$$\lambda \equiv \gamma_1 \pm j\omega_1 \tag{4}$$

The value ΔP_{e1} is given as eq. (5).

$$\begin{aligned} \Delta P_{e1} &= A_{sm} \sin(\omega_{sm} t + \phi_{sm}) \\ &\quad + A_1 e^{\gamma_1 t} \sin(\omega_1 t + \phi_1) \end{aligned} \tag{5}$$

A_{sm}, A_1	:	amplitude for each component
ϕ_{sm}, ϕ_1	:	phase differences
		between each component and P_{sm}

The delivered power change ΔP_{g1} of generator is defined as eq. (6).

$$\Delta P_{g1} = P_{g1} - P_1 \tag{6}$$

P_1	:	active power of generator
		at steady state without SMES

The value ΔP_{g1} is given as eq. (7).

$$\Delta P_{g1} = \Delta P_{e1} - F_{g1} \tag{7}$$

In the steady state, the second term of eq. (5) disappears. The amplitude of ΔP_{e1} is given as eq. (8).

$$\begin{aligned} |\Delta P_{e1}| &= A_{sm} \\ &= |G(j\omega_{sm})| \cdot |F_{g1}| \\ &\approx P_0 k_{g1} \omega_1^2 \frac{1}{\sqrt{(\omega_{sm}^2 - \omega_1^2)^2 + 2\gamma_1^2(\omega_{sm}^2 + \omega_1^2)}} \end{aligned} \tag{8}$$

In order to measure $|\gamma_1|$ accurately, the angular frequency ω_{sm} of SMES is set to ω_1.

F_{g1} in eq. (7) can be neglected because $\Delta P_{e1} \gg F_{g1}$ when ω_{sm} is set to the natural angular frequency.

The amplitude of ΔP_{g1} is given as eq. (9).

$$|\Delta P_{g1}| = \frac{P_0 k_{g1} \omega_1}{2|\gamma_1|} \tag{9}$$

However, fluctuating in natural angular frequency may causes power system instability[2]. So the stabilizing control of power system by use of SMES is added as shown in Figure 2. Then, the active power P_{sm} of SMES is given as eq. (10).

$$P_{sm} = P_{ref} - k_{sm} \frac{dP_{g1}}{dt} \tag{10}$$

P_{ref}	:	reference signal of SMES $P_{ref} = P_0 \sin(\omega_1 t)$
k_{sm}	:	the gain of stabilizing control

With stabilizing control of SMES, $|\Delta P_{g1}|$ is given as eq. (11).

$$\frac{1}{|\Delta P_{g1}|} = \frac{\omega_1}{P_0} k_{sm} + \frac{2|\gamma_1|}{P_0 k_{g1} \omega_1} \tag{11}$$

In one-machine infinite bus system, the relation between stabilizing gain k_{sm} and $1/|\Delta P_{g1}|$ is linear. The relation is obtained by measuring $1/|\Delta P_{g1}|$ in several k_{sm}. $1/|\Delta P_{g1}|$ without stabilizing control can be obtained by extrapolation of $1/|\Delta P_{g1}|$ with stabilizing control.

2.2 *Multi-Machine System*

In one-machine infinite bus system, the real part of the eigenvalues can be measured by derivative power change in the system. It can be calculated from the inverse of the amplitude of the deviation of active power, $1/|\Delta P|$. In multi-machine power system, $1/|\Delta P|$ without stabilizing control may also become the factor corresponding to the real parts of the eigenvalues.

Figure 3 shows the concept of measuring the real part of the eigenvalues of multi-machine system.

The angular frequency ω_{sm} of SMES is set to one of the natural angular frequencies, ω_k. The stabilizing control in multi-machine system is given as eq. (12).

$$P_{sm} = P_{ref} - k_{sm} \frac{dP_{ti}}{dt} \tag{12}$$

P_{ti}	:	stabilizing signal (active power of Ti)
P_{ref}	:	reference signal of SMES $P_{ref} = P_0 \sin(\omega_k t)$
k_{sm}	:	the gain of stabilizing control

Stabilizing signal P_{ti} is set to one of the active power of generators or transmission lines in power system.

The power change ΔP_{ti} is defined as eq. (13).

$$\Delta P_{ti} = P_{ti} - P_i \tag{13}$$

P_i	:	active power of Ti at steady state without SMES

The value ΔP_{ti} is given as eq. (14).

$$\Delta P_{ti} = \Delta P_{ei} \pm F_{ti} \tag{14}$$

F_{ti}	:	derivative power change generated by SMES to generator or transmission line $F_{ti} = k_{ti} P_{sm}$
ΔP_{ei}	:	deviation of output power from transfer function $\boldsymbol{G}(s)$ of power system

In one-machine infinite bus system, F_{g1} can be neglected in measuring the real part of eigenvalue. However, F_{ti} cannot always be neglected in multi-machine system.

The relation between stabilizing gain k_{sm} and $1/|\Delta P_{ti}|$ is obtained by measuring $1/|\Delta P_{ti}|$ in several k_{sm}. $1/|\Delta P_{ti}|$ without stabilizing control may be obtained by extrapolation of $1/|\Delta P_{ti}|$ with stabilizing control. $1/|\Delta P_{ti}|$ without stabilizing control may become the factor corresponding to the real parts of the eigenvalues.

3 SIMULATED SYSTEM

3.1 *Power system simulator*

FOR the simulation, the Advanced Power System Analyzer (APSA system) was used. It is a large scale analogue type power system simulator. The ratings of the APSA system are 50V for the voltage, 0.5A for the current and 43.3VA for the power. The APSA system consists of many analogue or digital generator models, many analogue transmission line models and so on. A certain power system model is made by combination of these models. Real-time simulations can be performed. The power system model is more similar to a real power system than a system model using digital computer simulations.

A SMES model was designed and made for the APSA system [3],[6]. A SMES is replaced by three AC current amplifiers with delta-connection.

3.2 *Simulated power system*

Simulations for measuring the real part of the eigenvalues were carried out on the sample 5-machine longitudinal power system shown in Figure 4. The constants of the simulated system are listed in Table 1. The constants of the generator in the system are listed in Table 2.

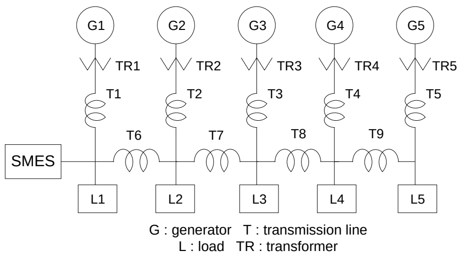


Figure 4: Simulated power system

Quantity	Value
Output of Generator : G1-G5	1.000 p.u.
Reactance of Transformer : TR1-TR5	0.140 p.u.
Reactance of Transmission Line : T1-T9	0.214 p.u.
Impedance of Load : L1-L5	0.882 p.u.

Table 1: Constants of simulated system

Symbol	Quantity	Value
x_d	d-axis synchronous reactance	1.700 p.u.
x'_d	d-axis transient reactance	0.380 p.u.
x''_d	d-axis subtransient reactance	0.280 p.u.
x_q	q-axis synchronous reactance	1.700 p.u.
x''_q	q-axis subtransient reactance	0.280 p.u.
x_l	leakage reactance	0.252 p.u.
T'_d	d-axis transient open circuit time constant	1.500 sec
T''_d	d-axis subtransient open circuit time constant	0.030 sec
T''_q	q-axis subtransient open circuit time constant	0.030 sec
T_a	armature time constant	0.400 sec
M	generator initial constant	8.000 sec

Table 2: Constants of generators

Generator model G1 has a governor, AVR (Auto Voltage Regulator) and PSS (Power System Stabilizer). Generator model G2, G3, G4 and G5 have governors and AVRs.

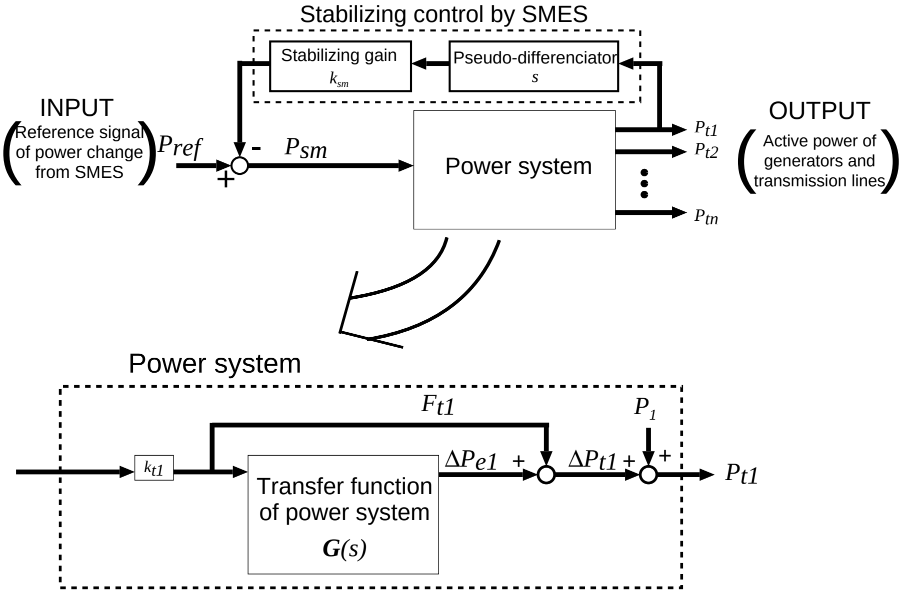


Figure 3: Concept of measuring the real part of the eigenvalues of multi-machine system

4 RESULTS OF SIMULATION

4.1 Natural frequencies

NATURAL frequencies of the system are obtained by use of the method described in [3],[4]. They are 0.15Hz, 0.81Hz, 0.98Hz and 1.10Hz. The eigenvalues whose real parts are rather large in comparison with the others are obtained by the method. Obtained natural frequencies are the ones related to the static stability of the power system.

Validity of obtained natural frequencies is examined in comparison with the off-line computer calculations. Table 3 shows the natural frequencies and the real parts of the eigenvalues of the system obtained by off-line computer calculations. S-matrix method[12] is used for calculations.

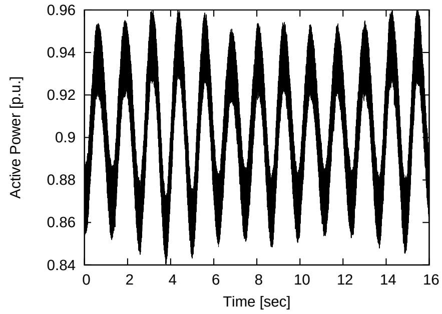
Natural frequency [Hz]	Real part of eigenvalue [1/sec]
0.11057	-0.20797
0.11304	-0.20967
0.11991	-0.21246
0.13494	-0.37591
0.14860	-0.22331
0.84806	-0.11946
1.07559	-0.29315
1.12937	-0.36873
1.14651	-0.40461

Table 3: Eigenvalues of power system by computer calculations

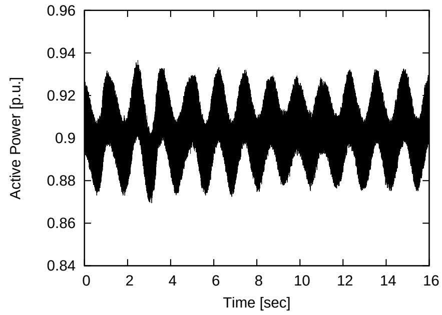
Validity of obtained natural frequencies is confirmed.

4.2 Factors corresponding to the real parts of the eigenvalues

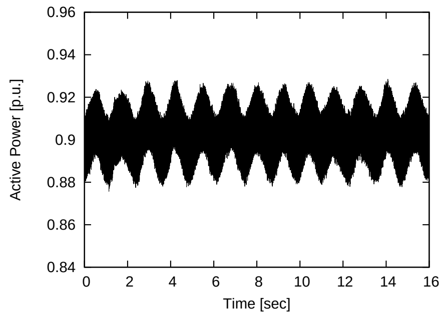
Examples of waveforms are shown in Figure 5. Figure 5 shows the waveforms of P_{t1} (active power of transmission line T1) in steady state. Amplitude of P_{ref} is set to 0.02p.u., frequency of P_{ref} is set to 0.81Hz. Stabilizing signal of SMES is set to P_{t1} (active power of transmission line T1).



(a) Stabilizing gain k_{sm}=0



(b) Stabilizing gain k_{sm}=10

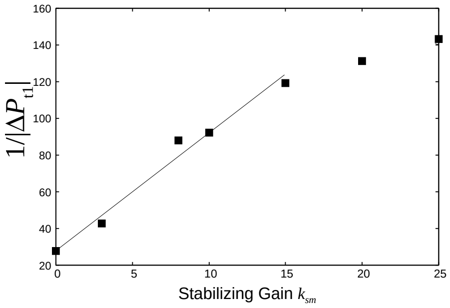


(c) Stabilizing gain k_{sm}=25

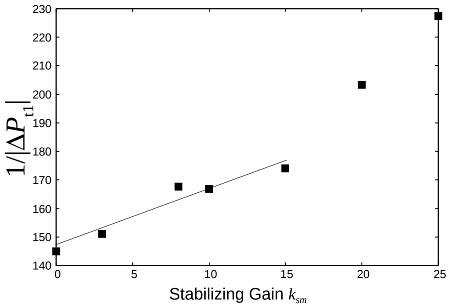
Figure 5: Results of simulation : waveforms of P_{t1} (active power of transmission line T1)

The relations between stabilizing gain k_{sm} and $1/|\Delta P_{t1}|$ are shown in Figure 6. Amplitude of P_{ref} of

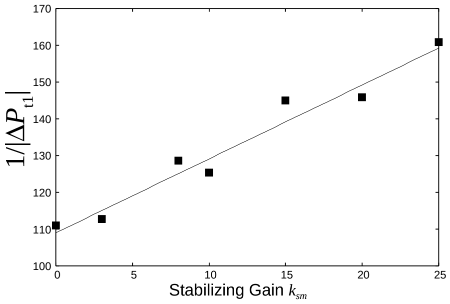
SMES is set to 0.02 p.u. . Frequency of P_{ref} is set to three cases of natural frequencies, 0.81Hz, 0.98Hz, 1.10Hz. $|\Delta P_{t1}|$ is obtained by Fourier transformation of ΔP_{t1}. $|\Delta P_{t1}|$ is defined as the amplitude of frequency component which is the same frequency of P_{ref}.



(a) 0.81Hz



(b) 0.98Hz



(c) 1.10Hz

Figure 6: Results of simulation : Relations between stabilizing gain k_{sm} and $1/|\Delta P_{t1}|$

$1/|\Delta P|$ without stabilizing control (i.e. $k_{sm} = 0$) can be measured in this simulation. It is because the simulated system was very stable system. $1/|\Delta P|$ without stabilizing control cannot always be measured.

In all cases, relations between k_{sm} and $1/|\Delta P_{t1}|$ are linear when k_{sm} is small. In case of 0.81Hz and 0.98Hz, relations between k_{sm} and $1/|\Delta P_{t1}|$ is nonlinear when k_{sm} is large. It may be because the effect of F_{t1} in stabilizing signal cannot be neglected. In other words, k_{sm} is larger than necessary when the relations are nonlinear.

5 CONCLUSIONS

A new method by use of power change of sinusoidal waveform for measurement of the real parts of the eigenvalues of multi-machine power system are described. Simulations of the sample 5-machine longitudinal power system are described. With the results of simulation, $1/|\Delta P|$ of main modes of natural frequencies can be obtained by extrapolation. The possibility of measuring the real part of the eigenvalues in multi-machine system by proposed method are confirmed by simulation.

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