Paper

Evaluation of Power System Stability by use of Superconducting Magnetic Energy Storage (SMES)

Member Orges Gjini (The University of Tokyo)
Member Tanzo Nitta (The University of Tokyo)

In this paper, a new method for the on-line identification of power system electro-mechanical modes (eigenvalues) by use of Superconducting Magnetic Energy Storage (SMES) is proposed. Modulated sinusoidal active power of small amplitude in the low frequency bandwidth (chirp signal) is given by SMES to the power system. From the system's response (active power oscillations at generator buses) low order models are estimated by output error modeling based on Gauss-Newton algorithm. Finally from the models estimated, eigenfrequencies and their damping are determined.
The method is useful in monitoring system steady state stability and in tuning power system control. The studies and results are based on the simulations of power system with SMES in PSCAD/EMTDC program.

keywords: SMES, power system, electro-mechanical modes, chirp signal, eigenvalue, transfer function.

1. Introduction

In power system analysis, results from eigenvalue method or power system simulations depend on the fact how accurately we know system parameters, its configuration and operating conditions. In a real power system, all these factors may be changed on the operating conditions. Interconnections with other systems and the effects of deregulation make all these issues more complex. For the above-mentioned reasons, without monitoring the level of stability in the system we may not improve it on time. The on-line identification of the system is needed to overcome these difficulties.

On methods of on-line identification, especially, on methods of obtaining eigenvalues of operating system, several papers have been published.(1)(2) Some of the methods use a signal input (for example, step function) to the AVR. By these methods, the system may be identified with some accuracy. However, it is not so easy to understand the disturbance due to the signal explicitly. By process of obtaining transfer functions, high order functions must be considered since disturbance of this kind at power system may be affected by control function of AVR.

It is desirable to find power apparatuses that can give small power disturbance without affecting power system operating condition. The stability of the power system may be estimated by investigating its response for the given disturbance. This corresponds to direct application of eigenvalue method.

Superconducting magnetic energy storage (SMES) is proposed and studied. It is useful not only for high efficient energy storage but also for frequency control, power system stabilization, voltage regulation because of the quick control of power.

In addition to the above mentioned good properties, SMES has a high impedance, that is, it behaves like current source. Due to this property, conditions of an operating power system are not affected by connection of SMES.(4)

Other energy storage systems such as battery energy system, flywheel system, and so on act as voltage sources, which may affect the operating conditions. Therefore SMES is the only power supply suitable.

By considering the new added application of SMES as mentioned above, its cost per application decreases.

On-line identification by use of SMES is already proposed (3)−(5). It can determine the eigenfrequencies in a multi-machine system, but damping can be determined only in case of one machine infinite bus system. The method uses constant frequency sinusoidal active power from SMES as input and the eigenfrequencies determination is based on the spectral analysis by use of Maximum Entropy Method (MEM). In case of one machine connected to the infinite bus, first the system is exited from a sinusoidal input with the same frequency as its eigenfrequency by SMES with stabilizing control then damping is calculated after the calculation of the power flow in the system.

The method of identification proposed here offers both determination of the eigenfrequencies and their damping in case of a multi-machine system. In this case, the power system is excited from a small power chirp (a modulated sinusoidal function with a frequency that grows from an initial value to a final one) given from SMES. From the system's response (for example active power oscillations at generator buses) low order models are estimated by output error modeling based on Gauss-Newton algorithm. Then from the models estimated, system's electro-mechanical modes (damping and eigenfrequency) are determined. In this study, data for different power system configurations simulated with SMES in the PSCAD/EMTDC program are used.

2. SMES system

SMES is used to generate a small power chirp to the power system without changing its operating conditions. A block diagram of SMES system (used in our simulations) is shown in Fig.1,

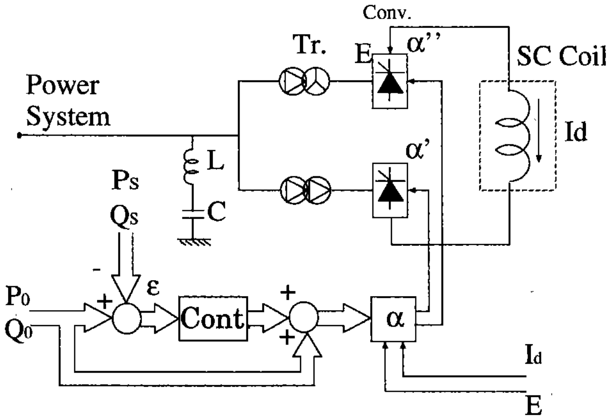

Fig.1 Block diagram of SMES and P-Q mode control system

where:
E - line voltage in the secondary of the transformer.
I_d - average value of the current in the superconducting coil.
α',α'' -firing angles of converter bridges.
SC - superconducting coil.
P_0, Q_0 - reference for active power and reactive power of SMES.
α - converter firing angle calculation block.

In simulation of SMES (Fig.1), a superconducting coil $L = 10.8$ H (the inductance of SMES in the lab.) is chosen. The transformer's secondary voltage is $E = 1$kV and the superconducting coil current $I_d = 5$kA. The stored energy is $W = 135$MJ. These parameters are confirmed to be suitable for our purpose of identification. Two transformers are connected in star-delta and delta-delta to make possible 12-pulse converter operation for simultaneous active and reactive power control and a fast charging of SMES. Reactive power compensation is realized through constant capacitors, connected in the input of the system.

The simultaneous active and reactive power control (Fig.1) is the basic mode of operation. In this mode SMES can give modulated, controlled, small active power to the system (up to 6 Hz). A current control mode of SMES is designed to control SMES at the moment of the connection to the power system and during initial charging. Controlling the current, we can assure that SMES will have a smooth connection to the power system and the converter system is also protected from over-currents in the moment of connection.

For having a continuous operation of SMES the current of the superconducting coil must be constant. Therefore compensation of losses in transformers and bridges is needed. The losses, which depend on the current I_d, are measured and compensated separately in the control system.

3. Electromechanical mode identification method (One machine-IB system example)

The method of power system identification proposed here, deals with the problem of building mathematical models of the power system based on the observed data from the system. The data consist of input and output records. In this study, data available from the simulations of power system in EMTDC program are used and a model has been built based on an output error modeling.

The process, in case of one machine connected to the infinite bus (Fig.2), goes through these basic steps as follows.

The specifications of the generator, transmission line and transformer used in simulation are shown in Table 1, Table 2 and Table 3, respectively. The length of the tie line is 100 km.

Step 1: The design of the experiment and collection of input-output data is realized in the PSCAD/EMTDC program.

The input given by SMES to the power system is an active power chirp (a modulated sinusoidal function with a frequency that grows from an initial value to a final one) shown in Fig.3. As shown from the spectrum in figure the energy of the input waveform from SMES is concentrated on the low frequency region from 0 to 3Hz. A narrow bandwidth is necessary for a good precision in the estimation.

The amplitude of the input oscillations 1 MW (as shown in Fig.3) is found to be effective in our study cases and constitutes less than 1% of the system's power. The output data are the generator's active power oscillations recorded at the generator bus Fig.4.

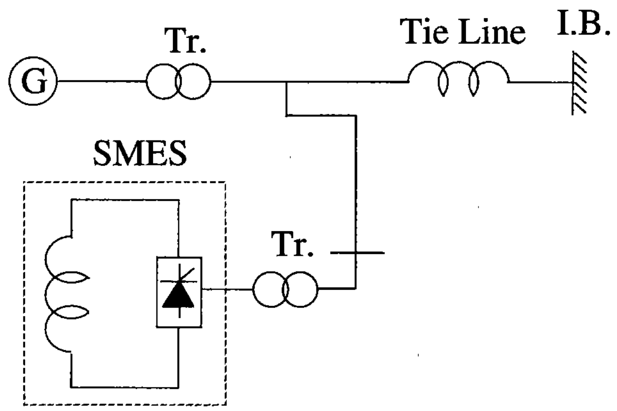

Fig.2 Schematic of simulated one machine infinite bus system and SMES

Table 1 Specification of generator

	120MW	x_q	0.770p.u.	T_a	0.278sec
V_L	13.8kV	x'_d	0.314p.u.	T'_{do}	6.550sec
H	3.117sec	x_d"	0.280p.u.	T_{do}"	0.039sec
x_d	1.014p.u.	x_q"	0.375p.u.	T_{qo}"	0.701sec

Table 2 Specification of transmission line

V_L	230kV	$R_{ad.}$	2.034cm
$D_{bundles}$	45cm	D_{12}	10m
D_{ground}	30m	D_{23}	10m
R	0.03206Ω/km	D_{31}	20m

Table 3 Specification of transformer

	120MVA	ratioV	13.8/230kV	x_l	0.005p.u.

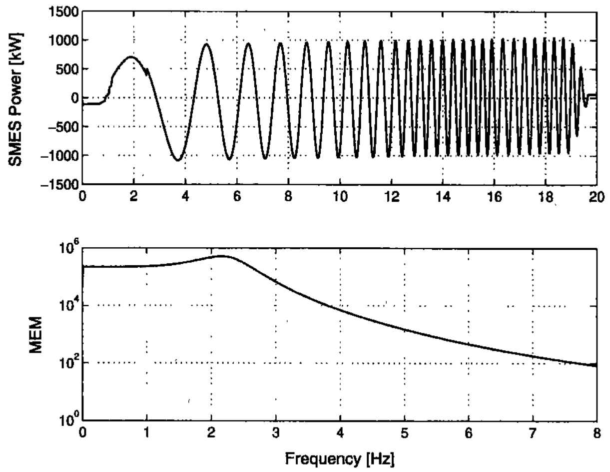

Fig.3 SMES input of chirp signal and frequecy characteristic.

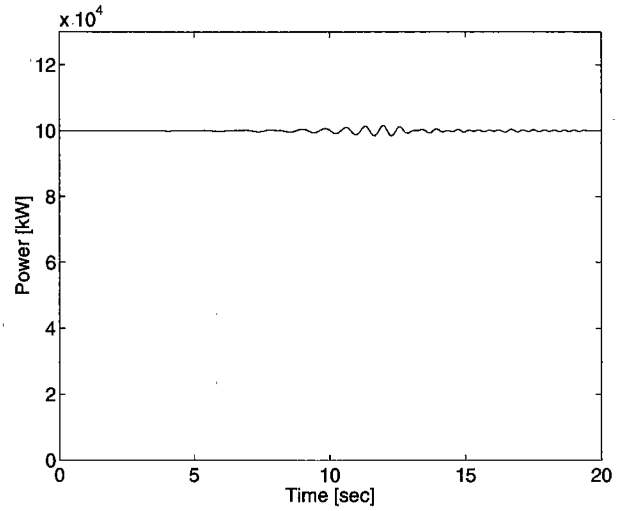

Fig.4 Power of generator for power of chirp signal from SMES

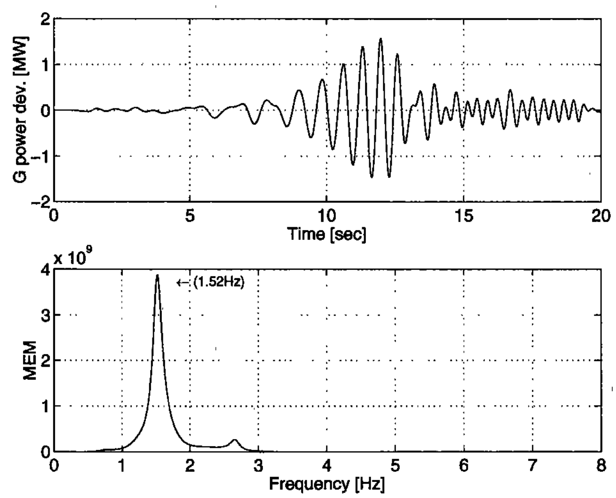

Fig.5 Deviations of power of generator and the spectram by MEM(Maximum Entropy Method)

From figure it can be concluded that the disturbance in the generator active power is small enough compared to its rating power. In Fig.5 from the spectral analysis of the generator active power oscillations is found out the eigenfrequency of the system at 1.52 Hz. Because the input from SMES has a flat spectrum as shown in Fig.3, it does not show up on the system's response spectrum in Fig.5. Determination of SMES input waveform, its time duration and the location of the recorded output are important decisions taken during this step.

Step 2: Examination of data and filtering to enhance important frequency ranges and reduce the noise influence. This is done in connection with the first step. The data recorded from the experiment are decimated and low-pass filtered. The knowledge of the power system mechanical modes location in low frequency region stands in the basis of decisions made during this step.

Step 3: Selection of a model structure and determination of the model order. This is done from a theoretical point of view, combined with the experience from best results achieved during simulations (as discussed in 4).

A general input-output set of discrete models can be written as:

$$A(q)y(t) = \frac{B(q)}{F(q)}u(t-n_k) + \frac{C(q)}{D(q)}e(t), \quad \cdots\cdots (1)$$

A, B, C, D, F are polynomials and n_k is the time delay.

From this model many other special cases can be deduced as the case below which is considered in this study:

$$y(t) = \frac{B(q)}{F(q)}u(t-n_k) + e(t), \quad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where:

$$B(q) = b_1 + b_2 q^{-1} + \cdots + b_{n_b} q^{-n_b+1} (3)$$

$$F(q) = 1 + f_1 q^{-1} + \cdots + f_{n_f} q^{-n_f}, \cdot (4)$$

where:

$e(t)$: white noise

n_k: number of delay

n_f: number of poles

n_b: number of zeros plus one

The problem is to find those parameters for the model, which will give the best fit of the estimated output to the recorded one. Therefore it is introduced the following vector of parameters, which should be determined:

$$\theta = \left[b_1 b_2 \cdots b_{n_b} f_1 f_2 \cdots f_{n_f}\right]^T \quad \cdots\cdots (5)$$

From above, the estimated output can be written as:

$$\hat{y}(t,\theta) = \frac{B(q)}{F(q)} u(t-n_k) \quad \cdots\cdots (6)$$

In case of a second order model chosen, the above equations can be written as

$$y(t) = \frac{b_1 + b_2 q^{-1}}{1 + f_1 q^{-1} + f_2 q^{-2}} q^{-1} \cdot u(t) + e(t)$$
$$= \frac{b_1 q + b_2}{q^2 + f_1 q + f_2} u(t) + e(t), \quad \cdots\cdots (7)$$

where

$$B(q) = b_1 + b_2 \cdot q^{-1} \quad \cdots\cdots (8)$$
$$F(q) = 1 + f_1 \cdot q^{-1} + f_2 \cdot q^{-2}. (9)$$

The error for a candidate model is given as

$$\varepsilon(t,\theta) = y(t) - \hat{y}(t,\theta) \quad \cdots\cdots (10)$$

and a possible criterion:(N: number of data)

$$\Im = \frac{1}{N} \sum_{t=1}^{N} \frac{1}{2} \varepsilon^2(t,\theta) \quad \cdots\cdots (11)$$

Step 4: Computation of the best model according to input-output data and the chosen fit criterion. In this study a quadratic prediction error criterion is minimized using an iterative Gauss-Newton algorithm.(6) (If no lower value of criterion is obtained, a gradient search is used.)

The estimated discrete transfer function for the recorded output is given as

$$G(q) = \frac{B(q)}{F(q)} = \frac{-0.25q^{-1} + 0.2489q^{-2}}{1 - 1.978q^{-1} + 0.986q^{-2}} \quad \cdots (12)$$

The above transfer function has two poles and one zero as

$$\begin{cases} p = 0.988 \pm j0.095 \\ z = 0.995 \end{cases}$$

The corresponding continuous model:

$$G(s) = \frac{-25.18s - 16.88}{s^2 + 1.309s + 92.6} \quad \cdots\cdots (13)$$

has two poles and one zero as following:

$$\begin{cases} p = 0.65 \pm j9.6 \\ z = -0.67 \end{cases}$$

In the above discrete to continuous transformation, a state space representation, is obtained from the discrete transfer function model. Then discrete system matrices are transformed to respective continuous ones through the transformation $z = e^{sT}$. Finally the corresponding continuous transfer function model is obtained from the state space form.

After simulating the response of the model estimated, in Fig.6 there are plotted the measured and estimated outputs. It is shown that there is a good fit of the output from the estimated model to the measured output (system response).

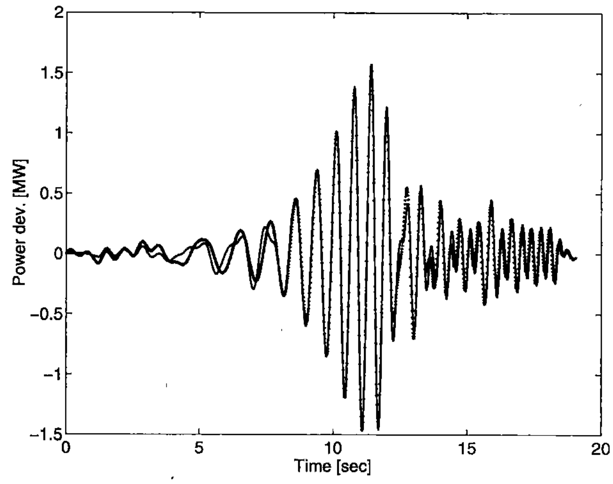

Fig.6 The estimated and measured output of the estimated model (thin line: recorded response, thick line: response of model estimated.)

4. Assessment discussion of the method

In this section, an assessment of the method is conducted by comparing its results with those of eigenfrequency analysis and eigenvalue one, and by identifying known models. First of all it is obvious that there is good agreement between the simulated output and the recorded one. Further more it is easy to verify that the frequency 9.6rad/sec found from the identification corresponds to that one found from the spectral analysis (1.52 Hz as shown in Fig.5(c)).

Let us compare the results from the estimated model obtained above with the those from the eigenvalue analysis. The calculation of eigenvalues includes the dynamics of the exciter. For the operating point, we get Heffron-Phillips constants of $K_1 = 1.9316$, $K_2 = 1.4500$, $K_3 = 0.4031$, $K_4 = 0.3893$, $K_5 = 0.1182$ and $K_6 = 0.386$, and the eigenvalues of $-0.647 \pm j9.628$, -5.894 and -43.198.

It is not difficult to verify that the two dominant eigenvalues (which are located near the imaginary axis on the s-plane and dominate the response) calculated $-0.647 \pm j9.628$ agree well with estimated ones $-0.65 \pm j9.6$. The other two eigenvalues calculated play a secondary role in the system response and in evaluation of the system steady state stability.

Let us consider a model represented by a known transfer function. We used the same input as that given from SMES to estimate the poles of the model. Then the estimated poles are compared with the known ones.

a) We considered the following transfer function:

$$G(s) = \frac{(s+15+j2)(s+15-j2)}{(s+0.2+j6)(s+0.2-j6)} \times \frac{(s+10)}{(s+3.5+j9)(s+3.5-j9)} \quad \cdots (14)$$

and estimated its poles by using a second order and a forth order model. The output fit is shown in Fig7.

Because the good fits of the second order model and that of the fourth order model to the system response, their estimated dominant poles are the same ($-0.2 \pm j6$) and they both agree with the true poles of the system (given from the known transfer function). In case of fourth order model the two remaining estimated poles agree with the true ones ($-3.5 \pm j9$) too. The estimation of the zeros is considered in following. For the fourth oder model, the zeros are obtained to be -7.914, $-12.865 \pm j8.327$ and for the second order model, -8.165. Then the estimation of zeros has some errors. Therefore, it is concluded that generally the method is suitable for estimation of poles of the system. It is also possible in some cases (when non dominant poles are near dominant ones) that the second order estimated model does not give a very good fit to the system response. This is because of strong non-dominant poles influence to the output. In these cases we can search for a better fit, using a fourth order model. But dominant poles estimated are the same, even though the second order model fit is not as good as the forth order one. It is important to notice that by estimation of dominant poles we can evaluate how stable a system is.

b) Now let's consider another known transfer function:

$$G(s) = \frac{(s+20)(s+30)}{(s+1.1+j11)(s+1.1-j11)} \times \frac{(s+40)}{(s+0.3+j7)(s+0.3-j7)} \quad \cdots\cdots (15)$$

By using the response for an input signal (denoted by I_1), a model (denoted by M_1) is estimated. Then by using the same response and an input signal, ampliutude of which is K times larger than that of I_1, (See Fig.8) another model (denoted by M_2) is estimated. The poles of M_2 are the same as those of M_1 and $G(S)$ too. That is, the poles can be obtained without considering amplitudes of input and output.

In both cases the fit of responses is shown in Fig. 9. The estimated poles agree with each other and with those of the known model. This shows that, we can estimate the dominant poles of the system by using only the output (generator power oscillations) and the input (SMES signal) to the system.

c)The time that the input from SMES is applied to the system is an important parameter. If the time interval would be too short, it would be difficult to have a good fit of the model response to that of the system and there would be large errors in the estimated poles. This is because, the input applied for a very short time, is not able to "excite" the power system (which has usually a large inertia). On the other hand, a very long interval, it will take longer than needed for the estimation, which will reduce the speed of the identification process. The left part of Fig. 10 shows the results of the recorded response and the response of model estimated for the time interval of 10 sec., and the right one, for that of 20 sec.. It has been found out that an interval around 20 sec is an optimal one. For intervals longer than 20 sec there is no substantial change in the estimated model compared to 20 sec interval case. In very short interval case (10 sec.) the error in the estimated model is unacceptable, and is result of the poor fit of the estimated model response to that one from the system. A 20 sec interval is suitable also because generally we expect no substantial change in power system operating conditions (during steady state operation) within 20 sec intervals.

d) The issue of amplitude of the input power from SMES is discussed. The input waveforms in the power system, used for estimating its mechanical modes, are relative small input active power oscillation from SMES. A small amplitude input will cause smaller power oscillations in each generator bus, without disturbing the normal operation of the system. But on the other hand the amplitude of the input must be large enough to excite the system (because of the losses in the system, the input given from SMES could not reach the machines far from it). So the choice of the amplitude

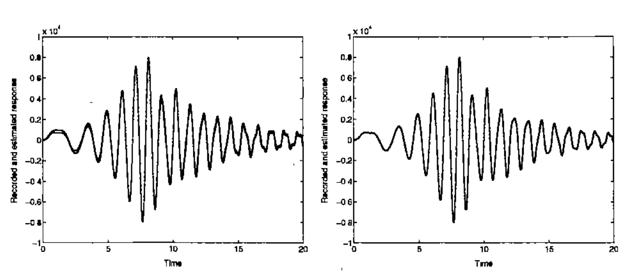

Fig.7 Recorded and estimated output (second order and forth order system) (thin line: recorded response, thick line: response of model estimated)

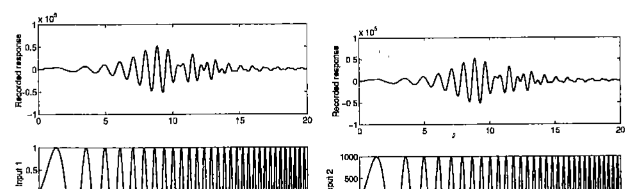

Fig.8 Real input-output and multiplied input-real output data

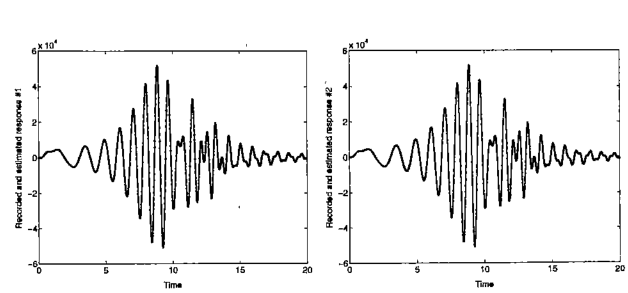

Fig.9 Output fit for estimated models from the data in Fig.8.

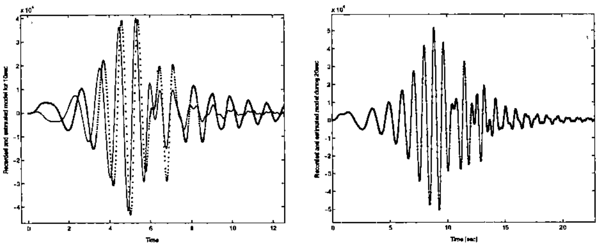

Fig.10 Time interval of 10 sec. and 20 sec. (Thin line:recorded response, thick line: response of model estimated)

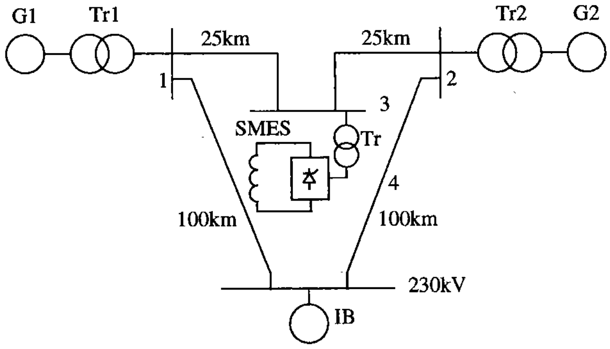

Fig.11 Two machine-IB system with SMES

is a trade off between not disturbing the power system operation and being enough exciting for the identification process. The right amplitude is determined by experiment and 1MW has been found effective in our simulation. In real power systems, we have always some power fluctuations. Then the amplitude of power of SMES must be considered with taking the fluctuations into account. This problem is still open for discussion.

By using effective filtering on the recorded data and by choosing a relative short interval for the identification (20 sec), the effect of noise and other disturbances from outside the system is expected to be highly reduced.

5. Application in a multi-machine system

In this section, the electro-mechanical mode identification of a two machine - infinite bus system is discussed. It should be emphasized that the methodology and results are not dependent on the number of machines in the system. As an example, the case of a two-machine system is considered here. The input is given from SMES and the responses of active power oscillations at both generator buses are recorded from the simulation of the system with SMES in EMTDC. The configuration of power system considered is shown in Fig.11.

Two machines are connected to the infinite bus through two transmission lines (230kV, 100km) and with each other through another 50km transmission line. SMES is connected at four different locations,

Table 4 Specification of generator G1

	100MW	x_q	0.770p.u.	T_a	0.278sec
V_L	13.8kV	x'_d	0.314p.u.	T'_{do}	6.550sec
H	3.117sec	x_d"	0.280p.u.	T_{do}"	0.039sec
x_d	1.014p.u.	x_q"	0.375p.u.	T_{qo}"	0.071sec

Table 5 Specification of controller of exciter system

K_a	100	E_{fmin}	-5	E_{fmax}	5
T_a (sec)	0.02	T_b (sec)	1.0	T_c (sec)	1.5

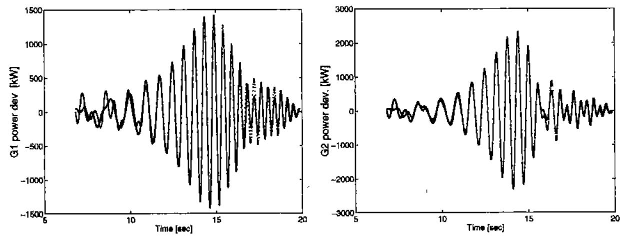

Fig.12 Output fit of estimated models to the responses of G1 and G2 respectively

(marked by numbers in Fig. 11, where point 4 is at midpoint of the transmission line.), and simulations are repeated for the same operating point of the power system.

The specifications of generator G1, G2, transmission lines, transformer, and controller of the exciter systems are shown in Table 4, Table 1, Table 2, Table 3 and Table 5, respectively.

The voltage of the infinite bus is 205 kV. The output active powers (reactive powers) of G1 and G2 are 85MW (48MVAR) and 102MW (49MVAR), respectively.

After recording the SMES input and system responses, the mechanical modes of the simulated system are estimated. Fig.12 shows G1 and G2 responses and estimated model responses for location of SMES at bus 1 by using a second order model. When using a forth order model, the estimation is not valid. In this case, power flow through the transmission line between G1 and G2 is very small. Then the degree of dominant electro-mechanical oscillation may be one. Then at first, a lower model must be used.

It is easy to conclude from Table 6 that the estimated modes of the system in all four cases agree well with each other, which confirms again that the results of estimation are independent from the location of SMES in the system (as long as the operating conditions of the system remain unchanged in all cases).

For assessment purposes we analyzed the spectrum of generators' responses in all cases for different positions of SMES in the system. Fig.13 shows the spectra only for location of SMES at bus 1 and 2 (same results are obtained for two other locations of SMES).

From the spectrum we found out two eigenfrequencies

Table 6 Eigen values for location of SMES

SMES	G_1	G_2
loc.1	$-1.2 \pm j11$	$-0.58 \pm j9.8$
loc.2	$-1.1 \pm j11$	$-0.58 \pm j9.8$
loc.3	$-1.2 \pm j11$	$-0.60 \pm j9.8$
loc.4	$-1.0 \pm j11$	$-0.55 \pm j9.8$

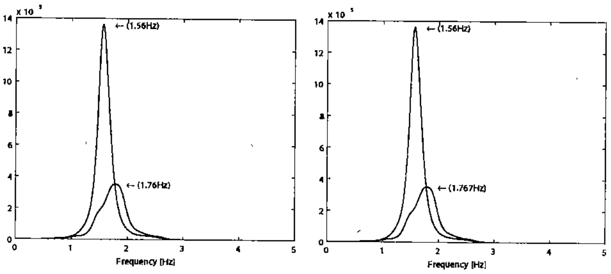

Fig.13 MEM spectrum of the responses of generators for SMES location 1 and 2, respectively

1.76 Hz and 1.56 Hz for G_1 and G_2 responses respectively. This frequencies correspond to 11.05 rad/sec and 9.8 rad/sec estimated from identification method. It is shown that to estimate electro-mechanical modes of a generator, the response only at the respective generator bus is needed.

6. Conclusions

In this paper is proposed a new method for the online identification of the electro-mechanical modes of the power system by use of SMES and by employing an output error model. This method uses only the recorded system responses to estimate its electromechanical modes and it is possible to be applied in a multi machine system case. Experiments by use of SMES with superconducting magnet in simulator of power system are necessary for further assessment of the method before those in real power systems.

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References

(1) for example, J. Matsuki and T. Okada: "On-line Calculation of Synchronizing and Damping Torque Coefficients of a Synchronous Generator", Proc. of 5th International Conference on Electrical Machines and Droves, pp.1645-1650, Sept., 1991

(2) H. Okamoto and A. Kurita: "A study on Transfer Function Identification of Power Systems Using Time Domain Data". Proc. of the 6th Annual Conference of Power & Energy Society, IEE of Japan, 265, 1995.

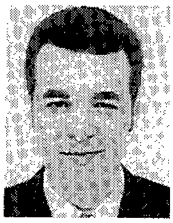
(3) T. Nitta, Y.Shirai, and Y.Ito: "Evaluation of steady state stability of electric power system by use of SMES", (in Japanese). Trans. IEE of Japan, Vol.116-B,No6,pp.678-684, June 1996.

(4) Y.Shirai, T.Nitta, and K.Shimoda: "Measurement of damping coefficient of electric power system by use of SMES", (in Japanese). Trans. IEE of Japan, Vol.116-B,No9 ,pp.1039-1045, Sept. 1996.

(5) Y.Shirai, K.Akita, K.Sekiya, T.Nitta, H.Ogawa, and H.Nishikaito: "On-line evaluation of eigen-vectors-of power systems by use of SMES", 13th PSCC '99 Norway, pp.971-976, June 1999

(6) For example, Lennart Ljung, "System Identification : theory for the user", Prentice Hall, 1987.

Orges Gjini (Member) Orges Gjini was born in Tirana, Albania on June 4, 1970. He received B.E. degree in Electrical Engineering from the Polytechnic University of Tirana (PUT) in 1993 and M.E.degree in Electrical Engineering from the University of Tokyo in 2000. He has been a member of the Faculty at PUT from 1993 until 1997, interested on power system and control. In April 2000 he joined Fuji Electric Corporate Research and Development Ltd., where he is now working on power electronics. This study was done when he was a graduate student at the University of Tokyo.



Tanzo Nitta Tanzo Nitta was born in Hyogo Pref., Japan on August 2, 1944. He received his B.E. and D.E. degree in Electrical Engineering from Kyoto University, Japan in 1967, 1969 and 1978, respectively. He is now a professor of the University of Tokyo. His areas of interest are applied superconductivity, electrical machines and network theory. He is a member of IEEE and the Cryogenic Engineering Society in Japan.