THE APPLICATION OF SELF-TUNING CONTROL TO POWER SYSTEM WITH SMES

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Abstract:
In this study, the self-tuning control algorithm is applied to the synchronous machine and SMES (superconducting magnetic energy storage) unit for maintaining stability. The self-tuning control scheme is based on explicit identification to enhance the damping of the electromechanical mode oscillation of the system. A nonlinear model of the system is considered for simulation. Simulation results shown that the self-tuning control scheme applied both the system and SMES inputs considerably decreases the damping of system post fault.
Keywords: SMES, Self-tuning, PCS, RLS

I. Introduction

Even there are smooth system disturbances such as load change or severe disturbamces such as system fault, power system oscillations will occur. The stabilizing methods such as power system stabilizer (PSS), static var compensators (SVC) or phase shifter have been suggested for the keeping stability[1]. Sometimes, these alone can not be enough to control system oscillations. In recently years, it is the alternative to get from superconductive materials. Because of developed of high temperature superconductive materials, the application of these to power system is considered an important issue in electrical engineering.

The superconducting magnetic energy storage (SMES) is developed to store electric power in the superconducting magnetic inductor. The real power can be absorbed or released from the superconducting inductor according to system power requirements. SMES unit can also be applied to be a load frequency controller [2,3] and transmission line stabilizer [4], and to increase the stability of power system [5,6].

By using high speed electronic switches, the technology gives many chances for stability enhancement of power systems. The thyristor controlled SMES unit is a such device too. The SMES unit is located near the generator bus terminal to control the power balance of the synchronous generator during dynamic period. In literature, SMES controller and generator excitation controller are normally designed by employing linear control theory. Unfortunately, in the approach, controller design is based on linearized models for synchronous generator and SMES unit is not sufficient for stability investigations. Because of this, the controller designed at an operating point is not suitable another operating point. On the other hand, the power system is nonlinear due to its nature. To design the controller, this nonlinearity must be considered.

In this paper, self-tuning nonlinear controller is considered to control synchronous generator and SMES together. The paper investigates the stability enhancement of a power system having an SMES unit by considering the nonlinear system model and the self-tuning control application retaining the nonlinearities in the dynamics. The self-tuning control strategy considered has been investigated on a synchronous machine and SMES unit connected to an infinitive system bus through two equivalent transmission lines.

Simulation studies shown that the considered controller can ensure stability of the system under a large fault which may near the generator terminal.

II. Power Sytem Model

It is considered single machine-infinite bus system as shown in Fig.1.

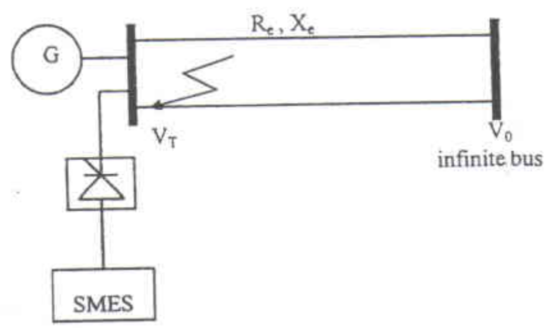

Fig.1 A single machine-infinite bus model.

A SMES unit is connected to the generator terminal bus. The synchronous generator is represented by a fourth order dynamical model [7].

$pE_d' = [-E_d' - (x_q - x_d') I_q] \quad T_{q0}'$
$pE_q' = [E_{fd} - E_q' + (x_d - x_d') I_q] / T_{d0}'$
$p\omega = [P_m - D\omega - P_{e} - P_{SM}] / M$
$p\delta = \omega_0 \, \Delta\omega$

The exciter is represented by second order dynamical model (Fig.-2), and the turbine and governor are represented by fourth order dynamical model (Fig.-3):

$E_{fd} = K_E[V_{tr} - V_t - V_s] / [1 + s T_E]$
$V_s = sK_F \, E_{fd} \,/\, [1 + s T_F]$
$P_r = K_G[\omega_r - \omega] / [1 + s T_{SR}]$
$P_h = P_r / [1 + s T_{SM}]$
$P_c = P_h / [1 + s T_{CH}]$
$P_m = sK_{RH} T_{RH} P_c / [1 + s T_{RH}]$

The terminal voltage of the generator are given below:

$V_d = E_d' - R_a I_d - x_d' I_q$
$V_q = E_q' - R_a I_q + x_d' I_d$
$V_d = -V_0 \sin\delta + R_e I_d + x_e I_q$
$V_q = V_0 \cos\delta + R_e I_q - x_e I_d$
$V_t^{\,2} = V_d^2 + V_q^2$

The variables used in equations above are given in nomenclature. All of the equations are represented by the transfer functions in the s domain. Mathematical model of the system including generator, exciter, turbine and governor is represented by 10th degrees nonlinear differential equations.

III. SMES Unit

Fig.-4 shows the basic structure of a SMES unit. Superconducting inductor coil is charged to a set value or less than full charge according to grid performance. The DC magnetic coil is connected to the AC grid through a Power Conversion System (PCS) which includes an inverter/converter (rectifier). When SMES inductor is charged, the superconducting coil conducts current, which supports an electromagnetic field with virtually no losses. The inductor is kept below the critical temperature and at extremely low temperature by liquid helium.

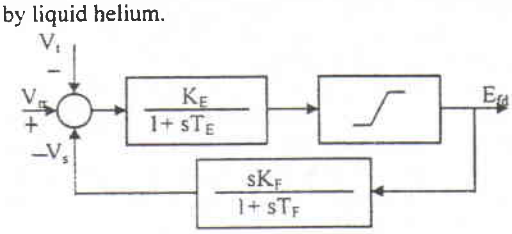

Fig. 2 The static excitation system

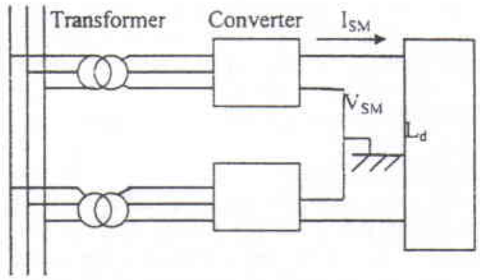

Fig.4 The configuration of SMES unit.

The performance of the superconducting inductor is explained as below[1,7]:

If there is a sudden increase in the load demand, its stored energy is immediately released through the PCS to the grid as AC. As the control mechanisms start working to set the power system to the new operating point, the superconducting inductor returns to initial value of its current.

If the load suddenly decreased, superconducting inductor immediately takes charges back to its full value inductor, so absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released and the superconducting inductor current attain its normal value.

As shown in Fig.-4, the SMES unit contains a transformer, a 12 pulse converter and superconducting inductor. The converter unit is forced commutated and α is the firing angle of PCS. If α is less than 90^0, the converter operates as a converter mode. If α is grater than 90^0, the converter operates as an inverter mode [7]. As a result, power can be absorbed from or release to the power system by controlling the firing angle of thyristor or similar the deviation angular speed. The voltage, current and power of superconducting inductor are given by

$V_{SM} = K_C \, \Delta\omega / [1 + sT_{DC}]$

$$I_{SM} = \left[\int_{t_0}^{t} V_{SM} \, d\tau \right] / L_d + I_{SM0}$$

$P_{SM} = I_{SM} \, V_{SM}$

and the energy stored is

$$W_{SM} = \int_{t_0}^{t} P_{SM}(\tau) d\tau + W_{SM0}$$

Such as V_{SM} and I_{SM} values are bounded by appropriate upper and lower limits.

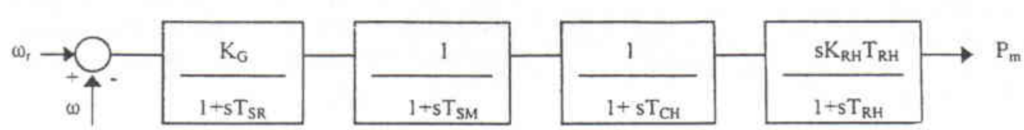

Fig. 3 The governor and turbine systems

Adding SMES dynamical equations to the machine equations, it is obtained the nonlinear seventeenth order differential equations in the form as following:

$$\dot{x}=f[x,u]$$

where the state vector is x, the control is represented u.

IV Self-Tuning Control

It is known that the stability is enhanced by the used to self-tuning controller to the system. The self-tuning controller is based on explicit identification techniques. In this study, it is adequately to describe the system by a third order discrete time model given as follows[8]:

$$y(t)=\sum_{i=1}^{3} a_i y(t-i)+\sum_{i=1}^{3} b_i u(t-i)$$

where a_i, b_i (i=1,2,3) are discrete time model (ARMA: autoregresive moving average) parameters of the system which are still to be estimated and, y(t)and u(t) are the system output and the deviation of rotor angular speed deviation, respectively, at time tT_s. T_s is sampling period. In this study, it is considered a performance index of the machine is given as follows:

$$I=y(t+1)^2+q'\,[py(t+1)]^2+m'\,[p^2\,y(t+1)]^2+r\,[u(t)]^2$$

where, q' ,m' ,r are constant weighted parameters of the system, py(t+1) is the first derivative of output of the system and p^2 y(t+1) is the second derivative of output of the system subject to u(t).

The opportance of maintaining the stability post fault in the system can be increased by selecting input signal such that the corresponding performance index is minimized. The first and second derivative of the system output used in performance index can be taken as follows:

$$p\,y(t+1)=[y(t+1)-y(t)]\,/\,T_s$$

$$p^2\,y(t+1)=[y(t+1)-2y(t)-y(t-1)]\,/\,T_s^2$$

Then, the performance index is given a form as follows:

$$I=y(t+1)^2+q[y(t+1)-y(t)]^2+m[y(t+1)-2y(t)-y(t-1)]^2+r[u(t)]^2$$

$$q=q'\,/\,T_s^2 \qquad m=m'\,/\,T_s^4$$

Then, the stabilizing input is described by minimizing the performance index subject to u(t).

The control input is achieved as folows:

$$u(t)=k[(q+2m)y(t)+my(t-1)-(1+q+m))s(t)]$$

where

$$k=b_1\,/\,[r+(1+q+m]b_1^2]$$

$$s(t)=\sum_{i=1}^{3} a_i y(t-i+1)+\sum_{i=1}^{2} b_i u(t-i+1)$$

The most known estimation method recursive least squares is applied to estimate model parameter of system identification. In this study, the recursive least squares algorithm is used to estimate the model parameters of system at every sample based on its measured input -output data:

$$y(k)=\Phi^T\,\theta\,(t-1)$$

$$\Phi^T=[y(t-1),y(t-2),y(t-3),u(t-1),u(t-2),u(t-3)]^T$$

$$\theta\,(t)=[a_1(t),a_2(t),a_3(t),b_1(t),b_2(t),b_3(t)]^T$$

then the estimate algorithm is as follows

$$\hat{\theta}\,(t+1)=\hat{\theta}(t)+h(t+1)[y(t+1)-\Phi^T(t+1)\,\theta(t)]$$

$$h(t+1)=P(t)\,\Phi(t+1)\,/[\beta+\Phi^T(t+1)P(t)\,\Phi(k+1)]$$

$$P(k+1)=[I-h(k+1)\,\Phi^T(t+1)]\,P(k)\,/\,\beta$$

where $\wedge$ refer to estimated values and $0\leq\beta\leq 1$.

The covariance matrix P(.) can be reset to P(0) after preselected number of sampling intervals where $P(0)=\alpha\,I$ (I:unit matrix is six by six) and $\alpha>>0$. Initial values of parameter matrix, θ_0, are given as (0.5 -0.3 0.3 -0.4 -0.6 -3.1).

Using the latest parameter estimates, each stabilizing signal is computed and then applied to the machine excitation input and SMES input as shown in Fig.-5.

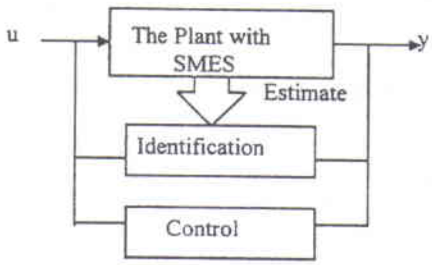

Fig.5 Self-tuning control scheme

V. Results

In this paper, it is simulated the dynamic performance of the system shown in Fig.-1. The parameters of the system are given in Appendix. For this purpose, it is assumed that a three phase short circuit is occured at the sending terminal of one of the transmission lines. The response of the system for the severe disturbance is investigated firstly for the situation of SMES unit is unconnected to the system and no control is applied to exciter. Secondly, it is considered that only SMES unit is connected to the system. Finally, it is considered that both exciter and SMES unit are controlled by using the self-tuning control scheme. All of the investigations are carried out for the initial load condition P_0=0.8 p.u. and power factor 0.85.

To investigate the transient performance of the system, the variations of some terminal variables are given for the fault considered (Fig.-6,7,8,9,10 and 11). These variables are terminal voltage, angular speed and rotor angle of the generator, and the voltage across the superconducting coil, the current through the coil and the energy stored in the SMES unit, respectively. From the Fig.-6,7 and 8, it is seen that the deviations of terminal variables of the generator are only a little improved when the SMES unit is connected to the system, but considerably improved when both excitation and SMES unit are controlled by using self-tuning control scheme. Fig.-9,10 and 11 show that the deviations of terminal variables of the SMES unit are considerably improved when the self-tuning control is applied.

VI. Conclusion

The transient response of the single machine-infinite bus system considered for the severe fault assumed are simulated in this study. It is investigated the effect of the SMES unit and the self-tuning control applied to both excitation and SMES unit. The results obtained (In the followins figures,—— , ... and - - - are represent the first, the second and the third situations considered in the simulation, respectively.) from the simulation show that the oscillations of terminal variables of the generator and SMES unit are damped out quickly by using the control scheme.

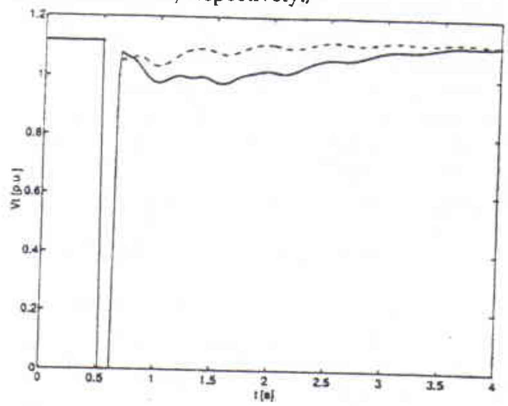

Fig.6 The terminal voltage

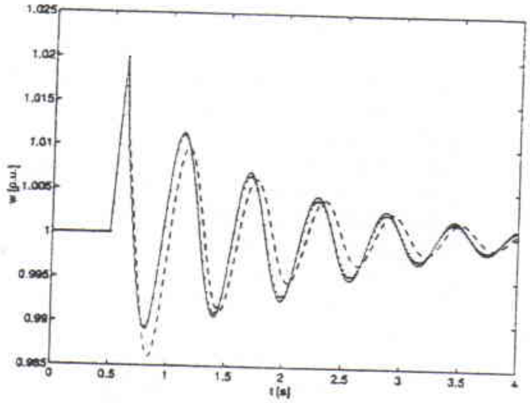

Fig.7 Angular speed

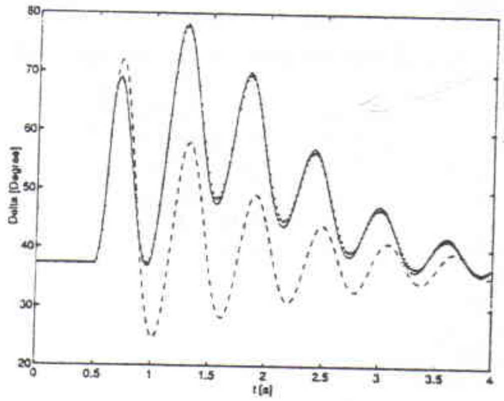

Fig.8 Rotor angle

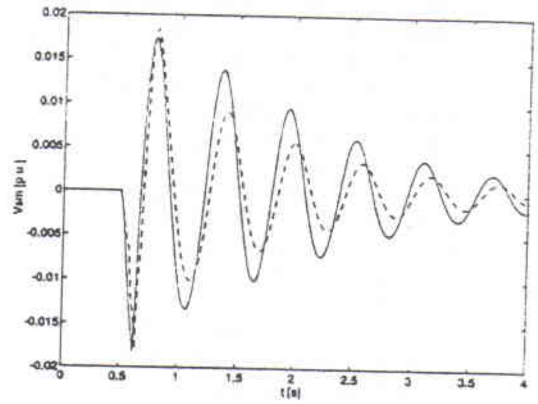

Fig.9 Terminal voltage of the SMES

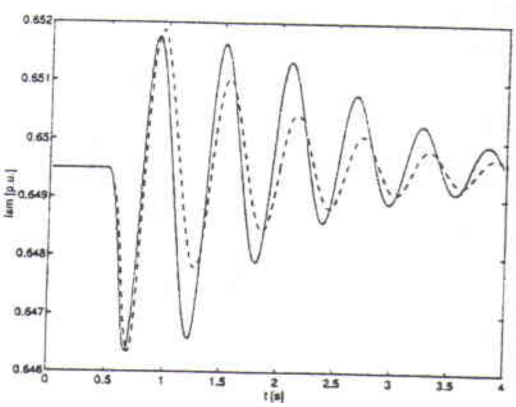

Fig.10 The current through the coil

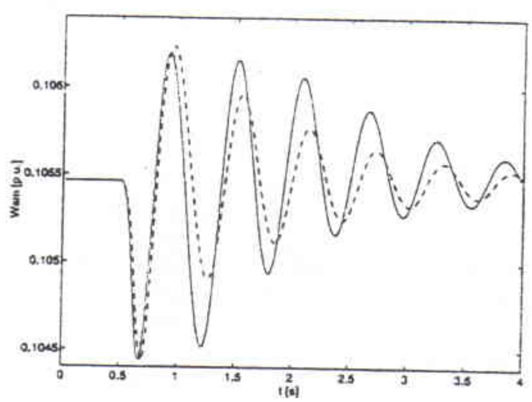

Fig.11 The energy stored in the SMES

Nomenclature

D	: damping coefficient
M	: inertia constant of generator
E_d'	: direct (d) axis transient voltage
E_q'	: quadrature (q) axis transient voltage
I_d	: d-axis armature current
I_q	: q-axis armature current
E_{fd}	: d-axis field voltage
T_{d0}'	: d-axis open circuit time constant
T_{q0}'	: q-axis open circuit time constant
V_s	: stabilizing transformer voltage
P_r	: speed relay output power
P_h	: servomotor output power
P_c	: steam chest output power
P_m	: generator input power
δ	: rotor angular position
$\Delta\omega$	: angular frequency variation (p.u.)
Δ	: change from nominal values
α	: converter firing angle
P_e	: electrical output power of generator
R_e	: equivalent resistance of transmission lines
x_e	: equivalent reactance of transmission lines
R_a	: armature resistance of generator
V_t	: generator terminal voltage
V_d	: d-axis component of terminal voltage
V_q	: q-axis component of terminal voltage
I_{SM}	: superconducting inductor current
V_{SM}	: voltage across the inductor
W_{SM}	: energy stored in superconducting inductor
P_{SM}	: power input to the SMES
L_d	: inductance of superconducting coil
ω_0	: base angular speed
ω_r	: governor reference angular speed
K_E	: exciter gain
T_E	: exciter time constant
K_F	: stabilizer circuit gain
T_F	: stabilizer circuit time constant
T_{SR}	: speed relay time constant
T_{SM}	: servomotor time constant
T_{CH}	: steam chest time constant
K_{RH}	: reheater gain
T_{RH}	: reheater time constant
K_C	: converter loop gain
T_{DC}	: converter circuit time constant
s	: Laplace operator
θ (.)	: estimate matrix
ϕ (.)	: regression matrix
P (.)	: covariance matrix

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Appendix

The system parameters used in this study are as follows[7]:

Synchronous generator and transmision line

Rated Power 160MVA	Rated voltage 15kV
Excitation voltage 375V	Field Current 926 A
Power 0.8 p.u.	Power Factor 0.85
x'_d=0.245	R_a=0.001096
M=4.74	x_d=1.7
D=0.	x_q=1.64
T'_{q0}=0.075s	T'_{d0}=5.9s
R_e=0.020	x_e=0.4

exciter

K_{AE}=400	T_{AE}=0.05s
K_F=0.025s	T_F=1.0s

Governor

K_G=3.5	T_{CH}=0.05s
T_{RH}=8s	T_{SR}=0.1s
T_{SM}=0.2s	K_{RH}=0.3

SMES unit

I_{SM0}=0.6495	V_{SM0}=0
L_d=0.5H	T_{dc}=0.026s
K_C=1.83	T_w=0.125s

$0.31\ I_{SM0} < I_{SM} < 1.38\ I_{SM0}$

$-0.438 < V_{SM0} < 0.438$