Application of Nonlinear PID Controller in Superconducting Magnetic Energy Storage

Xiaotao Peng, Shijie Cheng, and Jinyu Wen

Abstract: As a new control strategy, the Nonlinear PID (NLPID) controller has been introduced successfully in power systems. The controller is free of planting model groundwork during the design procedure and is therefore able to be achieved quite simply. In this paper, a nonlinear PID controller used for a superconducting magnetic energy storage (SMES) unit connected to a power system is proposed. The purpose of designing such a controller is to improve the stability of the power system in a relatively wide operation range. The design procedure takes into account the active and reactive power cooperative control scheme as well as the simple structure so as to be more apt to practical utilization. Simulation is carried out to investigate the performance of the proposed controller in a high order nonlinear power system model under the MATLAB environment. The results show satisfactory performance and good robustness of the controller. The feasibility of the controller is testified as well.

Keywords: Nonlinear configuration, nonlinear PID controller, superconducting magnetic energy storage (SMES), tracking-differentiator (TD).

1. INTRODUCTION

Due to the rapid development in the high temperature superconducting material and power electronics techniques, the SMES unit, which combines the superconducting conductor and the power electronics converter has become an important issue in electrical engineering. It stores electric power in the lossless superconducting magnetic coil. Power can be absorbed by or released from the coil according to the system requirement. In addition to the load leveling, it can also be used as a load frequency controller or a transmission line stabilizer aimed at increasing the stability of the power system. However, these superior characteristics will not be brought into play until an appropriate controller is used.

With the development of research involving the SMES unit, some novel control strategies such as fuzzy logic control, robust control and adaptive control have been introduced into the design of the controllers for the SMES unit [1-3]. However, such types of controllers are difficult to realize in practice due to their complex control algorithms and system structures. The linear PID (LPID) control method based on the classical control theory is still widely utilized for the design of the controller for the SMES unit. In designing such a controller, an accurate mathematic model is required to represent the controlled system, and the system must also be linearized at a certain operation point. Otherwise, the robustness of the controller will be subjected to the limitation [4]. In general, such variety of controller behaves satisfactorily if the controlled system is operating in the region that is in close proximity to the operation point at which the system is linearized. Otherwise, the performance of the controller will be subjected to the degradation.

In order to overcome the deficiency of the LPID controller, a nonlinear PID (NLPID) controller for SMES based on the nonlinear PID control theory is proposed in this paper. The nonlinear PID control strategy has the advantages of good robustness and less dependence on the mathematical models of the controlled system in the design procedure. Simulation results indicate that the NLPID control algorithm based SMES controller can enhance the damping characteristics and the stability of the power system by changing the energy storage in the SMES unit under the singular operation conditions. The stability limit of the power system is expanded as well.

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2. DESCRIPTION OF NONLINEAR PID CONTROLLER

2.1. Tracking-differentiator (TD)[5]

When constructing a dynamic system with a nonlinear function $g(v_1, v_2)$

$$\begin{cases} \dot{v}_1 = v_2, \\ \dot{v}_2 = -R \; g(v_1(t) - v_0(t), v_2), \end{cases} \quad (1)$$

the following result will be achieved.

$$\lim_{R\to\infty} \int_0^T |v_1(t) - v_0(t)| \; dt = 0 \quad \forall T > 0$$

When $R \to \infty$, $v_1(t) = \dot{v}_2(t) \to v_3(t)$, where $v_0(t)$ is the input signal of the dynamic system, R is the parameter of the system, $g(*)$ is a kind of nonlinear function and $v_3(t)$ is the generalized derivative of the $v_0(t)$. Actually, the tracking-differentiator is a kind of dynamic system that outputs the tracking signal $v_1(t)$ and its differential signal $v_2(t)$ of the input signal $v_0(t)$. With the help of this dynamic system, the difficulty of getting the differential signal from the discontinuous input signal or the feedback signal with noise is overcome.

2.2. Nonlinear PID controller [6,7]

The NLPID controller is a new control strategy that uses some nonlinear characteristics to improve the performance of the LPID controller. The basic configuration scheme of the NLPID controller is shown in Fig. 1 enclosed by a broken line.

In Fig. 1, $v(t)$ is the system reference input, and $u(t)$ and $y(t)$ are the input and the output of the controlled system respectively. ε_0, ε_1 and ε_2 are the deviation, the deviation integration and the deviation differential of the system output signal respectively, which can be represented by the following equations.

$$\begin{cases} \varepsilon_0 = x_{11} - x_{21}, \\ \varepsilon_1 = \int_0^t (x_{11} - x_{21}) dt, \\ \varepsilon_2 = x_{12} - x_{22}, \end{cases} \quad (2)$$

where $x_{11}(t)$ and its differential $x_{12}(t)$ are produced by TD I from the reference input $v(t)$. $x_{21}(t)$ and its differential $x_{22}(t)$ are produced by TD from the system output measurement $y(t)$.

In order to obtain satisfactory system response in a wide system operating condition area, the configuration and the parameter of the control should be appropriately selected The following two factors, the fast system

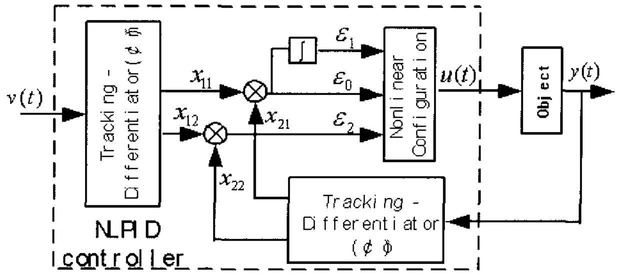

Fig. 1. The configuration of the NLPID controller.

response and the less overshoot, are the main objectives considered. For this reason, the general form presented in (3), which is similar to that of the linear control is used. The main difference of the NLPID compared with the LPID is that a nonlinear function is used. This nonlinear function with different variables ε_0, ε_1 and ε_2, together with the parameters constitutes the proportional, the integral and the differential parts of the NLPID control.

$$\begin{aligned} u(t) = \; & \beta_P fal(\varepsilon_0, \alpha, \sigma) + \beta_I fal(\varepsilon_1, \alpha, \sigma) \\ & + \beta_D fal(\varepsilon_2, \alpha, \sigma) \end{aligned} \quad (3)$$

In (3), $fal(\varepsilon, \alpha, \sigma)$ is a nonlinear function having the following form

$$fal(x, \alpha, \sigma) = \begin{cases} |x|^\alpha \, sign(x) & |x| > \sigma \\ x / \sigma^{1-\alpha} & |x| \le \sigma, \end{cases} \quad (4)$$

where x is the variable of the function taking the value of ε_0, ε_1 and ε_2 respectively according to its functional contribution. σ is the parameter used to determine the linear range of the function, and α is used to determine the nonlinear degree of the function. The fundamental principle of selecting these parameters is "small error large control and large error small control". In summation, the standard algorithm of the NLPID control is given in (5).

$$\begin{cases} \dot{x}_{11} = x_{12}, \\ \dot{x}_{12} = -R_1 sat(x_{11} - v(t) + x_{12}|x_{12}|/(2R_1), \theta_1), \\ \dot{x}_{21} = x_{22}, \\ \dot{x}_{22} = -R_2 sat(x_{22} - y(t) + x_{22}|x_{22}|/(2R_2), \theta_2), \\ \varepsilon_0 = x_{11} - x_{21}, \\ \varepsilon_1 = \int_0^t (x_{11} - x_{21}) dt, \\ \varepsilon_2 = x_{12} - x_{22}, \\ u = \beta_P fal(\varepsilon_0, \alpha, \sigma) + \beta_I fal(\varepsilon_1, \alpha, \sigma) + \beta_D fal(\varepsilon_2, \alpha, \sigma), \end{cases} \quad (5)$$

where $$sat(x,\theta)=\begin{cases} sign(x) & |x|\ge\theta \\ x/\theta & |x|<\theta. \end{cases} \tag{6}$$

These parameters of the controller have contact with the structure of the controlled system. How to select these parameters requires additional research. However, if a NLPID controller for a particular object has been designed, in terms of the principle discussed above, a group of parameters that have the characteristics of good robustness and wide adaptability can be explored.

3. THE STUDIED SYSTEM

Considering a single-machine-infinite-bus power system with its single-line diagram shown in Fig. 2, the model for the generator unit considered here is a detailed 5th-order model with the dynamic behavior of the exciter. The SMES unit is located at the bus bar near the generator terminal. The nonlinear dynamic behavior of the investigated model is described by the following equations:

$$\dot{\delta}=\omega_0(\omega-1), \tag{7}$$

$$\dot{\omega}=\frac{1}{T_J}(T_m-T_e-D\omega), \tag{8}$$

$$\dot{E}_q'=\frac{1}{T_{d0}'}[E_f-(x_d-x_d')i_d-E_q'], \tag{9}$$

$$\dot{E}_q''=\frac{1}{T_{d0}''}[E_q'-(x_d'-x_d'')i_d-E_q'']+\dot{E}_q', \tag{10}$$

$$\dot{E}_d''=\frac{1}{T_{q0}''}[(x_q-x_q'')i_q-E_d''], \tag{11}$$

$$\dot{E}_f=\frac{1}{T_f}[K_f(V_{ref}-V_t)-E_f], \tag{12}$$

where $T_e=P_e/\omega$, $P_e=U_di_d+U_qi_q$, $V_t=\sqrt{U_d^2+U_q^2}$. The list for the symbols used for the above mentioned power system is provided in the Nomenclature.

The independent active and reactive power exchange between the SMES unit and the interconnected power system can be specified by the following equations for simplicity [8]:

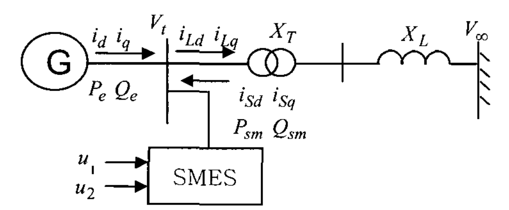

Fig. 2. A Single-machine-infinite-bus power system with SMES unit.

$$\dot{P}_{sm}=-\frac{1}{T}P_{sm}+\frac{1}{T}u_1, \tag{13}$$

$$\dot{Q}_{sm}=-\frac{1}{T}Q_{sm}+\frac{1}{T}u_2, \tag{14}$$

where u_1 and u_2 are the control signals of the SMES unit, T is the time delay constant and P_{sm} and Q_{sm} are the injected active and reactive powers of the SMES unit to the power system. When the SMES unit is connected to the power system, the following equations hold:

$$\begin{cases} P_{sm}=U_di_{sd}+U_qi_{sq}, \\ Q_{sm}=U_qi_{sd}-U_di_{sq}, \\ i_d+i_{sd}=i_{Ld}, \\ i_q+i_{sq}=i_{Lq}, \end{cases} \tag{15}$$

where i_{sd} and i_{sq} are the d-axis and the q-axis currents injected by the SMES unit to the power system. From the equations mentioned above, the injected current can be written as

$$i_{sd}=\frac{U_dP_{sm}+U_qQ_{sm}}{U_d^2+U_q^2}, \tag{16}$$

$$i_{sq}=\frac{U_qP_{sm}-U_dQ_{sm}}{U_d^2+U_q^2}. \tag{17}$$

The model mathematically described in this section is used to form a simulation platform on which the controller proposed can be tested. Modeling of the system and simulation studies are done under the MATLAB environment without lead-lag filter.

4. NLPID CONTROLLER FOR THE SMES UNIT

4.1. Design of the controller

This section describes the details of the control strategy based on the NLPID technique for the SMES connected to the power system shown in Fig. 2. In order to enhance the damping characteristics and stability of the power system, the diagram of the NLPID controller for the SMES unit is given in Fig. 3.

In Fig. 3, the generator represents the power system described by (7)-(11) in section III. Two nonlinear configurations and two tracking-differentiators are used to generate the control signals. u_1 and u_2 are two control signals that are used to control the real and reactive power exchanges between the SMES unit and the power system.

Generally, the SMES unit is used as a torque modulation stabilizer. The active power P_{sm} transferred

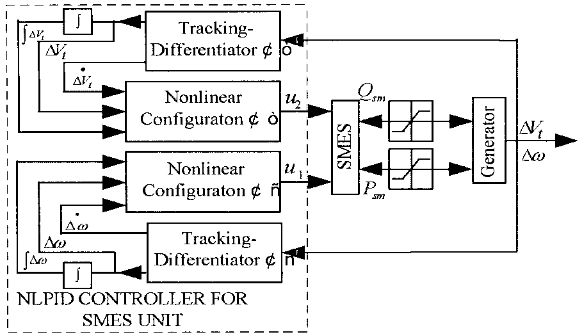

Fig. 3. Block diagram of nonlinear PID controller for SMES.

in the SMES unit is controlled continuously depending on the measured speed deviation of the rotor angular. To simplify the structure of the controller $\Delta\omega$ is selected as the controller input variable. The reference input of the controlled system is set to zero, with the aim of maintaining the synchronous operation of the power system. Thus, the TD used for the reference input, which is shown in Fig. 1, is omitted and the control equation of u_1 can be written as

$$u_1 = \beta_{P1} fal(\Delta\omega,\alpha,\sigma) + \beta_{I1} fal(\int \Delta\omega,\alpha,\sigma) + \beta_{D1} fal(\dot{\Delta\omega},\alpha,\sigma). \tag{18}$$

The reactive power control is usually employed for the purpose of voltage stabilization. The reactive power injection Q_{sm} of the SMES unit is controlled continuously depending on the measured generator terminal voltage deviation. So ΔV_t is selected as the feedback signal, and only one TD is needed. At the same time, in order to reduce the parameter design for the controller, the same nonlinear function is used for the nonlinear configuration Ⅱ. Then the control equation of u_2 can be written as

$$u_2 = \beta_{P2} fal(\Delta V_t,\alpha,\sigma) + \beta_{I2} fal(\int \Delta V_t,\alpha,\sigma) + \beta_{D2} fal(\dot{\Delta V_t},\alpha,\sigma). \tag{19}$$

Following the algorithm given above, the controller for the SMES unit connected to the power system is obtained. The controller discussed here is used for a single machine power system, and the parameters of the nonlinear PID controller are: $\beta_{P1} = 4.8$, $\beta_{I1} = 1.8$, $\beta_{D1} = 0.2$, $\beta_{P2} = 0.2$, $\beta_{I2} = 0$, $\beta_{D2} = 0$, $\alpha = 0.5$, $R_1 = 30$, $R_2 = 80$, $\theta_1 = \theta_2 = 0.001$, $\sigma = 0.001$. The simulation results will be given in the next part of this section.

When the generator described in Fig. 3 is replaced with one of the generators in the multimachine power system, the design approach of the nonlinear PID controller for SMES as mentioned above can be extended to be applicable to the multimachine power system. It will also have the advantage of improving the transient stability of the power system, and the effects are related to not only the distance between the SMES installation position and the fault place, but also parameters of the generators. If the SMES is installed near one generator bus terminal, the stability of the generator will be enhanced more evidently than those without installation of the SMES nearby. Therefore, by installing the SMES near the generator whose steady state is destroyed most easily will allow the transient stability of the entire system to be effectively enhanced.

4.2. Simulation results

The single machine power system for simulation is shown in Fig. 4. The location for the SMES installation has two cases. In case 1 the SMES is located at point A, and in case 2 it is located at point B, as the solid line and broken line show in Fig. 4. The fault considered here is a 0.1 second symmetrical three-phase short-circuit fault at point C of the transmission line followed by a successful reclosing.

Fig. 5 indicates the effectiveness of the SMES unit with the proposed controller in controlling the rotor angle and the generator terminal voltage at P_0 =0.85(p.u.) operation conditions in case 1. The curves of the active and reactive powers exchanging between the SMES unit and the power system are shown simultaneously. It is evident that with the SMES unit having the proposed controller, the oscillation of the power system is damped out quickly and the stability of the power system is enhanced tremendously. On the contrary, without the SMES unit the power system is prone to the occurrence of the oscillation under the fault.

Figs. 6 and 7 present the response of the generator rotor angle and terminal voltage at P_0 =1.2(p.u.) operation conditions in case 1 and case 2 respectively under the fault. With the SMES unit having the proposed controller, the rotor angle remains stable and the generator terminal voltage is kept in a reasonable variation after the fault in spite of case 1 or case 2. They also indicate that the stability limit of the power system is expanded successfully. However, without the

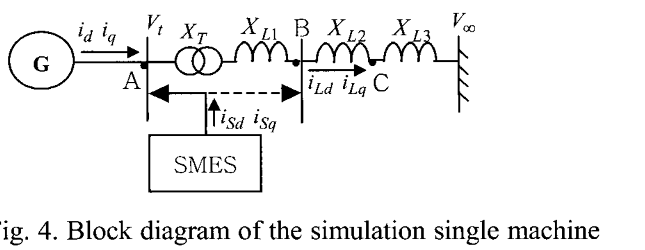

Fig. 4. Block diagram of the simulation single machine power system.

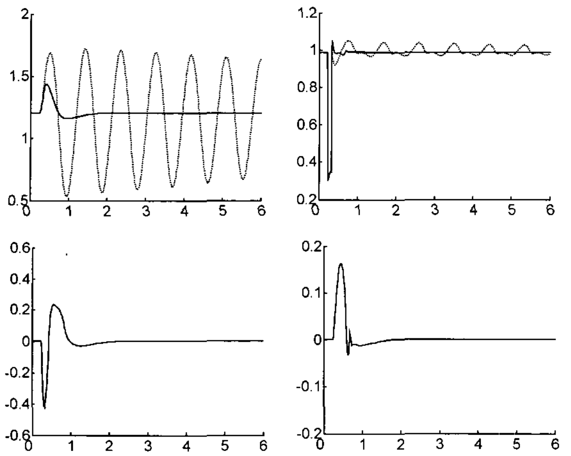

Fig. 5. The response of the system under the fault(P0= 0.85(p.u.)). Solid line: with the SMES using the proposed controller. Dotted line: without the SMES.

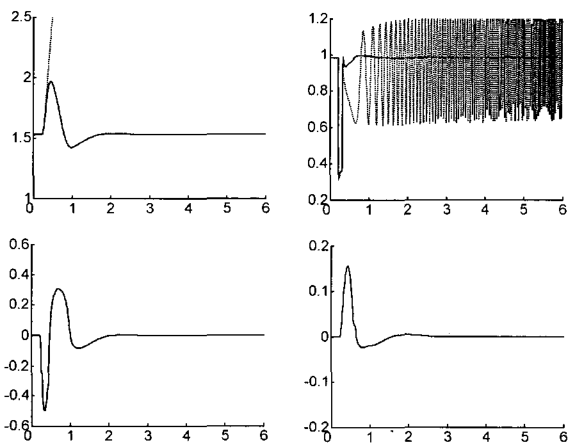

Fig. 6. The response of the system under the fault (P0= 1.2(p.u.)). Solid line: with the SMES using the proposed controller. Dotted line: without the SMES.

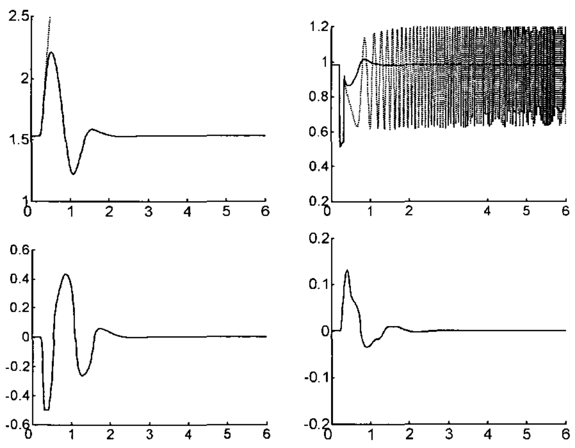

Fig. 7. The response of the system under the fault(P0= 1.2(p.u.)). Solid line: with the SMES using the proposed controller. Dotted line: without the SMES.

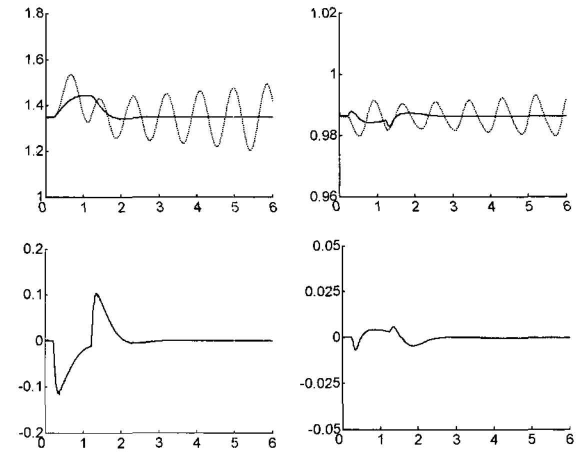

Fig. 8. The response of the system under the instantaneous disturbance (P0=1.0(p.u.)). Solid line: with the SMES using the proposed controller. Dotted line: without the SMES.

SMES unit, the generator obviously loses its synchronization and the generator terminal voltage suffers vibration. Contrasting Fig. 6 with Fig. 7, it can be found that in case 1 (shown as Fig. 6) the overshoot of rotor angle is better than in case 2, but in case 1 the voltage sag of the generator terminal voltage is worse than in case 1. So, to enhance the generator damping characteristic, the SMES should be installed near the generator. As to the effect of SMES regulating the generator terminal voltage, it is in relation to the distance between the installation location and the fault spot.

Fig. 8 shows the contribution of the SMES unit with the proposed controller in case 1 on controlling the rotor angle and the generator terminal voltage under another kind of system disturbance, a one second +10% step-change of the mechanical torque Tm. The simulation results indicate that under the action of the SMES unit with the proposed controller, the damping characteristic of the power system is enhanced considerably, and the capability of the power system to prevent fluctuation of the generator terminal voltage is also intensified.

From the simulation results shown above, it can be seen that the proposed controller for the SMES unit has excellent performances not only on enhancing the damping characteristic and transient stability of the power system, but also on the robustness and the adaptability of the controller.

5. CONCLUSION

In this paper, the NLPID control theory is employed to design a NLPID controller for the SMES unit connected to a power system. Design of the controller is based on the principle that the uncertainty of the power system and the errors of the mathematical models can be taken into account by adopting the nonlinear feedback rule that can realize dynamic feedback compensation. Simulation results indicate that the proposed controller can effectively enhance both the dynamic performance of the power system power angle stability and the voltage of the place at which the SMES unit is installed. The robustness and adaptability of the controller are demonstrated as well.

6. NOMENCLATURE

δ rotor angle of the generator
ω rotor angular speed
ω_0 synchronous speed of the rotor angular
T_e electromagnetic torque
i_d d-axis current of the generator
x_d synchronous reactance of d-axis stator winding
x_d' transient reactance of d-axis stator winding
x_d'' sub-transient reactance of d-axis stator winding
x_q synchronous reactance of q-axis stator winding
x_q'' sub-transient reactance of q-axis stator winding
E_f field exciter voltage
U_d d-axis terminal voltage
U_q q-axis terminal voltage
T_m mechanical torque
V_t generator terminal voltage
T_j inertia constant
D damping coefficient
T_{d0}' d-axis transient time constant
T_{d0}'' d-axis sub-transient time constant
T_{q0}'' q-axis sub-transient time constant
K_f exciter gain
T_f exciter time constant
E_q' q-axis transient voltage
E_q'' q-axis sub-transient voltage
E_d'' d-axis sub-transient voltage

APPENDIX

The system data and the operating quantities per unit are:

x_d=1.79 x_d'=0.17 x_d''=0.12 x_q=1.71
x_q''=0.335 T_{d0}'=7.65s T_{d0}''=0.0314 T_{q0}''=0.0623
D=0.2 X_T=0.05 X_{L1}=0.05 X_{L2}=0.1
X_{L3}=0.3 T=25ms K_f=200 T_f=10ms

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