ISTANBUL UNIVERSITY –
JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING
YEAR : 2005 (1271-1278)
VOLUME : 5
NUMBER : 1

APPLICATION OF NONLINEAR PID CONTROLLER IN SUPERCONDUCTING MAGNETIC ENERGY STORAGE

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ABSTRACT

As a new control strategy, Nonlinear PID(NLPID) controller has been introduced in the power system successfully. The controller is free of planting model foundation in the design procedure and realized simply. In this paper, a nonlinear PID controller used for superconducting magnetic energy storage (SMES) unit connected to a power system is proposed. Purpose of designing such 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 and the simple structure so as to be apt to the practical use. Circuit design and implementation of the proposed controller is presented subsequently. At the same time, 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: *SMES, tracking-differentiator, nonlinear PID controller*

1. INTRODUCTION

Due to the rapid development in the technique of high temperature superconductuing material and power electronics, the SMES unit which combines the superconducting conductor and the power electronics converter has become an important issue in the 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 aiming in 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 in the SMES unit, some novel control strategies such as the fuzzy logical control, the robust control and the adaptive control have been introduced into the design of the controllers for the SMES unit[1-3]. However, such kinds of controllers are difficult to realize in practice due to their complex control algorithm and system structure. The linear PID (LPID) control method based on the classical control theory is still widely used for the design of the controller for SMES unit. In design such controller, an accurate mathematic model is required to represent the controlled system, and

Received Date : 07.09.2004
Accepted Date: 14.1.2005

also the system must be linearized at a certain operation point. Otherwise, the robustness of the controller will be subjected to the limitation [4]. As in general, such kind of controller behaves satisfactory if the controlled system is operating in the region which is near 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 depending on the mathematical models of the controlled system in the design procedure. Simulation results show 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 different operation conditions. The stability limit of the power system is expanded as well.

2. DESCRIPTION OF NONLINEAR PID CONTROLLER

2.1 Tracking-Differentiator(TD)[5]

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

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

then□ the following result will be achieved .

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

When $R \to \infty$, $\dot{v}_1(t) = v_2(t) \to v_3(t)$, 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. $v_3(t)$ is the generalized derivative of the $v_0(t)$. Actually, 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 show in Fig. 1 enclosed by broken line .

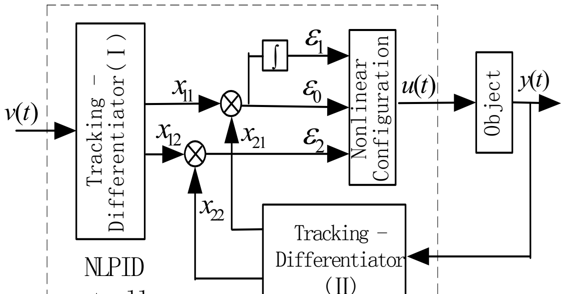

Figure 1. The configuration of a NLPID

In figure 1 $v(t)$ is the system reference input. $u(t)$ 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.

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

where $x_{11}(t)$ and its differential $x_{12}(t)$ are produced by TD□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 get satisfactory system response in wide area of system operating condition, the configuration and the parameter of the control should be appropriately selected The following two factors, the fast system response and the less overshoot, are the main objectives considered. For this reason, a general form shown in Eqn.(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.

$$u(t) = \beta_P fal(\varepsilon_0,\alpha,\sigma) + \beta_I fal(\varepsilon_1,\alpha,\sigma) + \beta_D fal(\varepsilon_2,\alpha,\sigma) \tag{3}$$

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

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

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 summarizing, the standard algorithm of the NLPID control is given in Eqn. (5) .

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

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 is needed to research more. However, if a NLPID controller for the certain object has been designed, in term of the principle discussed above a group of parameters which have the characteristics of good robustness and wide adaptability can be explored.

3. THE STUDIED SYSTEM

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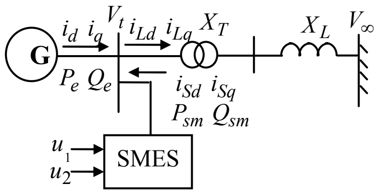

Figure 2. A Single-machine-infinite-bus power system with a SMES unit

Considering a single-machine-infinite-bus power system with its single-line diagram shown in Fig.2, the model for 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 are 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 $T_e = P_e/\omega$, $P_e = U_d i_d + U_q i_q$, $V_t = \sqrt{U_d^2 + U_q^2}$. The list for the symbols used for the above mentioned power system is given in the Nomenclature.

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

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

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

where u_1 and u_2 are the control signals of the SMES unit, T is the time delay constant. 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.

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

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

$$i_{sd} = \frac{U_d P_{sm} + U_q Q_{sm}}{U_d^2 + U_q^2} \tag{16}$$

$$i_{sq} = \frac{U_q P_{sm} - U_d Q_{sm}}{U_d^2 + U_q^2} \tag{17}$$

The model mathematically described in this section is used to form a simulation platform on which the controller proposed can be tested. The modeling of the system and simulation studies are done under the MATLAB environment

4. NLPID CONTROLLER FOR THE SMES UNIT

4.1 Design of the Controller

This section described 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.

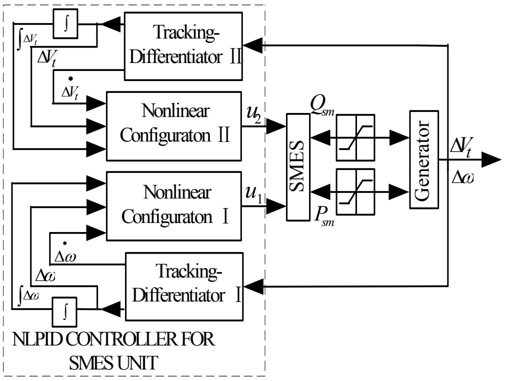

Figure 3. Block diagram of nonlinear PID for ***SMES***

In Fig.3, generator represents the power system described by Eqn.(7)-(11) in section □. Two nonlinear configurations and two tracking-differentiators are used to generate the control signals. u_1 and u_2 are two control signals which 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 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 input variable of the controller. The reference input of the controlled system is set to zero aiming to keep 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 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 parameters design for the controller, the same nonlinear function is used for the nonlinear configuration □. 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 parameters of the nonlinear PID controller are: $\beta_{P1} = 4.8$, $\beta_{I1} = 1.8$, $\beta_{D1} = 0.2$, $\beta_{P2} = 0.2$, $\beta_{I2} = 0$, $\beta_{D2} = 0$, $\alpha = 0.5$, $R_1 = 30$, $R_2 = 80$, $\theta_1 = \theta_2 = 0.001$, $\sigma = 0.001$. Circuit design and implementation of the controller and the simulation results will be given in the following part of this section.

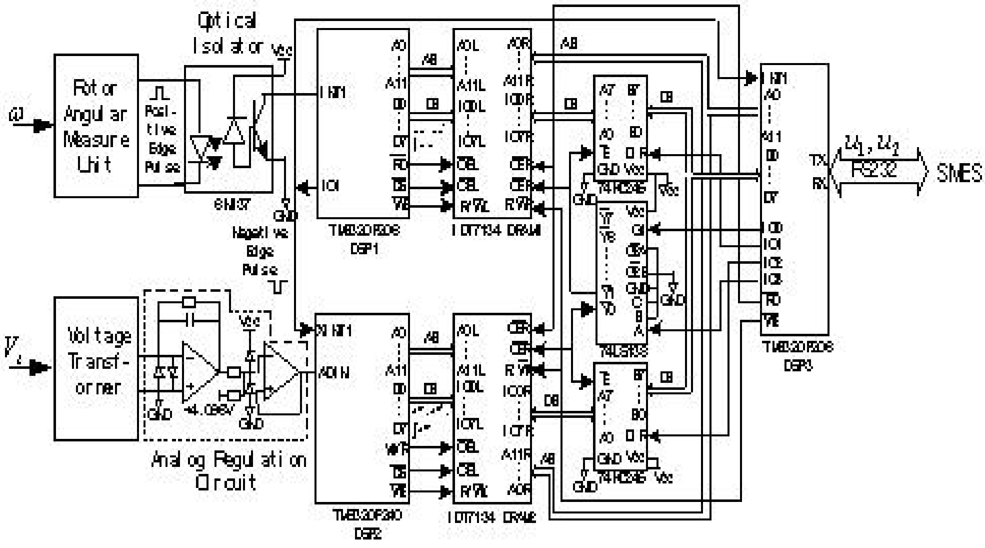

Figure 4. Circuit Configuration of nonlinear PID controller for SMES

4.2 Circuit Design and implementation of the Controller

Figure 4 shows the fundamental configuration of the controller considered in this paper, where AB and DB are address bus and data bus respectively. The main components are three digital signal processors (DSPs) and some auxiliary peripheral circuits.

In the figure, when the generator rotor move one cycle, a positive edge pulse will be generated by the rotor angular measure unit. This pulse will cause the external interrupt of the DSP1 instantly. With DSP1 responding the interrupt, it sends a negative edge pulse as external interrupt signal to both DSP2 and DSP3 at once. Thus the external interrupts of DSP2 and DSP3 will take place too. After the interrupts happen, DSP3 will wait for $\Delta\omega, \Delta\dot{\omega}, \int\Delta\omega$ and $\Delta V_t, \Delta\dot{V}_t, \int\Delta V_t$ until DSP1 and DSP2 work out these results and write them into the DRAMs. The deviations of rotor angular speed and generator terminal voltage can be computed according to the following equations:

$$\begin{cases} \omega = \pi / \Delta t \\ \Delta\omega = \omega - \omega_{ref} \\ \Delta V_t = V_t - V_{ref} \end{cases} \tag{20}$$

Where Δt is the time gap between two successive positive edge pulses. V_t is the actual value of generator terminal voltage which is sampled by DSP2 through analog regulation circuit and A/D convertor after the external interrupt of the DSP2 occuring. ω_{ref} and V_{ref} are the reference values. And in the light of Eqn. (5), $\Delta\omega, \Delta\dot{\omega}, \int\Delta\omega$ and $\Delta V_t, \Delta\dot{V}_t, \int\Delta V_t$ can also be worked out by DSP1and DSP2 respectively. Once the results of these variables are saved into the DRAMs , DSP3 will fetch them and produce the controller output u_1 and u_2 according to Eqn. (18) and Eqn. (19) immediately . u_1 and u_2 are transferred to the microprocessor of SMES from DSP3 through a high speed serial port (115.2Kbps).

4.3 Simulation Results

The fault considered here is a 0.1 second symmetrical three-phase short-circuit fault near the generator bus terminal followed by a successful reclosing. Fig.5 and Fig.6 show the effectiveness of the SMES unit with the proposed controller in controlling the rotor angle and the generator terminal voltage at two different operation conditions. 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 with th proposed controller, the oscillation of the powe system is damped out quickly and the stability c the power system is enhanced tremendously a the two different system operating condition On the contrary, without the SMES unit, th power system is prone to the occurrence of th oscillation under the fault. Especially, at t operation condition P_0 =1.2(p.u.), the generat loses its synchronization and the generat terminal voltage appears vibration after the fault. However, wi the SMES unit with the proposed controller, t rotor angle remains stable and the generat terminal voltage is kept in a reasonable variati . It also indicates that the stability limit of t power system is expanded successfully.

Fig.7 shows the contribution of the SMES unit with the proposed controller on controlling the rotor angle and the generator terminal voltage under another kind system disturbance, a on second +10% step-change of the mechanica torque T_m . The simulation results show tha under the action of the SMES unit with th proposed controller, the damping characteristi of the power system is enhanced considerably and the capability of the power system to preven fluctuation of the generator terminal voltage i also intensified.

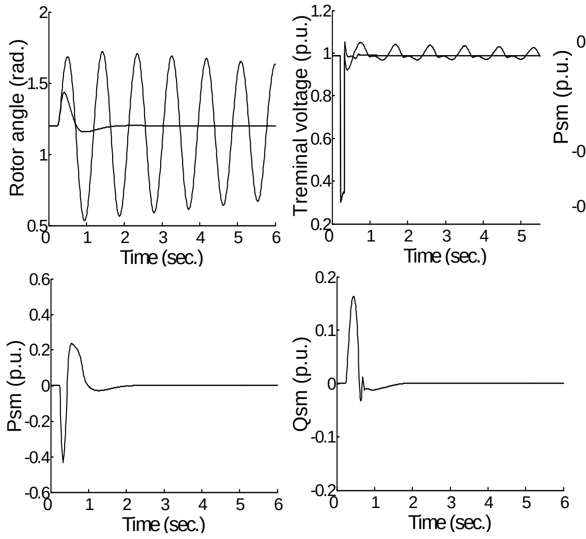

Figure 5. The response of the system under the fault (P_0=0.85(p.u.))Sold line: with the SMES using the proposed controller Dotted line: without the SMES

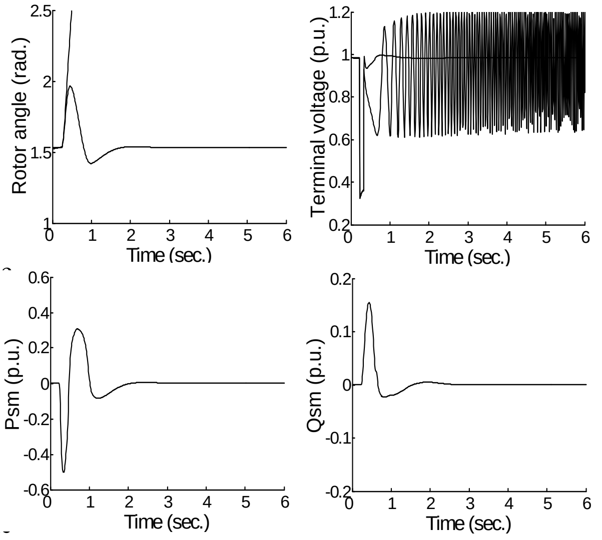

Figure 6. The response of the system under the fault (P_0=1.2(p.u.)) Sold line: with the SMES using the proposed controller Dotted line: without the SMES

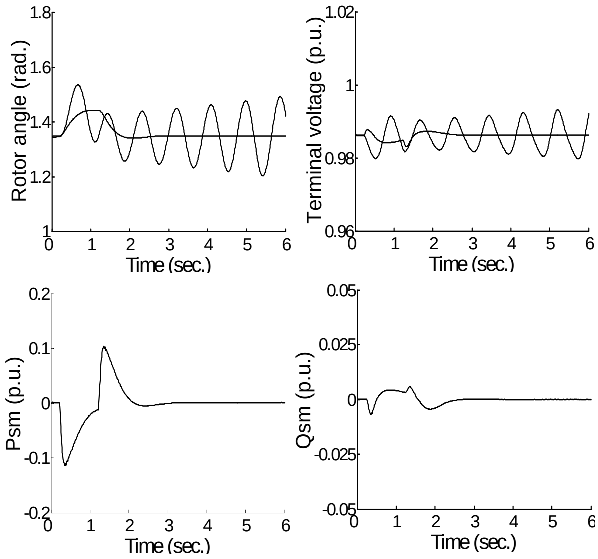

Figure 7. The response of the system under the instantaneous disturbance (P_0=1.0(p.u.)) Sold line: with the SMES using the proposed controller Dotted line: without the SMES

From the simulation results shown above, it is can be seen that the proposed controller for the SMES unit has the 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 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 show 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 is demonstrated as well.

6. ACKNOWLEDGEMENT

This work was supported by the High Tech Research & Development Programme of China, under Grant 2002AA306331.

7. 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

8. APPENDIX

The system data and the operating quantities in per unit are:

$x_d=1.79$ $x'_d=0.17$ $x''_d=0.12$ $x_q=1.71$
$x''_q=0.335$ $T'_{d0}=7.65\text{s}$ $T''_{d0}=0.0314$ $T''_{q0}=0.0623$
$D=0.2$ $X_{TL}=0.5$ $T=25\text{ms}$ $K_f=200$
$T_f=10\text{ms}$

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