Paper

Nonlinear Excitation Control of Two Sets of Adjustable Speed Generators/Motors at Rotary Type Frequency Converter Station for Performance Improvement of Power System Dynamics

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There are 50 Hz and 60 Hz power systems in Japan, which are interconnected by power electronics based static type frequency converter station. Frequency converter can be realized by using Adjustable Speed Generators/Motors (ASGMs), which are excited by AC voltage, and so-called rotary type frequency converter. The rotary type frequency converter can also function as a power system stabilizer by effectively utilizing rotational energy stored in rotors. Nonlinear excitation control for the rotary type frequency converter is proposed to enhance performance of the rotational energy utilization and to improve stability of power system. The control performance is examined for a power system model by digital dynamic simulation. It is made clear that the proposed nonlinear excitation control is effective even though local information of the rotary type frequency converter is just used and that it has robustness against various load flow conditions.

Keywords: adjustable speed generator/motor, frequency converter, power system, stability, nonlinear control

1. Introduction

With enthusiastic development of power electronics, several applications have been realized; adjustable speed generator/motor (ASGM) is an example of them, which has been applied to pumped storage power plant in Japan. With the same structure as an induction machine with AC excitation, the adjustable speed generator/motor can vary the angular speed and input/output power can be controlled rapidly by effective excitation control. It can enhance stability of power system and can also make it robust to some uncertainty by controlling active/reactive power appropriately [(1)~(4)].

Up to the present day, 50 Hz and 60 Hz power systems in Japan have been interconnected by power electronics based static type frequency converter station. According to the characteristics of ASGM, the frequency converter station can also be realized by using two sets of ASGMs and so-called rotary type frequency converter station. Actually it can commonly be realized by other rotary machines such as synchronous machine or even induction machine as K. Hu and et al. have proposed in Ref. (5). The rotary type frequency converter can not only function in power interchange between two power systems, but also enhance the power system stability and effectively utilize rotational energy for power system stabilization by appropriate excitation control. These functions do not exist in the static type frequency converter station. It is known that the rotary type frequency converter is favorable in aspect of overall cost compared with the newly self-commutated converter type frequency converter station and is expected to be advantageous in total system consideration.

Various control schemes of the rotary type frequency converter (eigenvalue based control method and energy function based control method) have been designed and proposed in Ref. (6), where it has been shown that those controllers can improve the stability of power system effectively. Most of them are the typical linear controllers which are based on the linearization using approximation of Taylor series expansion around a certain operating point. Effective operating regions of such controllers are in the neighborhood of the operating point and it is not guaranteed that at the point far from the operating point, the designed controllers are still effective and can function properly. Since power systems constantly experience changes in operating conditions due to variations in generation and load patterns, as well as changes in transmission networks and the frequency converter operates in various levels of power interchange, it seems necessary to find the more effective and robust control system for the rotary type frequency converter.

In recent years, nonlinear control theories have been employed to take into account the nonlinearity of power system. With the advance in the application of differential geometric techniques to control system design, the feedback linearizing control (FLC) has been introduced for power system control and has already made

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significant progress as can be seen in generator control [7][8], FACTS device (e.g. SVC, STATCOM) [9][10] and HVDC system [11]. FLC is not the approximated linearization as in the linear control methods; there is no disadvantage of linear control methods mentioned above. Since, subject to the availability of an accurate model and measurement of the power system, the nonlinear dynamics of the power system may be cancelled and replaced with some desired linear behavior in the control design, the FLC is suitable for the transient stability of power system and it can provide better performance than its linear counterpart when severe and sudden disturbances happen in the power system.

In this paper, nonlinear excitation control for the rotary type frequency converter is proposed by using FLC technique to linearize the nonlinear system, then, optimal control is incorporated to control the linearized system to achieve better performance in term of stability improvement by the rotary type frequency converter in power system. The proposed controller is applied to excitation system of ASGM(s) in the rotary type frequency converter in the power system, control performance, in both effectiveness and robustness, is examined by digital dynamic simulation.

2. Rotary Type Frequency Converter

2.1 Model of ASGM ASGM is a kind of rotating machines whose structure is similar to that of an induction machine, rotor windings are excited by AC voltage applied by cycloconverter or GTO inverter. By the similar derivation as Park model of synchronous machine, physical variables of ASGM such as linkage fluxes, voltage and current are transformed to be variables in the d, q axes coordinate system, which are rotating at the sum of the rotor angular speed ω_r and the frequency of the AC excitation voltage ω_c. A model of ASGM is expressed in Eq. (1)$\sim$(11). The equivalent circuit of ASGM is illustrated in Fig. 1.

$$\omega_0 \Psi_d = -(X_1 + X_m)\, i_d + X_m i_{fd} \quad \cdots\cdots (1)$$

$$\omega_0 \Psi_q = -(X_1 + X_m)\, i_q + X_m i_{fq} \quad \cdots\cdots (2)$$

$$\omega_0 \Psi_{fd} = -X_m i_d + (X_2 + X_m)\, i_{fd} \quad \cdots\cdots (3)$$

$$\omega_0 \Psi_{fq} = -X_m i_q + (X_2 + X_m)\, i_{fq} \quad \cdots\cdots (4)$$

$$v_d = -\omega \Psi_q + \dot{\Psi}_d/\omega_0 - R_1 i_d \quad \cdots\cdots (5)$$

$$v_q = \omega \Psi_d + \dot{\Psi}_q/\omega_0 - R_1 i_q \quad \cdots\cdots (6)$$

$$v_{fd} = -\omega_c \Psi_{fq} + \dot{\Psi}_{fd}/\omega_0 + R_2 i_{fd} \quad \cdots\cdots (7)$$

$$v_{fq} = \omega_c \Psi_{fd} + \dot{\Psi}_{fq}/\omega_0 + R_2 i_{fq} \quad \cdots\cdots (8)$$

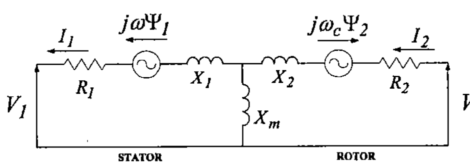

Fig. 1. Equivalent circuit of ASGM

$$P_m = \frac{\omega_r}{\omega_0}\left(e_{fd} i_d + e_{fq} i_q\right) \quad \cdots\cdots (9)$$

$$\dot{e'}_q = -\frac{\omega_0 R_2\left(e'_q + X_m i_d\right)}{X_m + X_2} - \omega_c e'_d + \omega_0 \frac{R_2 e_{fd}}{X_m} \quad \cdots\cdots (10)$$

$$\dot{e'}_d = -\frac{\omega_0 R_2\left(e'_d - X_m i_q\right)}{X_m + X_2} + \omega_c e'_q - \omega_0 \frac{R_2 e_{fq}}{X_m} \quad \cdots\cdots (11)$$

where X_1, X_2: stator and rotor leakage reactance, X_m: mutual reactance, R_1, R_2: stator and rotor resistance, e'_d, e'_q: d and q axes internal voltage, e_{fd}, e_{fq}: d and q axes excitation voltage, P_m: mechanical power, ω_0: synchronous angular speed [rad/s].

2.2 Model of Rotary Type Frequency Converter The configuration of the rotary type frequency converter is illustrated in Fig. 2. The rotary type frequency converter consists of two sets of ASGMs. Each stator of ASGM is connected to the power system. The windings of each rotor of ASGM are excited by AC voltage and two rotors are connected through the shaft mechanically.

Fig. 3 shows the mechanical model of the rotary type frequency converter, where the inertia of shaft can be neglected for simplicity. If both rotors are directly connected and the shaft torsional oscillatory phenomenon is disregarded, it can be considered that rotor angular speeds of both ASGMs are equal; thus mathematical expression can be represented in Eq. (12).

$$\frac{2H_T}{\omega_{r0}}\frac{d\omega_r}{dt} = -P_{mA} - P_{mB} - \frac{D_T}{\omega_{r0}}\left(\omega_r - \omega_{r0}\right) \quad \cdots\cdots (12)$$

where ω_{r0} is a reference rotor angular speed,

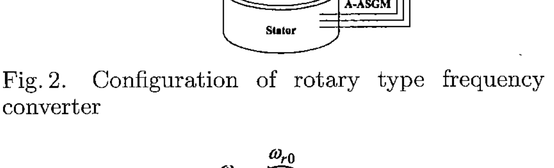

Fig. 2. Configuration of rotary type frequency converter

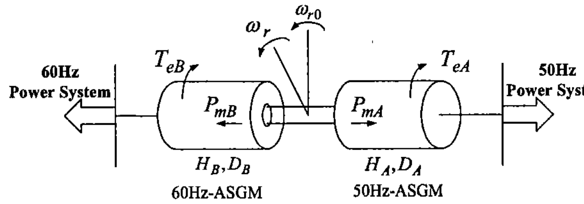

Fig. 3. Mechanical model

$H_T = H_A + H_B$ and $D_T = D_A + D_B$,
A, B are used for 50 Hz ASGM and 60 Hz ASGM.

3. Nonlinear Control Method

Since nonlinear system can be seen, in general, in the engineering world such as robot system, chemical processing, including power system, they can be all expressed in the following form.

$$\left.\begin{array}{l} \dot{X}(t) = F(X(t)) + \sum_{i=1}^{m} g_i(X(t))U_i \\ Y(t) = h(X(t)) \end{array}\right\} \cdots\cdots (13)$$

where $X \in R^n$ is state vector, U_i is control variables, $F(X)$ and $g_i(X)$ n-dimensional function vectors, $h(X)$ p-dimensional output function vector $(i = 1, 2, \ldots, m)$.

A nonlinear control system as in Eq. (13), possessing the feature that it is nonlinear to state vector $X(t)$ but linear to control variables U_i, is called an affine nonlinear system $(i = 1, 2, \ldots, m)$.

Based on nonlinear control theory, the nonlinear control scheme can be shown in Fig. 4. Firstly, taking into account the outputs of nonlinear system expressed in Eq. (13), and appropriate coordinate transformation obtained by FCL technique is employed to linearize the nonlinear system. At this point, nonlinearity in the system may be cancelled and replaced with some desired linear behavior in the control system design to which typical linear control method such as PID control, robust control and optimal control can be applied. Then, control values for the linearized system are determined and by employing the inverse coordinate transformation, the orginal control values can be calculated and feedback to the original nonlinear system. This algorithm is iterated every sampling time.

The main point of this algorithm is the appropriate coordinate transformation obtained by FLC technique. An image of linearization by the coordinate tranformation can be seen in Fig. 5 [12].

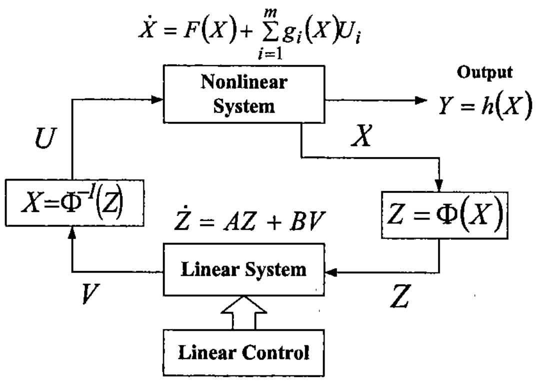

Fig. 4. Nonlinear control outline

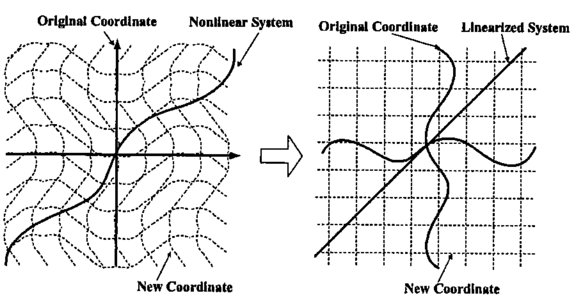

Fig. 5. Image of linearization by coordinate transformation

4. Nonlinear Excitation Control

4.1 Control Scheme By defining q_I-axis as the direction of internal induced voltage of ASGM and d_I-axis as the direction perpendicularly lagging behind q_I-axis, the excitation voltage of ASGM in the rotary type frequency converter can be divided into two components along those two axes. The active and reactive power of ASGM can be controlled via d_I-axis and q_I-axis components of the excitation voltage. In this paper, the following control scheme is proposed for excitation control of the rotary type frequency converter.

Change of d_I-axis component of the excitation voltage is used for the terminal voltage control of both ASGMs in the rotary type frequency converter in the form of the first order time constant lag transfer function as shown in Fig. 6. U_1 is a supplementary control value of d_I-axis excitation control system.

Change of q_I-axis component of the excitation voltage is used for the output power control of 50 Hz ASGM and rotor angular speed control for 60 Hz ASGM in the rotary type frequency converter in the form of the first order time constant lag transfer function as shown in Fig. 7 and Fig. 8, respectively. U_2 is a supplementary control value of q_I-axis excitation control system.

The supplementary control values U_1 and U_2 are determined by feedback linearizing control technique are shown in the next section.

4.2 Feedback Linearizing Control In this paper, nonlinear excitation control is applied to only 60 Hz ASGM in the rotary type frequency converter. The

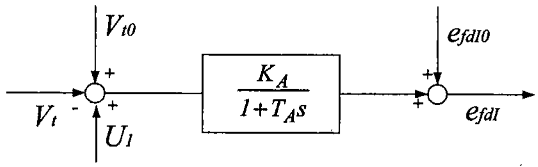

Fig. 6. d_I-axis excitation control system

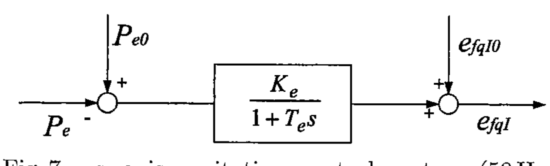

Fig. 7. q_I-axis excitation control system (50 Hz ASGM)

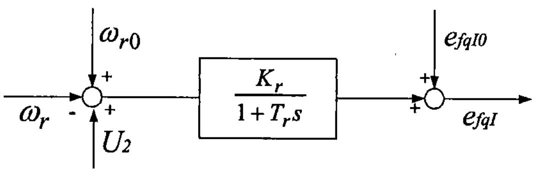

Fig. 8. q_I-axis excitation control system (60 Hz ASGM)

60 Hz ASGM system with the excitation controllers described in the previous section can be represented in the form of Eq. (13) with the following variables and parameters.

$$X = \begin{bmatrix} \delta - \delta_0 & \omega_r - \omega_{r0} & e'_q & e'_d & e_{fdI} & e_{fqI} \end{bmatrix}^T \quad \cdots\cdots (14)$$

$$F = \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \end{bmatrix}^T \quad \cdots\cdots (15)$$

$$U = \begin{bmatrix} U_1 & U_2 \end{bmatrix}^T \quad \cdots\cdots (16)$$

$$Y = \begin{bmatrix} h_1 & h_2 \end{bmatrix} = \begin{bmatrix} \delta - \delta_0 & V_t - V_{t0} \end{bmatrix} \quad \cdots\cdots (17)$$

where

$$f_1 = \omega_r + \omega_c - \omega_0 \quad \cdots\cdots (18)$$

$$f_2 = \frac{\omega_{r0}}{2H_T}\left[-P_{mA} - P_{mB} - \frac{D_T}{\omega_{r0}}(\omega_r - \omega_{r0})\right] \quad \cdots\cdots (19)$$

$$f_3 = -\frac{\omega_0 R_2 (e'_q + X_m i_d)}{X_m + X_2} - \omega_c e'_d + \frac{\omega_0 R_2 e_{fd}}{X_m} \quad \cdots\cdots (20)$$

$$f_4 = -\frac{\omega_0 R_2 (e'_d - X_m i_q)}{X_m + X_2} + \omega_c e'_q - \frac{\omega_0 R_2 e_{fq}}{X_m} \quad \cdots\cdots (21)$$

$$f_5 = -\frac{1}{T_A}\left[e_{fdI} + K_A V_t - (e_{fdI0} + K_A V_{t0})\right] \quad \cdots\cdots (22)$$

$$f_6 = -\frac{1}{T_r}\left[e_{fqI} + K_r \omega_r - (e_{fqI0} + K_r \omega_{r0})\right] \quad \cdots\cdots (23)$$

$$g_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & K_A/T_A & 0 \end{bmatrix}^T \quad \cdots\cdots (24)$$

$$g_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & K_r/T_r \end{bmatrix}^T \quad \cdots\cdots (25)$$

According to the feedback linearizing control technique (13)(14), the relative degrees with respect to the output variables of ASGM should be checked first. In this system, there are two output variables that are the change of rotor angle and the change of terminal voltage.

For the first output variable, $h_1(x) = \delta - \delta_0$:

$$\begin{aligned} & h_1(x) = \delta - \delta_0 \Rightarrow L_{g1}h_1(x) = L_{g2}h_1(x) = 0 \\ & L_F h_1(X) = \dot{\delta} = \omega_r - \omega_{r0} \Rightarrow L_{g1}L_F h_1(X) \\ & \qquad = L_{g2}L_F h_1(X) = 0 \\ & L_F^2 h_1(X) = \dot{\omega}_r \Rightarrow L_{g1}L_F^2 h_1(X) \\ & \qquad = L_{g2}L_F^2 h_1(X) = 0 \\ & L_F^3 h_1(X) = L_F \dot{\omega}_r = \alpha(X) \Rightarrow \\ & \left.\begin{aligned} L_{g1}L_F^3 h_1(X) &= \frac{\partial\alpha}{\partial X}\cdot g_1 = \frac{\partial\alpha}{\partial e_{fdI}}\cdot\frac{K_A}{T_A} = C_{11} \neq 0 \\ L_{g2}L_F^3 h_1(X) &= \frac{\partial\alpha}{\partial X}\cdot g_2 = \frac{\partial\alpha}{\partial e_{fqI}}\cdot\frac{K_r}{T_r} = C_{12} \neq 0 \end{aligned}\right\} \end{aligned} \quad \cdots\cdots (26)$$

where $L_F h(X) = \partial h(X)/\partial X \cdot F(X)$ is the Lie derivative of $h(X)$ along $F(X)$.

For the second output variable, $h_2(x) = V_t - V_{t0}$:

$$\begin{aligned} & h_2(X) = V_t - V_{t0} = L_{g1}h_2(X) = L_{g2}h_2(X) = 0 \\ & L_F h_2(X) = \dot{V}_t = \beta(X) \Rightarrow \\ & \left.\begin{aligned} L_{g1}L_F h_2(X) &= \frac{\partial\beta}{\partial X}\cdot g_1 = \frac{\partial\beta}{\partial e_{fdI}}\cdot\frac{K_A}{T_A} = C_{21} \neq 0 \\ L_{g2}L_F h_2(X) &= \frac{\partial\beta}{\partial X}\cdot g_2 = \frac{\partial\beta}{\partial e_{fqI}}\cdot\frac{K_r}{T_r} = C_{22} \neq 0 \end{aligned}\right\} \end{aligned} \quad \cdots\cdots (27)$$

Then

$$\begin{aligned} & \det\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \\ & = C_{11}C_{22} - C_{12}C_{21} \\ & = \frac{K_A K_r}{T_A T_r}\left(\frac{\partial\alpha}{\partial e_{fdI}}\cdot\frac{\partial\beta}{\partial e_{fqI}} - \frac{\partial\beta}{\partial e_{fdI}}\frac{\partial\alpha}{\partial e_{fqI}}\right) \\ & = \Gamma \neq 0 \end{aligned} \quad \cdots\cdots (28)$$

From Eqs. (26), (27) and (28) and based on nonlinear control theory, if Γ value is not equal to zero, the relative degrees with respect to those two output variables become 4 and 2, respectively. The equation for this value is so complicate that it is difficult to mathematically prove that this value is not equal to zero. However, it can be checked by digital dynamic simulation whether this condition is satisfied.

When this condition is satisfied, the sum of two relative degrees becomes 6 that is equal to the number of state variables in ASGM system, according to the FLC technique, the original nonlinear system in Eq. (13) can be completely linearized to be a linear system by the following coordinate transformation.

$$\Phi(X) = \begin{bmatrix} h_1 & L_F h_1 & L_F^2 h_1 & L_F^3 h_1 & h_2 & L_F h_2 \end{bmatrix}^T \quad \cdots\cdots (29)$$

The linearized system with the new state variables in Eq. (29) is expressed in Eq. (30).

$$\dot{Z} = AZ + BV \quad \cdots\cdots (30)$$

where

$$Z = \begin{bmatrix} \delta - \delta_0 & \omega_r - \omega_{r0} & \dot{\omega}_r & \alpha & V_t - V_{t0} & \beta \end{bmatrix}^T \quad \cdots\cdots (31)$$

$$V = \begin{bmatrix} V_1 & V_2 \end{bmatrix}^T \quad \cdots\cdots (32)$$

and

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \quad \cdots\cdots (33)$$

The linearized ASGM system can also be written in the following form.

$$\left.\begin{aligned}\dot{z}_1 &= z_2\\ \dot{z}_2 &= z_3\\ \dot{z}_3 &= z_4\\ \dot{z}_4 &= V_1 = a_1 + C_{11}U_1 + C_{12}U_2\\ \dot{z}_5 &= z_6\\ \dot{z}_6 &= V_2 = a_2 + C_{21}U_1 + C_{22}U_2\end{aligned}\right\} \cdots\cdots\cdots\cdots (34)$$

where

$$\left.\begin{aligned}a_1 &= L_F^4 h_1(X) = L_F\alpha(X)\\ a_2 &= L_F^2 h_2(X) = L_F\beta(X)\end{aligned}\right\} \cdots\cdots\cdots\cdots (35)$$

The derivation of above parameters are shown in details in Appendix 1. In Eq. (34), new control values of the linearized system are V_1 and V_2. Optimal linear control is adopted to determine the appropriate values of V_1 and V_2 which minimize a scalar performance index in the form shown in Eq. (36) [15].

$$J = \int_0^\infty \left(Z(t)^T QZ(t) + V(t)^T RV(t)\right) \cdots\cdots (36)$$

where Q and R matrices, both symmetric matrices, are positive semidefinite and positive definite, respectively.

Under the state feedback law, the control values are in the form of linear combination of state variables as shown in Eq. (37).

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = -\begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} \end{bmatrix} Z = -KZ \cdots\cdots\cdots\cdots (37)$$

In order to achieve the performance improvement of the rotary type frequency converter by utilizing the rotational energy effectively, the weighting matrix $Q = diag(1, 100000, 1, 1, 1, 1)$ and $R = diag(1, 1)$ are selected. The obtained K controller gain matrix in Eq. (37) is shown in Appendix 2.

Finally, using the inverse coordinate transformation, the original supplementary control value U_1 and U_2 can be calcultated by the following eqautions.

$$\left.\begin{aligned}U_1 &= \frac{(V_1 - a_1)C_{22} - (V_2 - a_2)C_{12}}{C_{11}C_{22} - C_{12}C_{21}}\\ U_2 &= \frac{(V_2 - a_2)C_{11} - (V_1 - a_1)C_{21}}{C_{11}C_{22} - C_{12}C_{21}}\end{aligned}\right\} \cdots\cdots (38)$$

It should be noted that all parameters used for calculating the supplementary control values are all local information of the rotary type frequency converter such as terminal voltage and rotor angular speed.

It can be seen that the denominator of the formula in Eq. (38) is the same as Γ value in Eq. (28). In case that this Γ value is equal to zero, the supplementary control values U_1 and U_2 cannot be determined because they become infinite. This fact guarantees that the simulation results can check the condition in Eq. (28) and the applicability of nonlinear excitation control simultaneously.

5. Numerical Results

5.1 Model of Power System The control performance of the proposed nonlinear excitation control for ASGM system in the rotary type frequency converter is examined in a power system shown in Fig. 9 [6]. This system consists of 50 Hz and 60 Hz power systems, which are interconnected by the rotary type frequency converter using two sets of ASGMs. The 6^{th} order Park's model of generators are used and AVR and governor are applied to all generators, but no power system stabilizer (PSS) is used in any generators. All loads are of constant impedance type. As for the rotary type frequency converter, excitation frequency of AC voltage is set to be -5 Hz for 50 Hz ASGM and $+5$ Hz for 60 Hz ASGM, then the reference angular speed of both ASGMs is 55 Hz.

5.2 Transient Simulation in case of Nonlinear Excitation Control in only 60 Hz ASGM In this section, the proposed nonlinear excitation control is applied to only 60 Hz ASGM. The following simulations are done to examine the control performance of nonlinear excitation control.

(1) Simulation Case 1 The 3LG fault with 70 ms duration is considered to occur at node 11 in 60 Hz system when there is no interchange power transferred between 50 Hz system and 60 Hz system. In order to compare the control performance of the proposed nonlinear excitation control to another linear control, power system stabilizer (PSS) designed by eigenvalue based control method [6] for the rotary type frequency converter is taken into account. The simulation results show the comparison of parameters in generators and ASGMs among without (U_1 and U_2 are set to be zero) and with the proposed nonlinear excitation control, and with PSS. As for generators, since 50 Hz system has only one generator, the result of only generator A in 50 Hz system is shown by rotor angular speed and the results of generators in 60 Hz system are shown by rotor angles with respect to that of generator 1. As for ASGMs, the output powers, terminal voltages and rotor angular speed are considered.

From simulation results in Fig. 10, when applying the proposed nonlinear excitation control to 60 Hz ASGM and comparing to when without it, the dampings of generators 2, 3 and 4 in 60 Hz system and generator A in 50 Hz system are all improved and the amplitudes of the oscillation are reduced in all generators. As for

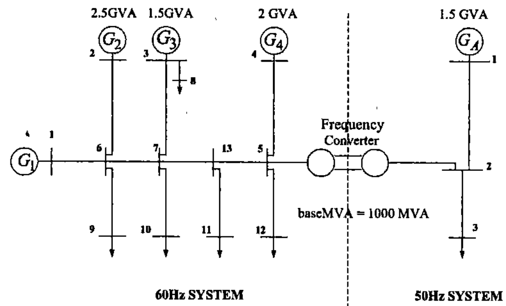

Fig. 9. Model power system

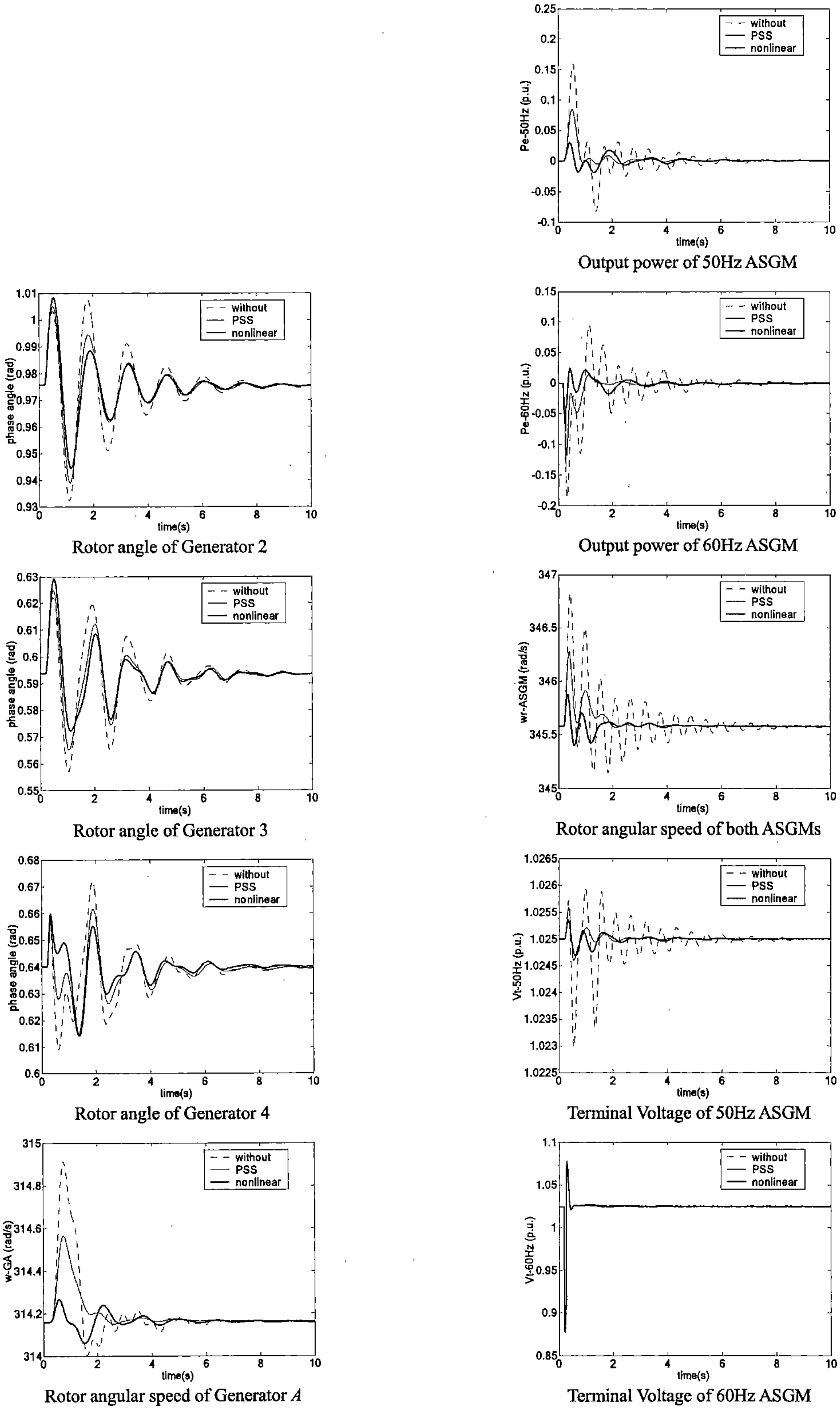

Fig. 10. Simulation results in Case 1

the rotary type frequency converter, dampings of 50 Hz ASGM and 60 Hz ASGM are improved as seen in output powers; the amplitudes of the oscillation are lessened. Voltage oscillations in 50 Hz ASGM are reduced, but those in 60 Hz ASGM seem to be unchanged.

The reason why the stability of generators in 50 Hz system and 60 Hz system are improved is described as follows:

In 50 Hz system, power flowing into system is affected by the nonlinear excitation control in 60 Hz ASGM and is regulated by APR controller in 50 Hz ASGM, which is shown in Fig. 7. It can be seen that the influence of fault in 60 Hz system becomes small.

In 60 Hz system, from 0 to 0.5 seconds, generators in

60 Hz system are in the swing-forth acceleration mode, as shown in the simulation results in Fig. 10. By the effect of the proposed nonlinear excitation control in 60 Hz ASGM and APR controller in 50 Hz ASGM, power absorbed by 60 Hz ASGM is lessened; hence the swing-forth acceleration of generators in 60 Hz system becomes larger that results in the slightly higher amplitudes of the oscillation. However, from 0.5 to 1.0 seconds, generators in 60 Hz system are in the swing-back acceleration mode, by the effect of the nonlinear excitation control, power absorbed by 60 Hz ASGM is maintained to be small; thus the swing-back acceleration is suppressed to become smaller.

From 1.0 to 2.0 seconds, generators in 60 Hz system are in the swing-forth acceleration mode again. In case of without the nonlinear excitation control, the 60 Hz ASGM releases power to 60 Hz system that results in hastening the acceleration. Conversely, the nonlinear excitation control attempts to make 60 Hz ASGM absorb power from 60 Hz system that will reduce the acceleration of 60 Hz system. According to the reason mentioned above, it can be said that the nonlinear excitation control is effective for improving the dampings of 60 Hz system.

The difference between power absorbed by 60 Hz ASGM from 60 Hz system and power released to 50 Hz system by 50 Hz ASGM is the power stored in the rotor (rotational energy). According to the reason mentioned above, when 60 Hz system is in the swing-back acceleration mode, ASGM attempts to release power to the system or slightly absorb power from the system. It is not necessary that the rotary type frequency converter absorbs much power and largely oscillates in order to improve the stability of 60 Hz system, but it actually attempts to absorb and supply power effectively for enhancing the stability of 60 Hz system. This is the effective utilization of rotational energy to improve power system dynamics.

When comparing the control performance of the proposed nonlinear excitation control with that of PSS designed based on eigenvalue based control method, it is clearly seen that the amplitudes of the oscillation in both ASGMs are smaller in case of the nonlinear excitation control as shown in the rotor angular speed and the dampings of generators in 60 Hz system become better; however, the amplitudes of the oscillation at the first swing of generators are larger according to the reason mentioned above. This comparison shows that the control performance of the proposed nonlinear excitation control is more effective, and by utilizing the rotational energy, the stability of 50 Hz and 60 Hz system is more highly improved.

As mentioned in the previous section, theΓvalue is not equal to zero because the nonlinear excitation control is effective for power system as seen in the simulation results, the change of this value in time domain is shown in Fig. 11. Fig. 12 shows the supplementary control values.

(2) Simulation Case 2 In the previous case, the 3LG fault duration, which defines the size of fault, is 70 ms; the nonlinear excitation control is effective in that condition. In order to check the control performance in aspect of effectiveness when the fault size becomes larger, the following simulation condition is taken into account.

In this case, the 3LG fault duration is changed from

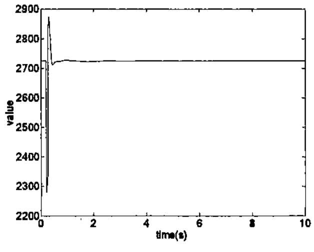

Fig. 11. Γ value

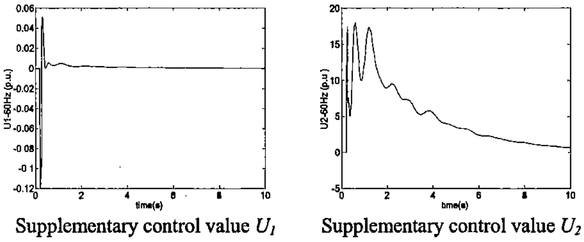

Fig. 12. Supplement control values

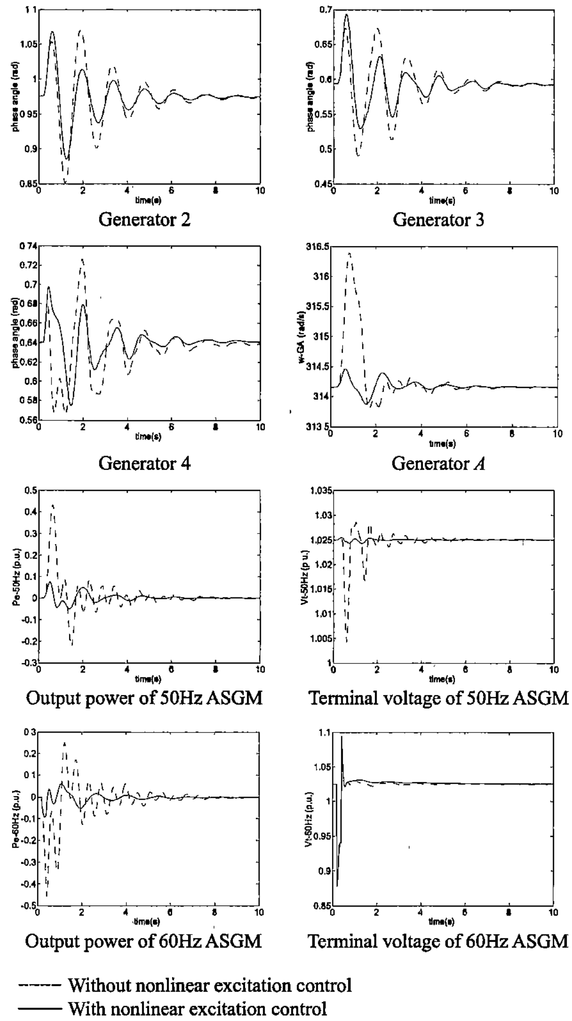

Fig. 13. Simulation results in Case 2

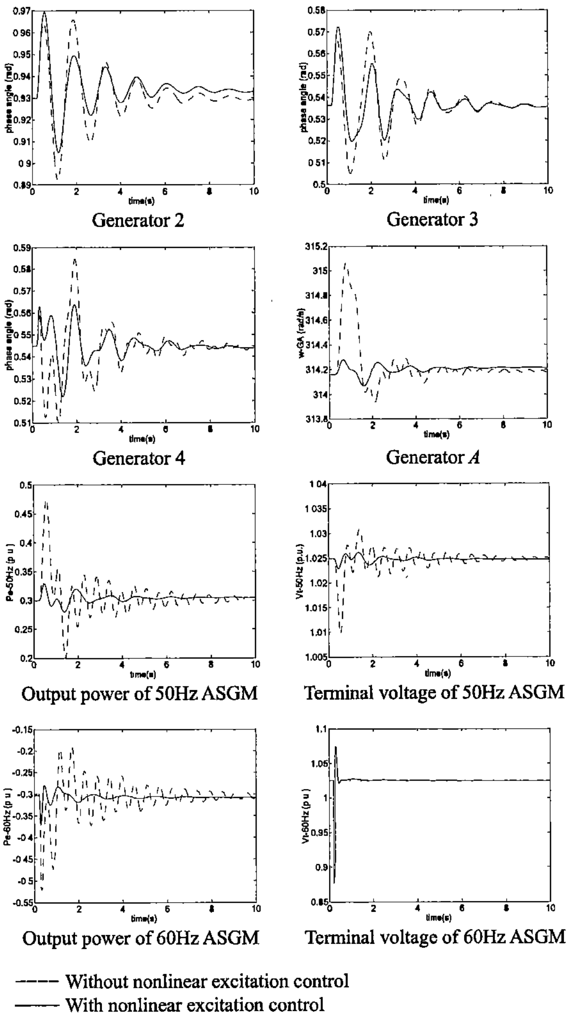

Fig. 14. Simulation results in Case 3

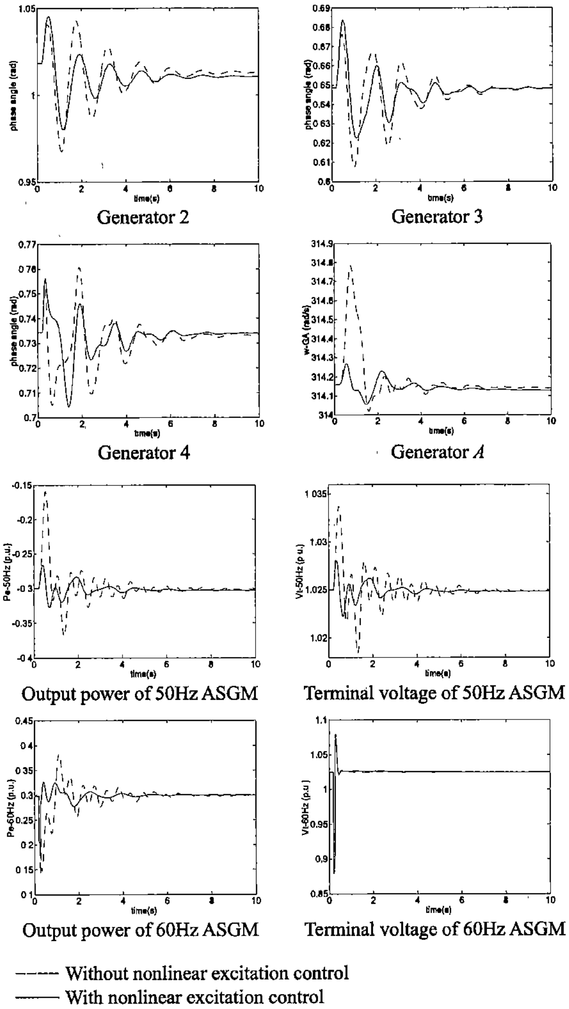

Fig. 15. Simulation results in Case 4

70 ms to 200 ms, and other conditions are the same as in Case 1.

From the simulation results in Fig. 13, when comparing with those in the Case 1, it can be seen that the shapes of responses are similar to those in Case 1, but with higher amplitude of oscillation. However, the nonlinear excitation control can improve the stability of the rotary type frequency converter, 50 Hz system and 60 Hz system. It can be said that the nonlinear excitation control has effectiveness to enhance the stability of power system even under the more severe condition.

(3) Simulation Case 3 Since frequency converters have to operate in different levels of power interchange between two systems, various load flow conditions have to be taken into account for the stability of the power system. Then, in this case, the interchange power from 60 Hz system to 50 Hz system is changed from 0 p.u. to 0.3 p.u., which is the maximum power transfer, and the other assumptions are the same as in Case 1.

From the simulation results in Fig. 14, it can be seen that the dampings of generator 2, 3 and 4 in 60 Hz system and generator A in 50 Hz system are all improved, and the amplitudes of oscillations are reduced, but the steady state errors appear in generator 2 and generator A, As for the rotary type frequency converter, the dampings of both ASGMs as seen in output powers become better and the amplitudes of the oscillations also become small. In this case, because of 0.3 interchange power from 60 Hz system to 50 Hz system and 3LG fault at node 11, the stability of the overall power seems to be worse, the slight steady state errors in rotor angle of generator 2 and angular speed of generator A indicate that the operating point shifts to the other position. The steady state error in angular speed of generator A is in the acceptable level. Thus, it can be said that the nonlinear excitation control is still effective for power system even in the maximum transfer condition.

(4) Simulation Case 4 In this case, it is assumed that interchange power is transferred from 50 Hz system to 60 Hz system by maximum transfer power 0.3 p.u. and other assumptions are the same as in Case 1. The simulation results are shown in Fig. 15.

From the simulation results in Fig. 15, the stability of generator 2, 3 and 4 in 60 Hz system and generator A in 50 Hz system are improved, but the steady state errors appear clearly in generator 2 and generator A as in Case 3. As for the rotary type frequency converter, the stability of both ASGMs is improved. It can be said that this nonlinear excitation control is effective for power system even in the maximum reverse transfer condition.

5.3 Discussion From the simulation results in Section 5.2, it can be discussed as follows.

The proposed nonlinear excitation control is effective for improving the performance of the rotary type frequency converter and enhancing the stability of the power system by utilizing rotational energy stored in the rotor more effectively even though using just local information of ASGMs, it also has robustness to various load flow conditions defined by distinct interchange power level and direction and to different fault durations.

In almost all the cases, only one-sided application of nonlinear excitation control in the rotary type frequency converter seems to be enough to handle various faults in the system. However, only one-sided application may not be effective for some contingencies; two-sided application should be taken into account to deal with those problems.

It is suggested that the performance of the proposed nonlinear excitation control may be improved by changing selection of weighting matrix Q and R in Eq. (36).

6. Conclusions

In this paper, nonlinear excitation control for the rotary type frequency converter using two sets of adjustable speed generators/motors is proposed and the control performance is examined in model power system by digital simulation. It is clear that the proposed nonlinear excitation control is effective, even though using just local information of ASGMs, for improving the performance of the rotary type frequency converter and for enhancing the stability of power system by effectively utilizing the rotational energy of the rotary type frequency converter. In addition, it also has robustness against different fault durations and various load flow conditions.

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Appendix

1. Nonlinear Control Parameters

In order to calculate the parameters for nonlinear excitation control, the following derivation is done.

The terminal voltage in the steady state can be calculated by Eqs. (1)∼(8), assuming that $\dot{\Psi}_d = \dot{\Psi}_q = 0$, then it can be expressed by Eq. (A1)

$$\left.\begin{aligned} v_d &= X_{eq} i_q + M e'_d - R_1 i_d \\ v_q &= -X_{eq} i_d + M e'_q - R_1 i_q \end{aligned}\right\} \cdots\cdots\cdots\cdots\cdots \text{(A1)}$$

where

$$X_{eq} = X_1 + \frac{X_2 X_m}{X_2 + X_m} \quad \text{and} \quad M = \frac{X_m}{X_2 + X_m} \cdots\cdots\cdots \text{(A2)}$$

The partial derivatives of currents with respect to the rotor angle of ASGM can be calculated by Eq. (A3).

$$\left.\begin{aligned} C_d &= \frac{\partial i_d}{\partial \delta} = i_q - M\left(B e'_d + G e'_q\right) \\ C_q &= \frac{\partial i_q}{\partial \delta} = -i_d + M\left(G e'_d - B e'_q\right) \end{aligned}\right\} \cdots\cdots \text{(A3)}$$

where $G + jB$ is a diagonal element corresponding to the ASGM of the reduced admittance matrix, which includes impedances of the ASGM and generators with detailed models.

The partial derivatives of currents with respect to internal voltages can be expressed by the following equations.

$$\left.\begin{aligned} D_{dd} &= \frac{\partial i_d}{\partial e'_d} = MG, \; D_{dq} = \frac{\partial i_d}{\partial e'_q} = -MB \\ D_{qd} &= \frac{\partial i_q}{\partial e'_d} = MB, \; D_{qq} = \frac{\partial i_q}{\partial e'_q} = MG \end{aligned}\right\} \cdots\cdots\cdots \text{(A4)}$$

The second-order derivative of currents with respect to the rotor angle and the internal voltages can be expressed by the following equations.

$$\frac{\partial C_d}{\partial \delta} = C_q \text{ and } \frac{\partial C_q}{\partial \delta} = -C_d \quad \cdots\cdots \text{(A5)}$$

$$\frac{\partial C_x}{\partial e'_z} = \frac{\partial D_{xy}}{\partial e'_z} = 0 \quad \cdots\cdots \text{(A6)}$$

where $x, y, z \in \{d, q\}$

The Parameters concerning the relative degrees of the ASGM system can be obtained as follows.

In Eq. (26), $\alpha(X)$ value can be determined by Eq. (A7)

$$\alpha(X) = -\frac{\omega_r}{2H_T}\left(\frac{D_T}{\omega_{r0}} f_2 + S(X)\right) \quad \cdots\cdots \text{(A7)}$$

and

$$S = S_1 f_1 + S_2 f_2 + S_3 f_3 + S_4 f_4 \quad \cdots\cdots \text{(A8)}$$

where

$$S_1(X) = \frac{\omega_r}{\omega_0} M\left(e'_d C_d + e'_q C_q\right) \quad \cdots\cdots \text{(A9)}$$

$$S_2(X) = \frac{1}{\omega_r}\left(P_{mA} + P_{mB}\right) \quad \cdots\cdots \text{(A10)}$$

$$S_3(X) = \frac{\omega_r}{\omega_0} M\left(i_q + e'_d D_{dq} + e'_q D_{qq}\right) \quad \cdots\cdots \text{(A11)}$$

$$S_4(X) = \frac{\omega_r}{\omega_0} M\left(i_d + e'_d D_{dd} + e'_q D_{qd}\right) \quad \cdots\cdots \text{(A12)}$$

In Eq. (27), $\beta(X)$ value can be obtained by Eq. (A13)

$$\beta(X) = J_1 f_1 + J_3 f_3 + J_4 f_4 \quad \cdots\cdots \text{(A13)}$$

where

$$J_1(X) = \frac{v_d}{V_t}\left(X_{eq} C_q - R_1 C_d\right) + \frac{v_q}{V_t}\left(-X_{eq} C_d - R_1 C_q\right) \quad \cdots\cdots \text{(A14)}$$

$$J_3(X) = \frac{v_d}{V_t}\left(X_{eq} D_{qq} - R_1 D_{dq}\right) + \frac{v_q}{V_t}\left(-X_{eq} D_{dq} + M - R_1 D_{qq}\right) \quad \cdots\cdots \text{(A15)}$$

$$J_4(X) = \frac{v_d}{V_t}\left(X_{eq} D_{qd} + M - R_1 D_{dd}\right) + \frac{v_q}{V_t}\left(-X_{eq} D_{dd} - R_1 D_{qd}\right) \quad \cdots\cdots \text{(A16)}$$

As for the parameters for linearized system, it can be determined as follows.

In Eq. (35), $a_1(X)$ value can be determined by Eq. (A17).

$$a_1(X) = -\frac{\omega_{r0}}{2H_T}\left(\frac{D_T}{\omega_{r0}}\alpha(X) + W(X)\right) \quad \cdots \text{(A17)}$$

and

$$W(X) = \sum_{i=1}^{6} W_i(X) f_i(X) \quad \cdots\cdots \text{(A18)}$$

where

$$W_1(X) = \frac{M\omega_r}{\omega_0}\left\{\left(e'_d C_q - e'_d C_q\right) f_1 + C_q f_3 + C_d f_4\right\} + N_1\left(-C_d S_3 + C_q S_4\right) + \frac{S_1}{\omega_r} f_2 - \frac{\omega_{r0} S_2 S_1}{2H_T} \quad \cdots\cdots \text{(A19)}$$

$$W_2(X) = S_1 + \frac{S_1}{\omega_r} f_1 - \frac{\omega_{r0} S_2}{2H_T}\left(\frac{D_T}{\omega_{r0}} + S_2\right) + \frac{S_3}{\omega_r} f_3 + \frac{S_4}{\omega_r} f_4 \quad \cdots\cdots \text{(A20)}$$

$$W_3(X) = \frac{\omega_r}{\omega_0} M\left(C_q f_1 + 2D_{qq} f_3\right) + \frac{S_3}{\omega_r} f_2 - \frac{\omega_{r0} S_2 S_3}{2H_T} + S_3 T_1 + S_4 T_2 \quad \cdots\cdots \text{(A21)}$$

$$W_4(X) = \frac{\omega_r}{\omega_0} M\left(C_d f_1 + 2D_{dd} f_4\right) + \frac{S_4}{\omega_r} f_2 - \frac{\omega_{r0} S_2 S_4}{2H_T} + S_3 T_3 + S_4 T_4 \quad \cdots\cdots \text{(A22)}$$

$$W_5(X) = \frac{N_2}{e'}\left(S_3 e'_q + S_4 e'_d\right) \quad \cdots\cdots \text{(A23)}$$

$$W_6(X) = \frac{N_2}{e'}\left(S_3 e'_d - S_4 e'_q\right) \quad \cdots\cdots \text{(A24)}$$

In Eq. (35), $a_2(X)$ value can be determined by Eq. (A17).

$$a_2(X) = \sum_{i=1}^{6} Q_i(X) f_i(X) \quad \cdots\cdots \text{(A25)}$$

where

$$Q_1(X) = N_1\left(-C_d J_3 + C_q J_4\right) + P_1 f_3 + P_2 f_4 + \frac{1}{V_t}\left(-v_d\left(X_{eq} C_d + R_1 C_q\right) + v_q\left(X_{eq} C_q + R_1 C_d\right) + \left(X_{eq}^2 + R_1^2\right)\left(C_d^2 + C_q^2\right) - J_1^2\right) f_1 \quad \cdots\cdots \text{(A26)}$$

$$Q_2(X) = J_1 \quad \cdots\cdots \text{(A27)}$$

$$Q_3(X) = P_1 f_1 + J_3 T_1 + J_4 T_2 + \frac{1}{V_t}\left(M^2 - 2M\left(X_{eq} D_{dq} + R_1 D_{qq}\right) + \left(X_{eq}^2 + R_1^2\right)\left(D_{dq}^2 + D_{qq}^2\right) - J_3^2\right) f_3 \quad \cdots\cdots \text{(A28)}$$

$$Q_4(X) = P_2 f_1 + J_3 T_3 + J_4 T_4 + \frac{1}{V_t}\left(M^2 + 2M\left(X_{eq} D_{qd} - R_1 D_{dd}\right) + \left(X_{eq}^2 + R_1^2\right)\left(D_{dd}^2 + D_{qd}^2\right) - J_4^2\right) f_4 \quad \cdots\cdots \text{(A29)}$$

$$Q_5(X) = \frac{N_2}{e'}\left(J_3 e'_q + J_4 e'_d\right) \quad \cdots\cdots \text{(A30)}$$

$$Q_6(X) = \frac{N_2}{e'}\left(J_3 e'_d - J_4 e'_q\right) \quad \cdots\cdots \text{(A31)}$$

The value of parameters appearing in the above equations can be obtained by the following relations.

$$e' = \sqrt{e'^2_d + e'^2_q} \quad \cdots\cdots \text{(A32)}$$

$$N_1 = \omega_0 R_2 M \text{ and } N_2 = \frac{\omega_0 R_2}{X_m} \cdots\cdots\cdots\cdots \text{(A33)}$$

$$T_1(X) = -N_1\left(\frac{1}{X_m} + D_{dq}\right) - \frac{e'_d N_2}{e'^2} e_{fq} \cdots\cdots\cdots\cdots\cdots\cdots \text{(A34)}$$

$$T_2(X) = \omega_c + N_1 D_{qq} - \frac{e'_d N_2}{e'^2} e_{fd} \cdots\cdots\cdots \text{(A35)}$$

$$T_3(X) = -\omega_c - N_1 D_{dd} + \frac{e'_q N_2}{e'^2} e_{fq} \cdots\cdots\cdots \text{(A36)}$$

$$T_4(X) = -N_1\left(\frac{1}{X_m} - D_{qd}\right) + \frac{e'_q N_2}{e'^2} e_{fd} \cdots\cdots\cdots\cdots\cdots\cdots \text{(A37)}$$

$$P_1(X) = \frac{1}{V_t}\left(-M\left(X_{eq}C_d + R_1 C_q\right) + \left(X_{eq}^2 + R_1^2\right)\left(C_d D_{dq} + C_q D_{qq}\right) - J_1 J_3\right) \cdots\cdots\cdots\cdots\cdots\cdots \text{(A38)}$$

$$P_2(X) = \frac{1}{V_t}\left(M\left(X_{eq}C_q - R_1 C_d\right) + \left(X_{eq}^2 + R_1^2\right)\left(C_d D_{dd} + C_q D_{qd}\right) - J_1 J_4\right) \cdots\cdots\cdots\cdots\cdots\cdots \text{(A39)}$$

Finally, the Γ value in Eq. (29) can be calculated by Eq.(A40).

$$\Gamma = \frac{\omega_{r0}}{2H_T} N_2^2 \left(S_3 J_4 - S_4 J_3\right) \cdots\cdots\cdots\cdots\cdots \text{(A40)}$$

2. ASGM and Control Parameters

(1) ASGM parameters

Parameters	Values [p.u.]
X_1	0.123
X_2	0.143
R_1	0.00126
R_2	0.00102
X_m	3.25
H	5[sec]
Capacity	300 [MVA]

(2) Control parameters

50Hz ASGM	K_A	100.0	K_e	10.0
	T_A	0.010	T_e	0.10
60Hz ASGM	K_A	100.0	K_r	0.40
	T_A	0.010	T_r	0.10

(3) Optimal controller gain matrix

$$K = \begin{bmatrix} 1 & 316.52 & 93.05 & 13.68 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1.732 \end{bmatrix}$$

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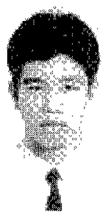

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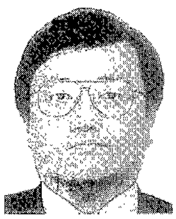

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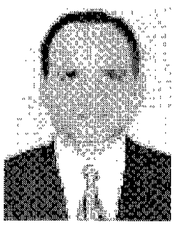

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