Controller Design for Static Reactive Power Generator in Transmission System

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Abstract -- This paper describes a controller design for the static reactive power generator in the transmission system. The controller of static reactive power generator was designed using a mathematical model and non-linear state feedback. The performance of controller was verified using computer simulation with EMTP code and experimental work with scaled-model. The dynamic interaction with a simple power system was also analyzed using both the simulation model and hardware scaled-model. Both simulation and experimental results prove that the controller using PI block and non-linear state feedback offers better performance than the controller using PI block only.

Key Words : FACTS (Flexible AC Transmission System), SRPG(Static Reactive Power Generator), EMTP (Electro-magnetic Transients Program), TACS(Transient Analysis of Control System), PI(Proportional Integral)

I. INTRODUCTION

FACTS was proposed by Electric Power Research Institute [1,2] to improve the dynamic performance of power transmission system. Several FACTS equipment are readily available or still under development, based on the solid-state switch with conventional thyristors and the voltage source inverter with GTO thyristors. All these equipment provide controllability to the ac transmission system by adjusting the reactive power in shunt, the series impedance of transmission line, or the active and reactive power in series.

The SRPG was proposed by several researchers [3,4,5] to compensate the reactive power in power systems. It can draw or supply the reactive current from or to the power system. This function is identical to the synchronous condenser with rotating mass, but its response time is extremely faster than that of the synchronous condenser. This rapidity is very effective to increase transient stability, to enhance voltage support, and to damp low-frequency oscillation for the transmission system.

In this paper a controller design using mathematical model and non-linear state feedback is described. The performance of controller was verified using computer simulations with EMTP code and experimental works with a hardware scaled-model. Many simulations and experimental works are also performed to analyze the dynamic interaction with the transmission system and to verify the increasi capability of power transmission.

II. BASIC OPERATION

The SRPG is composed of a voltage-source inverter wi a dc capacitor, coupling transformer, and signal generati and control circuit. The voltage-source inverter has sever modules connected in parallel and operates in multi-pul mode to reduce the harmonic level of the output voltage. Ideally the inverter output voltage is in phase with tl voltage at the common connection point. The SRPG c control the reactive power at the common connection poi by changing the inverter firing-angle only. The dc capacit is required to maintain energy balance between the ac and terminal so that it can draw or supply the required reacti power.

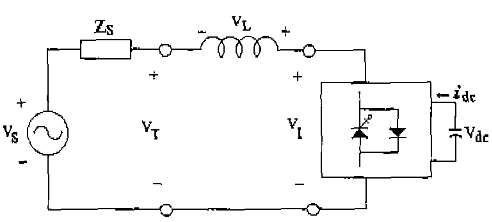


Fig. 1. SRPG operation principle

Fig. 1 shows a single-phase equivalent circuit in which th SRPG is connected to the ac transmission system. Th exchange of the active and reactive power between th inverter and the ac power system can be controlled b changing the phase angle between the inverter outp voltage and the bus voltage at the common connection poin The SRPG supplies reactive powers to the ac system if th magnitude of V_I is greater than that of V_T. It draws reactiv power from the ac system if the magnitude of V_T is greate than that of V_I.

Fig. 2 shows the phasor diagrams for steady states i capacitive and inductive mode, and for transition states fron capacitive to inductive or inductive to capacitive mode. Th terminal voltage V_T is equal to the sum of the inverte voltage V_I and the voltage across the coupling transforme V_L in both capacitive and inductive mode. The transitio from capacitive to inductive mode occurs by changing the firing angle from zero to positive value. The active power is transferred from the dc capacitor to the terminal and makes the dc link voltage drop. The transition from inductive to capacitive mode occurs by changing the firing angle from zero to negative value. The active power is transferred from the terminal to the dc capacitor and makes the dc link voltage rise.

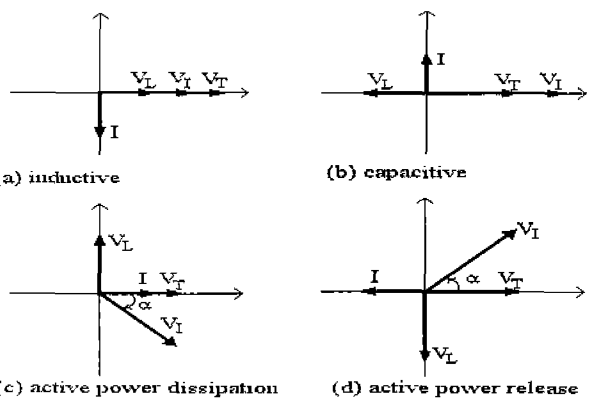


Fig. 2. SRPG phasor diagram

In the actual SRPG there are some losses in the transformer windings and the inverter switches. These losses consume the active power from the ac terminal in steady state operation. Because of these losses, a slight phase difference between the inverter voltage and the terminal voltage exists.

II. CONTROLLER DESIGN

Fig. 3 shows an equivalent circuit for the SRPG connected to the transmission line. The inductances in series account for the leakage of the coupling transformer, while the resistances in series represent conduction losses of the inverter and transformer. The circuit also includes a resistance in shunt with the capacitor to represent the switching losses of the inverter.

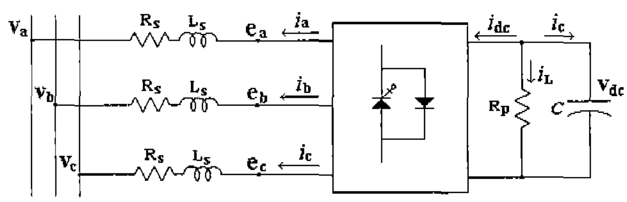


Fig. 3. Three-phase equivalent circuit

The three circuit equations in the ac side can be derived from Fig. 1 for each phase using Kirchhoff's voltage law. Two circuit equations in the dc side are derived from a power balance relationship between the ac and dc side, and applying Kirchhoff's current law for the dc node.

The inverter output voltage is assumed to have a linear relationship to the dc link voltage by neglecting the voltage harmonics produced in the inverter.

Applying d-q transform for the ac circuit and combining the dc circuit equation, the transformed state-equations for the SRPG is obtained as the following,

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & 0 & 0 \\ 0 & -\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_s}{L_s} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} (e_a - v_a) \\ (e_b - v_b) \\ (e_c - v_c) \end{bmatrix} \quad (1)$$

where, m is the ratio for the dc link voltage to the maximum phase voltage of the inverter and $|v_T|$ is d-q transform of v_{Ta}, v_{Tb}, v_{Tc}.

The state equation is non-linear regarding to the input variable α. However, the variations of i_d, i_q, and v_{dc} are linear with respect to small deviations of α about a steady-state equilibrium point. The perturbation equations about an equilibrium point of α_0 can be derived by neglecting second order terms as shown in the following,

$$\frac{d}{dt}\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & \frac{m\cos\alpha_o}{L} \\ -\omega & -\frac{R}{L} & \frac{m\sin\alpha_o}{L} \\ -\frac{3}{2C}m\cos\alpha_o & -\frac{3}{2C}m\sin\alpha_o & -\frac{1}{R_l C} \end{bmatrix}\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta v_{dc} \end{bmatrix} \quad (2)$$

$$+\begin{bmatrix} -\frac{1}{L} & -\frac{m v_{dco}\sin\alpha_o}{L} \\ 0 & -\frac{m v_{dco}\cos\alpha_o}{L} \\ 0 & \frac{3}{2C}m(i_{dco}\sin\alpha_o - i_{qo}\cos\alpha_o) \end{bmatrix}\begin{bmatrix} \Delta v_T \\ \Delta\alpha \end{bmatrix}$$

where, Δv_T is a differential of v_T.

The transfer function of $\Delta i_q(s)/\Delta\alpha(s)$ at two equilibrium points in the capacitive and inductive operation can be obtained from the equation (2) by a numerical computation. In this paper it is assumed that a SRPG with a rating of 200 MVA is connected to an 154 kV transmission system. The parameters required in the state equation (2) are shown in the following.

$L = 94.4mH$, $C = 12.7\mu F$, $R = 2.37\Omega$, $R_l = 18626\Omega$

$V_o = 88.9\ KV$, $m = 1.273$, $i_{qo} = \pm 750\ A$

Two transfer functions of $\Delta i_q(s)/\Delta\alpha(s)$ about an equilibrium point of -0.7° for capacitive operation and +0.7° for inductive operation are obtained using numerical computation as shown in the following.

(a) capacitive operation : $\alpha_o = -0.7^o$

$$\frac{\Delta i_q(s)}{\Delta\alpha(s)} = \frac{2894(s+8.2+j1326.6)(s+8.2-j1326.6)}{(s+23.8)(s+15.4+j1473)(s+15.4-j1473)}$$

(b) inductive operation : $\alpha_o = +0.7^o$

$$\frac{\Delta i_q(s)}{\Delta\alpha(s)} = \frac{2110(s+10.8+j1553.7)(s+10.8-j1553.7)}{(s+23.8)(s+15.4+j1473)(s+15.4-j1473)}$$

The Bode plots of the above two transfer functions are analyzed using MATLAB to confirm system stabilities. The results show that the system is stable in capacitive operation, but unstable in inductive operation, which is shown in Fig 4a.

A nonlinear state feedback is applied to improve stability margins [6]. The nonlinear feedback function $\Delta i_q'$ was defined as the following equation.

$$\Delta i_q' = \Delta i_q - g\,[\,i_{q0} - \hat{i}_{q0}\,] * \Delta v_{dc} \tag{3}$$

where, g is a gain factor to be set by simulation and $\hat{i}_{qo}$ is the critical reactive current defined as the following.

$$\hat{i}_{qo} = \frac{2\omega C}{3m} v_{dco} \tag{4}$$

Two transfer functions of $\Delta i_q'(s)/\Delta\alpha(s)$ about an equilibrium point of -0.7° in capacitive operation and +0.7° in inductive operation are obtained using numerical computation as shown in the following.

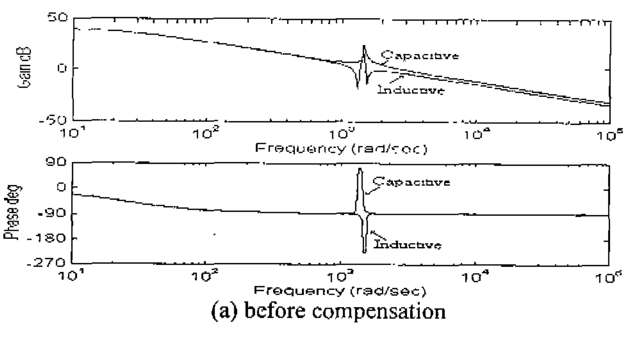
(a) capacitive operation : $\alpha_o = -0.7^o$

$$\frac{\Delta i'_q(s)}{\Delta\alpha(s)} = \frac{4736(s+14.7+j842.8)(s+14.7-j842.8)}{(s+23.8)(s+15.4+j1473)(s+15.4-j1473)}$$

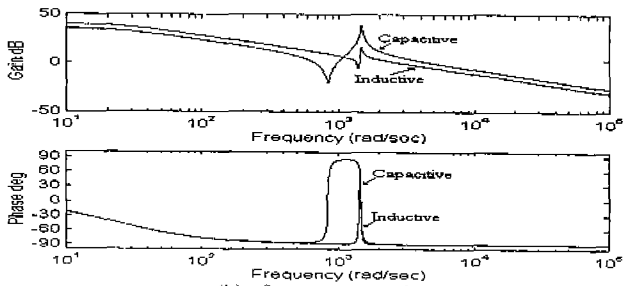
(b) inductive operation : $\alpha_o = +0.7^o$

$$\frac{\Delta i'_q(s)}{\Delta\alpha(s)} = \frac{2869(s+14.6+j1417.6)(s+14.6-j1417.6)}{(s+23.8)(s+15.4+j1473)(s+15.4-j1473)}$$

The Bode plot for each operation is prepared using MATLAB as shown in Fig. 4b. In both capacitive and inductive operation the system is.



(a) before compensation



(b) after compensation

Fig. 4. Bode plot for $\Delta i_q'(s)/\Delta\alpha(s)$

In the actual controller design a first-order time delay element is considered for the non-linear state feedback loop to eliminate the saturation effect in the dc capacitor voltage. And a proportional and integral compensation element is added to obtain zero steady-state error in i_q. Fig. 5 shows a control block diagram for the SRPG considering the above.

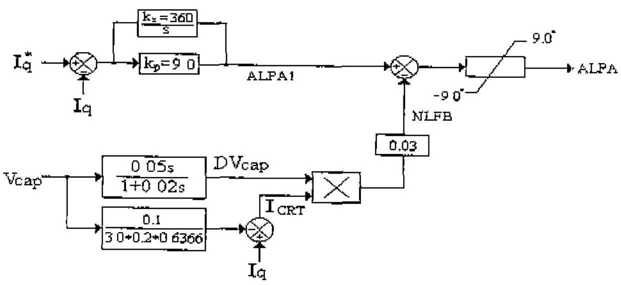


Fig. 5. SRPG controller

IV. EMTP SIMULATION

The EMTP is very effective to test the control system and analyze the interaction between the SRPG and the ac transmission system [7]. Normally the actual SRPG consists of a 48-pulse inverter to reduce the level of harmonics in the output voltage. However, the simulation model consists of a 12-pulse voltage-source inverter with two 6-pulse bridges connected in parallel to save the simulation time without neglecting the simulation effect. The bus voltage is detected and its zero-crossing point is used as a reference point to generate the gate signals. Since the bus voltage changes as the reactive power is regulated, a phase-locking procedure has to be considered.

The control circuit shown in Fig. 5 is modeled using the TACS. Three input currents into the inverter are measured and converted to d and q components. The q component current is compared with the reference reactive current i_q^*. The difference is provided into the PI controller to generate the firing angle. The voltage across the dc capacitor is measured and provided into a first order time delay element and amplifier to calculate the critical reactive current $\hat{i}_{qo}$. This critical current is compared with the measured reactive current i_q , and the difference is multiplied by the output of the time delay element to calculate the adjustment value of firing angle.

A typical case was considered that the SRPG controls the reactive power in the 154 kV transmission line. The power system was represented by one machine connected to the infinite bus as shown in Fig. 6.

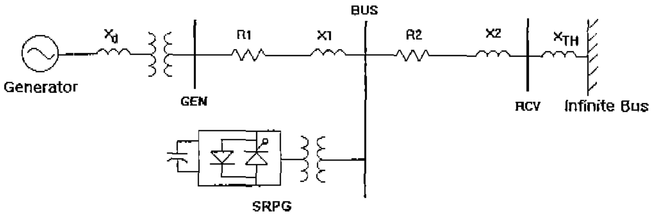
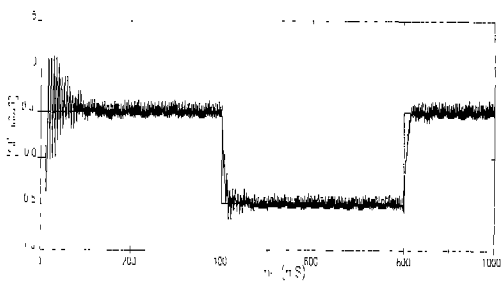


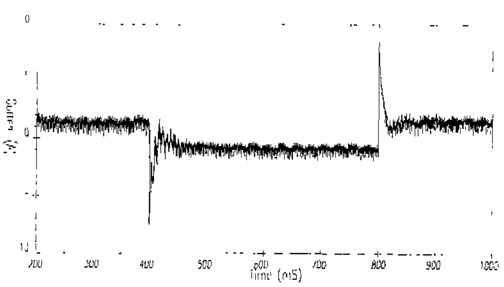
Fig. 6. Simulation model for dynamic interaction

The generator with the output voltage of 13.8 kV is connected to the transmission line through a three-phase step-up transformers. The generator was represented by a synchronous machine model in the EMTP. The 154 kV transmission line, whose length was assumed to be 160 km, was modeled by distributed parameters in the EMTP.

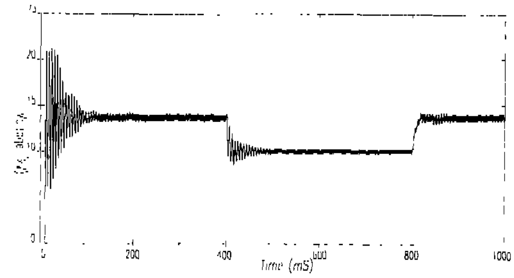
The scenario considered in this simulation is as the following. The SRPG starts to operate at t=0 for charging the dc capacitor until the dc link voltage of the inverter reaches 14 kV. Then it starts to operate at t=100 ms to supply the leading reactive power. The leading reactive power supplied from the SRPG is changed to the lagging reactive power at t=400 ms and changed to the leading reactive power again at t=800 ms. The simulation is completed at 1000 ms for the purpose of saving the computer running time.



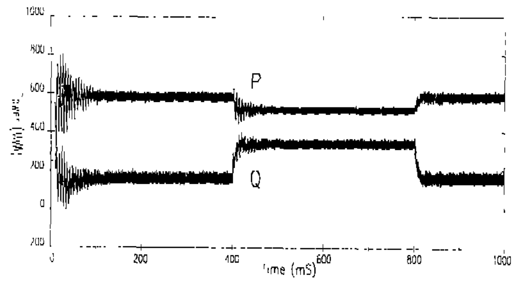
(a) reactive current



(b) inverter firing angle



(c) dc capacitor voltage



(d) transmitted active and reactive power

Fig. 7. Simulation results

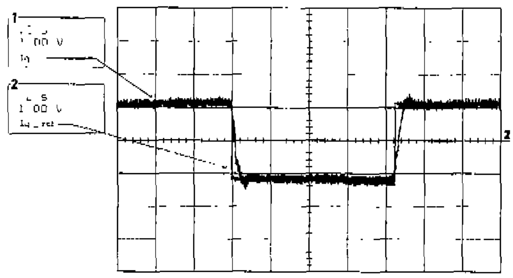
Fig. 7a shows a simulation result that the output reactive current of the SRPG follows the reference reactive current which is expressed by a straight line. This result shows that the control system of the SRPG works properly to regulate the reactive power required at the ac power system. The transients from 0-70 ms is due to the hard start-up for charging dc capacitor. Fig. 7b shows the variation of the firing angle during the operation. From 0-100 ms, the firing angle goes up to 8° in order to charge the dc capacitor up to 14 kV. After the dc link voltage builds up, the firing angle is maintained about 0.7° to compensate the inverter losses. It goes down to -7° at 400 ms and it maintains -0.7° from 400-800 ms. It goes up to 8° at 800 ms to response for the variation of reactive power. Fig 7c shows the variation of dc capacitor voltage. The voltage maintains at 14kV to supply leading reactive power and at 10kV to supply lagging reactive power from 400-800ms. After 800ms it is goes back to 14kV. Fig. 7d shows the active and reactive power transmitted through the transmission line. As expected, the transmitted active power decreases in the inductive operation and increases in the capacitive operation.

V. SCALED-MODEL EXPERIMENT

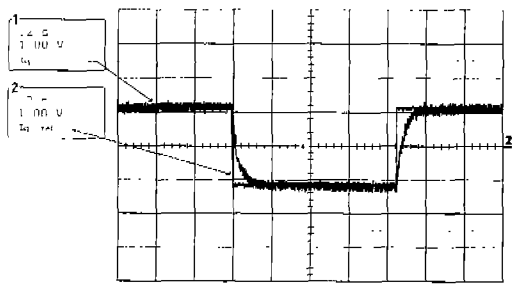
A hardware scaled-model of 2kVA rating has been built to verify the operation of controller and to confirm the simulation results. Instead of using 8 voltage-source inverter module in parallel, PWM scheme was used to reduce the hardware size. An Intel 80C196KC microprocessor system was built to implement the non-linear state feedback control for the calculation of firing angle and to generate switching pulses. This system contains 16-bit internal registers with

488 byte capacity, two timer and counter, one HSI(high speed input) for detecting input pulse width, one HSO(high speed output) for generating the output pulse with arbitrary width, 8 A/D channel, and 4 serial ports.

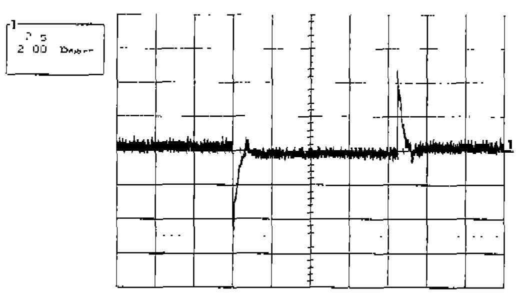
The power circuit model has built to simulate the generator, transmission line, and infinite bus with a voltage scale of 1/1000. A three-phase voltage-source inverter with diode bridge converter was built to simulate the generator, and two three-phase reactors were used to simulate the transmission line. It is assumed that the 3-phase power outlet operates as the infinite bus.



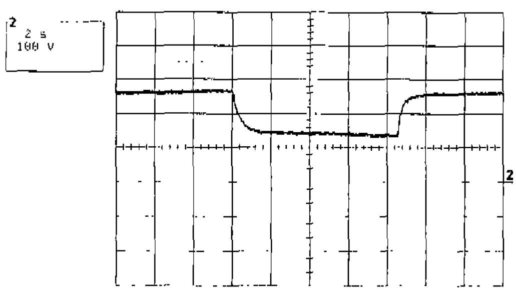
(a) reactive current (proposed)



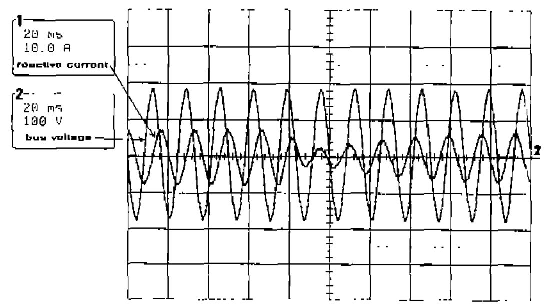
(b) reactive current (PI control)



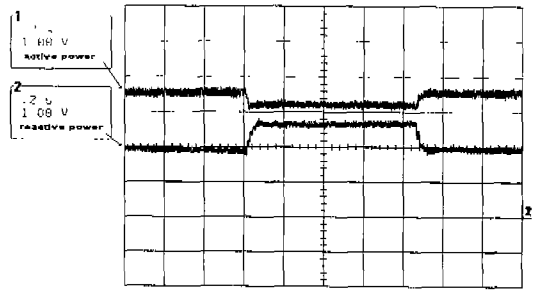
(c) inverter firing-angle



(d) dc capacitor voltage



(e) reactive current and bus voltage



(f) transmitted active and reactive power

Fig. 8. Experimental results

Fig. 8 shows the experimental results for the scaled mod of ARPG with the proposed controller with non-linear sta feedback. Fig. 8a shows that the output reactive curre follows the reference reactive current properly. Fig. 8 shows the tracking characteristic of the reactive current i case of using PI control only. It is conclude that th proposed controller provides much faster tracking than th controller with PI only. Fig. 8c shows the variation of firin angle during the whole operation. It goes down to -7° fc adapting the state transition from the capacitive to inductiv operation. And it maintains -0.7° for 700 ms and goes up t 8° to response for the variation of reactive power. Fig 8 shows the variation of dc capacitor voltage. The voltag maintains at 180V to supply leading reactive power and a 60V to supply lagging reactive power for 800ms. Afte 800ms it is goes back to 180V to supply leading reactiv power. Fig. 7e shows the variation the bus voltage and th reactive current at the connection point. The current into th SRPG leads the bus voltage by 90°. And it suddenly change from capacitve to inductive state by changing the firin angle, which takes about one cycle of power frequency. Fig 7f shows the active and reactive power transmitted throug the transmission line. As expected, the transmitted activ power decreases in the inductive operation and increases ir the capacitive operation.

VI. CONCLUSION

In this paper a controller for the SRPG was designed wit mathematical model by considering the non-linear stat feedback. A simulation model with the EMTP codes wa developed to verify the controller operation and to analyze the interaction between the SRPG and the ac transmission system.

The controller operation and the dynamic interaction with a simple power system were also analyzed using by experimental work with scaled-model. It is proven that the experimental results are exactly coincidence with the simulation results. The controller using PI block and non-linear state feedback offers better performance than the controller using PI block only.

The developed simulation model would be very effective to evaluate the performance of the SRPG connected in the ac transmission system and to obtain design parameters for the actual SRPG hardware system.

ACKNOWLEDGMENT

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