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An Intelligent Controller for the Integrated Generation Control System

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Abstract—This paper proposed an integrated generation control system and, more particularly, to an integrated generation control system for enhancing the dynamic stability of a generation system or the stability of the output from generators operated in parallel. This paper also proposed fuzzy rules of a fuzzy-sliding filament model for the integrated generation control system.

Keywords—automatic voltage regulator (AVR), power system stabilizer (PSS), fuzzy-sliding filament model, integrated generation control system

I. INTRODUCTION

This is especially the case in the context of the quickly growing integration of distributed generation and loads into power transmission and distribution networks. Much previous work has cantered round the issue as to what effective role such widely used devices as the generator automatic voltage regulator (AVR) and power system stabilizer (PSS) play in the attenuation of these power system instabilities[1]-[3]. The focus has almost exclusive on the second criterion, oscillation instability as cured by suitably tuned PSS attached to appropriate generators [4]. Other related questions concern the best power system location for PSSs and how best to assess their proper tuning and robustness [5].

The functions of the AVR and the PSS in multi-machine power systems are widely documented [6]. The discussion of the definitions of large-signal transient stability and small-signal oscillation stability is experiential in [7]. The traditional method of analyzing oscillatory instability is small-signal eigne-analysis [8], [9]. The PSS model of a conventional AVR system [10], [11], which is a Proportional-Integral-Derivative (PID) controller that is regulated based on a deviation signal, and is a regulator most widely used in a continuous system. It is established that the AVR and PSS devices, suitably designed, at a given machine have roles that are separated by frequency. Proper AVR and PSS designs in appropriate frequency ranges to achieve the limits of transient stability and oscillation stability require minimum adverse interaction between AVR and PSS devices. This paper proposed fuzzy rules of a fuzzy-sliding filament model of the integrated generation control system to obviate or at least alleviate the problems encountered in prior art.

A sliding mode controller combined with fuzzy inference mechanism and adaptive algorithm is proposed for wind speed control [12]. In the sliding mode controller, a switching surface with an integral operation is designed. When the sliding mode occurs, the system dynamic behaves as a robust state feedback control system. In a general sliding mode control, the upper bound of uncertainties, including parameter variations and external mechanical disturbance, must be available [13], [14]. However, the bound of the uncertainties is difficult to obtain in advance for practical applications. A fuzzy sliding mode position controller is investigated to resolve the above difficulty, in which a simple fuzzy inference mechanism is utilized to estimate the upper bound of uncertainties. Furthermore, to reduce the control effort of the sliding mode controller, the fuzzy inference mechanism is improved by adapting the center of the membership functions to estimate the optimal bound of uncertainties [15]. Therefore, the integrated generation control system was designed based on fuzzy rules of a fuzzy-sliding filament model to cope with the nonlinear system. Simulation results are provided to show the effectiveness of the proposed overall integrated generation control system.

II. INTEGRATED GENERATION CONTROL SYSTEM

It is the primary objective of this paper to provide an integrated generation control system for enhancing the dynamic stability of a generator or the stability of the output from several generators operated in parallel. From the Fig. 1, there is shown an integrated generation control system according to the preferred embodiment of this paper. To achieve the foregoing objective, the integrated generation control system includes at least one integrated control module, a rectification module, a communication module, a rectifier, a permanent magnet alternator, a generator, a maintenance module, a local control unit and a battery. From the Fig. 1, the integrated control module includes an automatic voltage regulator, a power system stabilizer and an extensive gate controller. The rectification module is connected to the integrated control module. The communication module is arranged between the integrated control module and the rectification module. The rectifier is connected to the integrated control module and the rectification module. The permanent magnet alternator is connected to the rectifier. The generator is connected to the integrated control module.

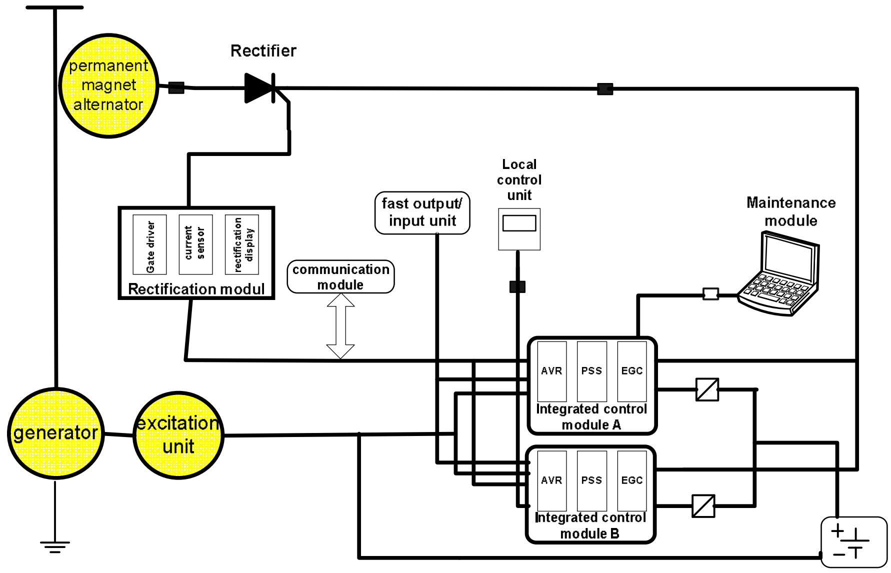

Fig. 1. An integrated generation control system

From the Fig. 1, the system includes two integrated control modules, a rectification module, a communication module, a rectifier, a permanent magnet alternator, a generator, a maintenance module, a local control unit and a battery. Each of the integrated control modules includes an AVR, a power system stabilizer (PSS) and an extensive gate controller (EGC). A fast output/input unit is connected to both of the integrated control modules. The rectification module is connected to both of the integrated control modules. The rectification module includes a gate driver, a current sensor and a rectification display. The communication module is arranged between the rectification module and both of the integrated control modules. The communication module may be a network communication interface. The rectifier is connected to both of the integrated control modules, the rectification module and the permanent magnet alternator. The rectifier may be a three-phase complementary silicon-controlled rectifier. The generator is connected to both of the integrated control modules. An excitation unit is arranged between the generator and both of the integrated control modules. The maintenance module is connected to both of the integrated control modules. The maintenance module may be a computer, a personal digital assistant (PDA) or a portable communication device. The local control unit is connected to both of the integrated control modules. The battery is arranged between the excitation unit and both of the integrated control modules.

In operation, the automatic voltage regulators of the integrated control modules together execute automatic voltage regulation, limitation and protection. Specific chips are used for exchange and storage of data, control over production of pulses, and A/D and D/A conversion. The automatic voltage regulators and the communication module together form an interface with other devices, and provide serial-port communication and watchdog diagnosis. In the communication module, the node addresses and control unit parameters for example are set by manually operating jumpers and switches. Via the communication module, the automatic voltage regulators regulate parameters related to rectification in the rectification module. The rectification module is a distributed control and regulation device. Via the gate driver, the rectification module pre-processes trigger control pulses in the rectifier, and ensures even flows between several rectifiers operated in parallel. By adjusting the parameters of each element and individually shifting the phase of each trigger pulse for leg current symmetrical regulator. Moreover, the rectification module isolates both of the integrated control modules from the trigger pulses of the gate driver, measures data of a current in the rectifier, and transfers the data of the current to the rectification display on which the data of the current are shown.

As discussed above, the automatic voltage regulator at least executes the following functions:

1. Control over the temperature of a rotor in the generator and detection of troubles such as monitoring of failures, measurement of a stable-voltage power supply, self-recovery, and comparison of detected signals of hardware with one another;
2. Over-current protection and loss-of-excitation protection such as actual power/virtual power protection;
3. Limitation such as under-excitation, over-excitation and voltage/frequency limitation;
4. Self-diagnosis such as software and hardware watchdog functions;

The power system stabilizer may include a digital signal processor to execute multi-functional measurement for fast processing of measured values, electric isolation and exchange of signals. All of the measured values are sampled by an A/D converter and the digital signal processor, and stored in a synchronous dual-port RAM.

Being a standard software function for a power system stabilizer, the power system stabilizer introduces an additional feedback signal of acceleration power to reduce the low-frequency oscillation of the generator, thus increasing the stability of the grid. As discussed above, the power system stabilizer exhibits at least the following functions:

1. Measurement and calculation of the current and voltage, effective and ineffective power, power factor and frequency in the generator 6 for acceleration of power;
2. Compliance of angular frequency of the rotor with a model control algorithm of an IEEE power system regulator; and
3. Measurement of high-impedance voltage without electric isolation.

The extensive gate controller is used as a backup channel in a single-channel layout. The extensive gate controller 13 produces pulses for controlling a current in an excitation system as field regulation backup. Via a high-frequency pilot exciter, the extensive gate controller may provide a high-frequency power supply for regulating excitation for forming pulses. The extensive gate controller may be connected to the automatic voltage regulator and the power system stabilizer. As discussed above, the extensive gate controller at least executes the following functions:

1. Field current regulation and follow-up control to ensure stable switch of the automatic voltage regulator in case of failure;
2. Back-up transient over-current and inverse time current-limiting protection.
3. Built-in self-sufficient power supply and DC short-circuit protection;
4. Monitoring of a gate flow rectifier and duo-rectifier switch; and
5. Independent power system and production of high-frequency pulses.

The maintenance module is a very convenient tool connected to the AVR control module through optical fibers and communication cards. With the maintenance module, parameters are set for the automatic voltage regulator, and the automatic voltage regulator is debugged and maintained. By manually operating the jumpers and switches, the node addresses of the communication module are set, and so is the extensive gate controller. As discussed above, the maintenance module at least executes the following functions:

1. Monitoring of the status values of the automatic voltage regulators via a machine/human interface;
2. Adjustment and modification of related parameters;
3. Check on and display of an internal record of data and deletion of a record of failures;
4. Reservation of current setting and registration of patterns; and
5. On-site control over the automatic voltage regulator.

In the digital automatic voltage regulator, a digital modularization technique is used for an excitation system. The automatic voltage regulator is used to execute various control over and regulation of the production of the pulses. As the core of the control circuit, the power system stabilizer is used for fast interception of the measured values. The digital automatic voltage regulator and the power system stabilizer together form an independent control channel. In a dual system design, there are two control channels mechanically isolated from each other for convenient on-line maintenance of the maintenance module. Each control channel may control several extensive gate controllers. The communication module and the fast output/input unit together satisfy non-urgent needs. The extensive gate controllers are mechanically separated from the control channels for filed regulation backup.

III. FUZZY-SLIDING FILAMENT MODEL

The paper provides an excitation control model. Variables related to its fuzzy sliding-mode controller model are defined as follows:

$$x_1(t) = \Delta\omega_r(t) \tag{1}$$

$$\dot{x}_1(t) = -\dot{\omega}_r(t) = -x_2(t) \tag{2}$$

where in $\Delta\omega_r$ stands for a differential of the angular speed of the rotor of the generator, and ω_r stands for the angular speed of the rotor of the generator.

The stable-status power output from the generator is defined as follows:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & -B/J \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ -K_t/J \end{bmatrix} \dot{i}_q^*(t) + \begin{bmatrix} 0 \\ 1/J \end{bmatrix} \dot{T}_m \tag{3}$$

where in J stands for the rotational inertia, T_m stands for the mechanical torque, and B stands for the frictional coefficient of the generator.

Eq. (3) may be rewritten as follows:

$$\dot{X}(t) = AX(t) + BU(t) + D\dot{T}_m \tag{4}$$

In consideration of interference, the formal may be expressed as follows:

$$\dot{X}(t) = (A + \Delta A)X(t) + (B + \Delta B)U(t) + (D + \Delta D)\dot{T}_m \tag{5}$$

where in ΔA, ΔB and ΔC can be expressed by parameters such as J, B, Kt and Tm. Eq. (5) can be rewritten as follows:

$$\dot{X}(t) = AX(t) + B(U(t) + F(t)) \tag{6}$$

F(t) stands for the lumped factor and can be expressed as follows:

$$F(t) = B^{-1}\Delta AX(t) + B^{-1}\Delta BU(t) + B^{-1}(D + \Delta D)\dot{T}_m \tag{7}$$

According to eq. (7), the switch interface of the overall operation can be achieved by the system parameters A and B.

A. A witch plane design:

A switch plane of a sliding-mode controller that includes integration can be designed as follows:

$$S(t) = C\left[X(t) - \int_0^t (A + BK)X(\tau)d\tau\right] = 0 \tag{8}$$

where C is a positive matrix, and K is a status feedback gain matrix. It can be learned from the switch plane (8) of the sliding-mode controller that if the system status trajectory (6) reaches the switch plane, i.e., $S(t) = \dot{S}(t) = 0$, the equivalent dynamic status of the system is determined as follows:

$$\dot{X}(t) = (A + BK)X(t) \tag{9}$$

Obviously, if the limit of the system (9) is placed in the left half plane, the differential of the angular speed of the rotor will reach zero like a convergent exponent. Therefore, there will not be any overshoot of the follow-up response, and the dynamic status of the system is like a status feedback control system.

B. Controller design:

Based on the switching surface, a switching control law which satisfies the hitting condition and guarantees the existence of the sliding mode is then designed. The sliding-mode rotational speed controller is defined as follows:

$$U(t) = KX(t) - f\,\mathrm{sgn}(S(t)) \tag{10}$$

wherein sgn() stands for a signum function and is defined as follows:

$$\mathrm{sgn}(S(t)) = \begin{cases} +1 & if \quad S(t) > 0 \\ -1 & if \quad S(t) < 0 \end{cases} \tag{11}$$

where f is defined by $|F(t)| \leq f$. $F(t)$ stands the switch plane for the overall operation and is defined as follows:

$$F(t) = B^{-1}\Delta AX(t) + B^{-1}\Delta BU(t) + B^{-1}(D + \Delta D)\dot{T}_m$$

C. Fuzzy-sliding controller:

In a sliding-mode controller, an upper limit of an unknown term such as parameter variation and external interference with the load must be known. It is however difficult to obtain the boundaries of an unknown item in practice. Hence, a fuzzy-sliding controller is disclosed according to this paper. A fuzzy inference mechanism is used to estimate the upper limit of an unknown item. The fuzzy inference mechanism can build an estimation model for the unknown item. In comparison with a conventional estimation device, the fuzzy inference mechanism, in which expert knowledge is used, is effective. K_f is used to replace f in eq. (10) as follows:

$$U(t) = KX(t) - K_f\, sgn(S(t)) \tag{11}$$

K_f is estimated by the fuzzy inference mechanism. Please refer to Fig. 2, which are diagrams showing membership functions for the fuzzy sets corresponding to switching surface S, $\dot{S}$. In the fuzzy inference mechanism, the processing of the data is based on the fuzzy set theory. Hence, the fuzzy set includes fuzzy control rules. To obtain the K_f output function, the center of gravity (COG) is used to calculate the output from the fuzzy inference mechanism as follows:

$$K_f = \frac{\sum_{i=1}^{25} w_i c_i}{\sum_{i=1}^{25} w_i} = \frac{\begin{bmatrix} c_1 & \cdots & c_{25} \end{bmatrix}\begin{bmatrix} w_1 \\ \vdots \\ w_{25} \end{bmatrix}}{\sum_{i=1}^{25} w_i} = \upsilon^T W \tag{12}$$

wherein w_i stands for a fired strength vector, c_i stands for the central value of the membership function of K_f.

Because there fuzzy subsets N, Z and P are defined as S and $\dot{S}$, the fuzzy inference method includes 25 rules as shown in Fig. 3. The power system stabilizer feeds the system frequency variation or effective power variation back to the excitation system to compensate the insufficient impedance in the high-speed excitation system after the quick responses. To avoid reduction of the synchronous torque, the power system stabilizer is made in an under-compensated design to increase the impedance in the generator and the dynamic stability of the system and enhance the synchronous torque in the transient stability of the generator.

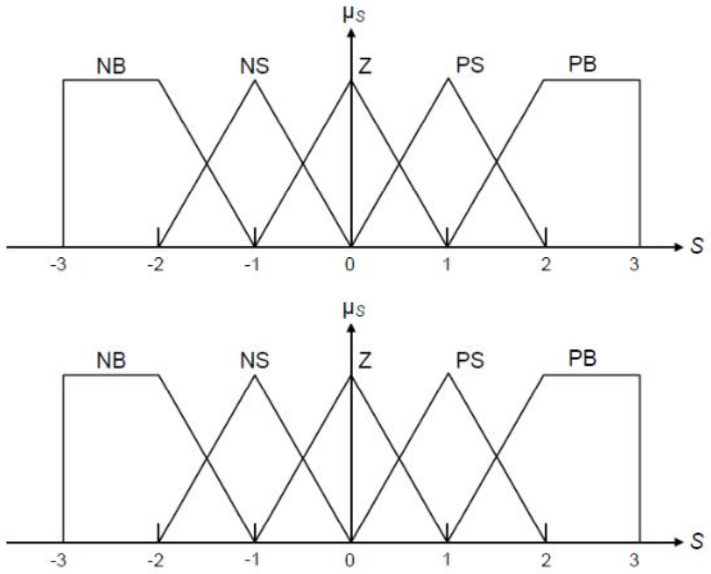

Fig. 2 Membership functions for the fuzzy

K_f		$\dot{S}$				
		NB	NS	Z	PS	PB
S	NB	H	H	VB	VB	B
	NS	VB	B	B	M	S
	Z	S	VS	Z	VS	VS
	PS	S	N	B	B	VB
	PB	B	B	VB	H	H

N : Negative *Z* : Zero *P* : Positive *H* : Huge
NH : Negative Huge *NB* : Negative Big *NM* : Negative Medium *NS* : Negative Small
PH : Positive Huge *PS* : Positive Small *PM* : Positive Medium *PB* : Positive Big
VS : Very Small *VB* : Very Big *B* :Big *M* : Medium

Fig. 3 Fuzzy rules

The power system stabilization device is synchronized with an on-line training model. There is provided a 3-level recurrent neural network (RNN) as shown in Fig. 4. The RNN is used for tracking the output power of the power system. The RNN is adaptive and suitable for use in a non-linear system. The RNN includes an input layer, a hidden layer and an output layer.

For the ith neuron in the input layer, the input and output are defined as follows:

$$net_i^1(N) = x_i^1(N) \tag{13}$$

$$O_i^1(N) = f_i^1\left(net_i^1(N)\right) = \frac{1}{1+e^{-net_i^1(N)}}, \quad i = 1,2 \tag{14}$$

where x_i^1 is the input signal on the input layer a, in the form of voltage, current or temperature, *N* stands for the iteration number of the neutral network, and O_i^1 stands for the output on the input layer.

Regarding the hidden layer b, when the data are entered to the network, the input vector is transferred into every function in the hidden layer b from the input layer a. That is, after the distance of the input vector from the center of each neutron is calculated, the function is transferred into the output from each neutron on the hidden layer b. The output and input are defined as follows:

$$net_j^2(N) = w_j^2 O_j^2(N-1) + \sum_i w_{ij}^2 x_i^2(N) \tag{15}$$

$$O_j^2 = f_j^2\left(net_j^2(N)\right) = \frac{1}{1+e^{-net_j^2(N)}},\ j = 1,\ldots,n \tag{16}$$

where *n* stands for the neutron.

Regarding the output layer c, each neutron is labelled by Σ. That is, all signals introduced into this neutron are added up. For the O^{th} neutron on the output layer, the input and output are defined as follows:

$$net_k^3(N) = \sum_j w_{jk}^3 x_j^3(N) \tag{17}$$

$$O_k^3(N) = f_k^3\left(net_k^3(N)\right) = net_k^3,\ k = 1 \tag{18}$$

where $O_k^3(N)$ stands for the output from the network and is the reference voltage of the output power, and w_{jk}^3 stands the weight of the j^{th} neutron on the hidden layer.

Regarding the supervised learning and training procedure, recurrent chain rules are used to calculate the error on each layer. The errors are sued to modify the weights. To describe the on-line learning rule, an error function E is defined as follows:

$$E = \frac{1}{2}\left(P_w - P_m\right)^2 = \frac{1}{2}e_m^{\ 2} \tag{19}$$

where P_w stands for the expected output power, P_m stands for the actual output power, and e_m stands for the error.

A learning algorithm based on a reverse-recurrent algorithm is defined as follows:

For the output layer, w_{jk}^3 is updated.

The reverse-recurrent error is defined as follows:

$$\delta_k = -\frac{\partial E}{\partial O_k^3} = \left[-\frac{\partial E}{\partial e_m}\frac{\partial e_m}{\partial O_k^3}\right] \tag{20}$$

The connective weight between the output layer and the hidden layer is defined as follows:

$$\Delta w_{jk}^3 = -\frac{\partial E}{\partial w_{jk}^3} = \left[-\frac{\partial E}{\partial O_k^3}\frac{\partial O_k^3}{\partial net_k^3}\right] = \delta_k O_j^2 \tag{21}$$

The connective weight between the output layer and the hidden layer is modulated as follows:

$$w_{jk}^3(N+1) = w_{jk}^3(N) + \eta_{jk}\Delta w_{jk}^3(N) \tag{22}$$

where η_{jk} stands for the learning speed of the connective weight between the output layer and the hidden layer.

For the hidden layer, w_j^2 and w_{ij}^2, connective weights Δw_j^2 and Δw_{ij}^2 are updated as follows:

$$\Delta w_j^2 = -\frac{\partial E}{\partial w_j^2} = \left[-\frac{\partial E}{\partial O_k^3}\frac{\partial O_k^3}{\partial O_j^2}\frac{\partial O_j^2}{\partial w_j^2}\right] = \delta_k w_{jk}^2 P_j^2 \tag{23}$$

$$\Delta w_{ij}^2 = -\frac{\partial E}{\partial w_{ij}^2} = \left[-\frac{\partial E}{\partial O_k^3}\frac{\partial O_k^3}{\partial O_j^2}\frac{\partial O_j^2}{\partial w_{ij}^2}\right] = \delta_k w_{jk}^3 Q_{ij}^2 \tag{24}$$

For the hidden layer, the modifications are defined as follows:

$$w_j^2(N+1) = w_j^2(N) + \eta_j\Delta w_j^2(N) \tag{25}$$

$$w_{ij}^2(N+1) = w_{ij}^2(k) + \eta_{ij}\Delta w_{ij}^2(N) \tag{26}$$

Where η_j and η_{jk} stand for the learning speeds of the connective weights w_j^2 and w_{ij}^2 between the output layer and the hidden layer.

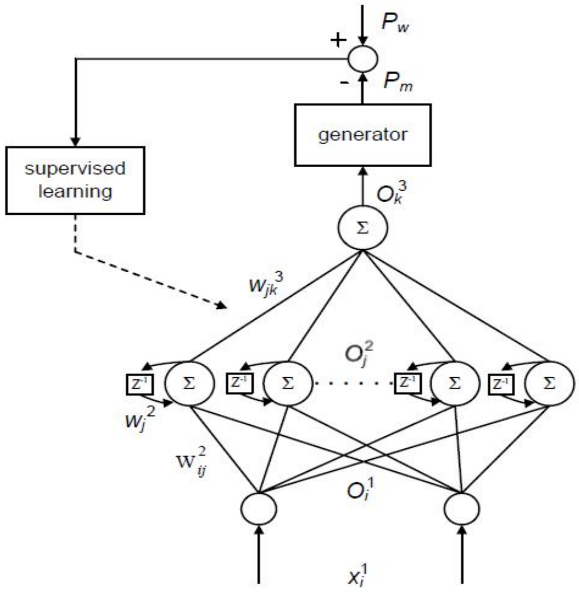

Fig. 4 RNN controller

As discussed above, the integrated control module, in the regulation by the power system stabilizer, the rotational-speed error, power error and/or frequency error are used as the additional control signals, and the additional feedback signal is introduced to suppress the low-frequency oscillation of the synchronous generator and increase the impedance against the electromechanical oscillation in the power system to enhance the dynamic stability in the power system. In general, the automatic voltage regulator exhibits a high gain for the quick response. The high-gain automatic voltage regulator reduces the impedance against the electromechanical oscillation in the power system. Hence, when a transient status occurs in the power system or a failure occurs in the power grid to interfere with the power system, a proper power system stabilizer is generally used to improve the stability in the transient status to avoid any influence on the quick response of the automatic voltage regulator or to quickly stabilize the generator or power system. However, the power system stabilizer advances or delays the phase of the function of the system to change the transfer function of the system. That is, the limits of the function of the system are moved so that the entire root trajectory of the generator is controlled to be in the left half plane, and the impedance in any transient status of the system is compensated, and unstable oscillation is prevented. Hence, the automatic voltage regulator and the system stabilizer can not only be used in an excitation system to stabilize the power output from a generator but can also be used to stabilize the output from many generators operated in parallel.

IV. SIMULATION RESULTS

The proposed control schemes and integrated generation control system were simulated. The integrated generation control system provided in this simulation is that the fuzzy sliding mode control and used as the driver of the power system stabilizer to control the output power. Fig. 5-Fig. 7 shows the dependence of the dynamic performances on sampling interval. It is notice that the PSS responses to a ±2% disturbance were simulated at P=45MW. Fig. 5 shows the PSS responses to a +2% disturbance were simulated at P=45MW and GCB was online. Similarly, Fig. 6 shows the PSS responses to a -2% disturbance were simulated at P=45MW and GCB was online. Fig. 7 shows he results of PSS for P=45MW and 2% disturbance when the P/Q active.

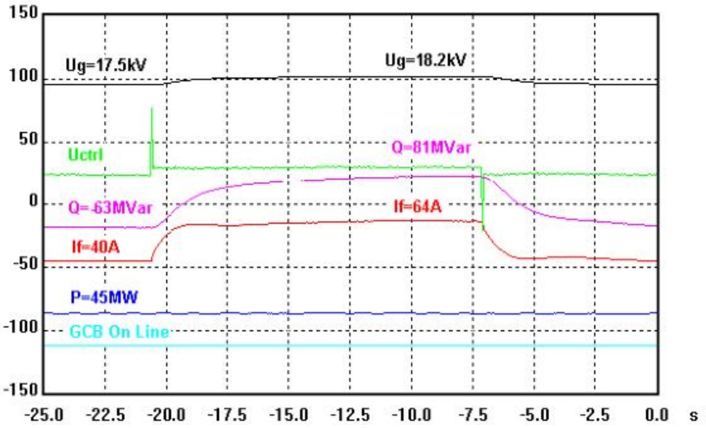

Fig. 5 The results of PSS is obtained for P=45MW to a +2% disturbance

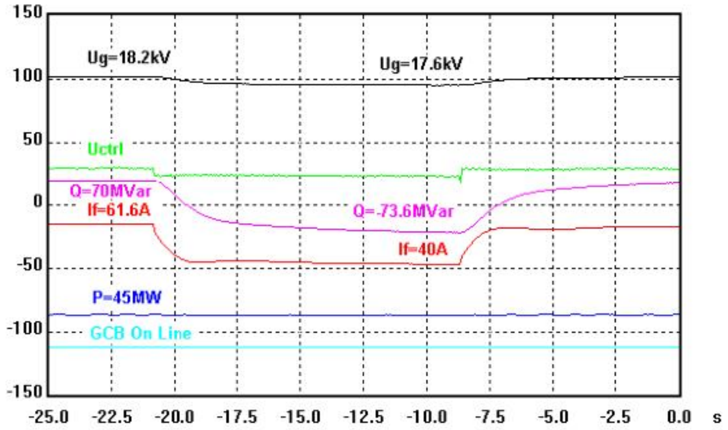

Fig. 6 The results of PSS is obtained for P=45MW to a -2% disturbance

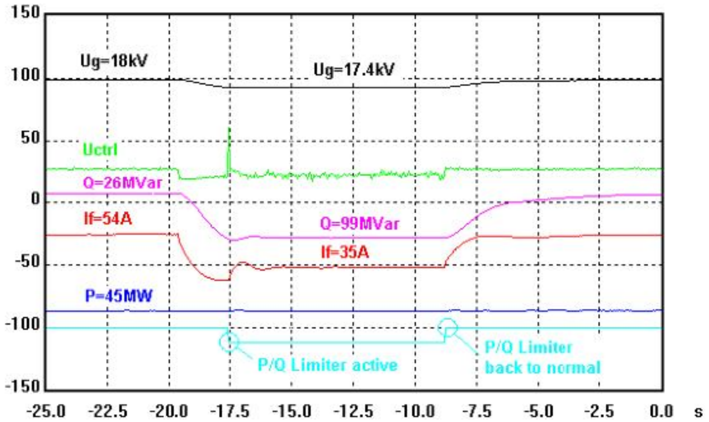

Fig. 7 The results of PSS for P=45MW and 2% disturbance when the P/Q active.

V. CONCLUSION

The contribution of the integrated generation control system provided in this paper is that the fuzzy sliding mode control and used as the driver of the power system stabilizer to control the output power. The power generation system can operate at a stable power. Related power disturbance simulation test conducted with that compared control method provided in the present invention is rapid, can control the output of the generator in real time in the case of disturbance occurred to the power system, and has a good stability and performance.

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