LOAD-FREQUENCY CONTROL WITH SUPERCONDUCTING MAGNETIC ENERGY STORAGE BY USING NN CONTROLLER

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ABSTRACT

This work investigates an application of layered neural network (NN) for load-frequency control at a single area power system included Superconducting Magnetic Energy Storage (SMES) unit. Also, the reheat effect non-linearity of the steam turbine is considered. So, the effects of SMES and NN controller are investigated.

I. INTRODUCTION

The load-frequency control is very important for power system operation and control. The load-frequency control (LFC) problem occurs due to sudden small load disturbances, which continuously perturb the normal operation of power system. The frequency must be fixed at a nominal value, to supply qualified power for consumers. Many control strategies have been proposed to obtain better performance in literature [1]-[9]. Because of the inherent non-linearity of power systems, NN techniques can be considered to build non-linear, adaptive controllers with improved performances. In the literature, the improvement in LFC with the addition of a small capacity superconducting magnetic energy storage (SMES) unit is studied [10], [11].

In this paper, a simple, isolated generator unit included SMES unit connected to a power line or electric bus that supplies for different consumers is considered. As load varies, the frequency of the generator unit varies. Frequency transients must be eliminated as rapidly as possible. To return back to the steady-state value of frequency after a given load variation, a control system is designed that acts on the setting of the steam admission valve of the unit turbine. Specially, if the rotating parts have low inertia in comparison with their power rating, during small load perturbations, increasing of the rotor inertia by flywheel attachment on the rotor shaft is not always acceptable due to the severe torsional stress developed during dynamic oscillations. To prevent the case, using of a fast acting SMES unit is preferred in power system [10]. It is known that most load-frequency control systems include an integral controller as secondary control. The integrator gain is set to a level that compromise between fast transient recovery and low overshoot in dynamic response of the system [12], [13]. Unfortunately, this type of controller is slow and impossible in account to generating unit non-linearities.

An application of the NN configuration to load-frequency controller is proposed in this study. The model of non-linear system to be controlled is given by a set of differential equations, i.e., the system is a continuous dynamical system modelled by state space equations. So, the control rule to be imposed must cope with this dynamic. Since NN will be used to control the system, backpropagation through time algorithm is preferred to cope with the continuous time dynamics [14]-[17].

In the study, both the effect of SMES and the effect of NN are together investigated. During normal operation, the stored energy is taken about 20 MJ and 30 MJ because of factors of superconductor stability, mechanical forces and fatigue [18]. So, SMES is forced lower and upper current limits. Therefore SMES units are separated from the system if the inductor current reaches its limits and SMES units are again connected only when the control signal changes its sign. Whenever SMES unit is disconnected, it's noticed that the power system is equivalent to the one without SMES unit.

II. PLANT MODEL AND CONVENTIONAL CONTROL

Load-Frequency Control In Single-Area System

Mechanical power is supplied by a turbine and it is given to a synchronous generator for different consumers at a single-area system. Essentially, in practice, word "area" refers to a system including many parallel working generators [13]. The waveforms of electrical quantities at the output of the generator are mainly determined by the turbine steam flow. It is also affected by changes in user power demands [12]. When the electrical load suddenly increases, the generator shaft slows down, and the frequency of the generator decreases. The control system must detect the load variation and command the steam admission valve to open more so that the turbine increases the mechanical power production, counteracts the load increase, and brings the shaft speed and hence the generator frequency to their nominal values.

Figure 1 shows an schematically real-power control mechanism [12], [14]. By controlling the position of the governor controlled valves, measured by the coordinate x_E, control over the flow of steam through the turbine can be exerted, and thus the turbine torque determines the generator real power output P_G via the electromechanical mechanism.

In steady state, the opening of the valve is determined by the position of a device called the speed changer [12].

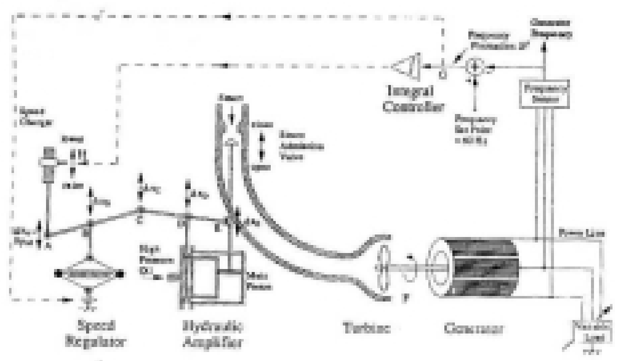

Figure 1 Conventional single-area power system

In conventional system, an integral controller with gain K_I gives rise to a supplementary control which is set on selected units and is used for reset action. The oscillation of the deviation of the frequency is diminished to zero by using supplementary control.

It is well known that most of devices used in power system are extremely non-linear. Moreover, the rate of the generating power ΔP_G is limited. It is known that these boundaries cause additional non-linearities. Small signal model in Laplace domain of single area system is shown in Figure 2 [5]. In this figure, the input of generator model is thus the sum of the turbine output power and the electric load perturbation.

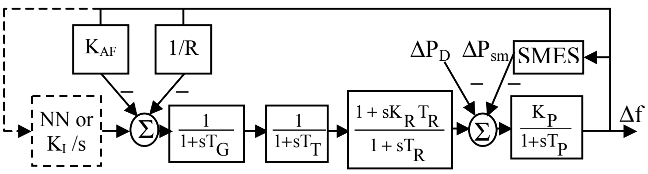

Figure 2. The model of single-area system

The equations of the system in discrete time domain are as following:

$$\Delta f(k) = \left(1-\frac{T}{T_P}\right)\Delta f(k-1) + K_P\frac{T}{T_P}\left(\Delta P_G(k-1) - \Delta P_D(k-1) - \Delta P_{sm}(k-1)\right) \tag{1}$$

$$\Delta P_R(k) = \left(1-\frac{T}{T_T}\right)\Delta P_R(k-1) + \frac{T}{T_T}\Delta x_E(k-1) \tag{2}$$

$$\Delta P_G(k) = \left(1-\frac{T}{T_R}\right)\Delta P_G(k-1) + K_R\Delta P_R(k) - \left(K_R - \frac{T}{T_R}\right)\Delta P_R(k-1) \tag{3}$$

$$\Delta P_{ref}(k) = \Delta P_{ref}(k-1) - K_I T\Delta f(k-1) \tag{4}$$

$$\Delta x_E(k) = \left(1-\frac{T}{T_G}\right)\Delta x_E(k-1) + \frac{T}{T_G}\left(\Delta P_{ref}(k-1) - \left(K_{AF} + \frac{1}{R}\right)\Delta f(k-1)\right) \tag{5}$$

The variables used in above equations are given in Reference [15]. Moreover, in order to project physical constraints, a generation rate limitation of 0.1 p.u. per minute (i.e. 0.0017 p.u. MW/sec.) is considered [7].

SMES System

The schematic diagram in Figure 3 shows the configuration of a thyristor controlled SMES unit [10], [11]. The SMES unit contains DC superconducting coil and converter which connected through Y-Δ / Y-Y transformer. Control of the converter firing angle provides the dc voltage E_d appearing across the inductor to be continuously varied between a wide range of positive and negative values. The inductor is initially charged to its rated current I_{d0} by applying a small positive voltage. Once the current reaches the rated value, it is maintained constant by reducing the voltage across the inductor to zero [11,18].

In load-frequency control operation, the DC voltage E_d across the inductor is continuously controlled depending on the sensed area control error signal. In some previous studies, it is taken depending on the sensed Δf signal [10], [11]. The inductor current deviation is used as a negative feedback signal in the SMES control loop. If the load demand changes suddenly, the feedback provides quickly restoration of current.

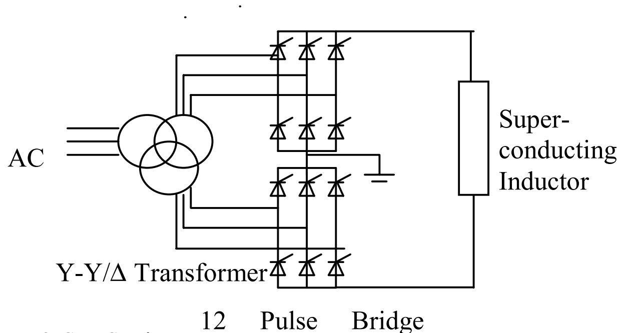

Figure 3. SMES unit

Inductor current must be restorated to its nominal value quickly after a system disturbance, so that it can respond to the next load disturbance [10], [11]. As a result, the inductor voltage deviation and current deviation for each area are taken as below equations:

$$\Delta E_{di}(k) = \left(1-\frac{T}{T_{dci}}\right)\Delta E_{di}(k-1) + K_{0i}\frac{T}{T_{dci}}\Delta f_i(k-1) - K_{Idi}\frac{T}{T_{dci}}\Delta I_{di}(k-1) \tag{6}$$

$$\Delta I_{di}(k) = \Delta I_{di}(k-1) + \frac{T}{L_i}\Delta E_{di}(k-1) \quad ; \; i=1,2 \tag{7}$$

where K_{Idi} is the gain for feed back ΔI_{di} , T_{dci} is converter time delay, K_{0i} (kV/unit ACE) is gain constant and L_i (H) is inductance of the coil. The deviation in the inductor real power of SMES in time domain unit is expressed as follows:

$$\Delta P_{smi}(t) = \Delta E_{di} I_{di0} + \Delta I_{di} E_{di0} \quad ; \quad i=1,2 \tag{8}$$

This value is assumed positive for transfer from ac grid to dc. The energy stored in SMES at any instant in time domain is given as follows:

$$W_{smi}(t) = \frac{L_i I_{di}^2}{2} \quad (\mathrm{MJ}) \quad ; \quad i=1,2 \tag{9}$$

As a result, the state space equations of the system with SMES unit are written as following:

$$x(k) = Ax(k-1) + Bu(k-1) + G \tag{10}$$

where G is a vector containing non-linear terms. The state variables and input for single-area system in the case of using conventional controller are

$$x^T = [\Delta f\ \Delta P_R, \Delta P_G, \Delta P_{ref}, \Delta x_E, \Delta E_d, \Delta I_d] \quad ; \; u = [\Delta P_D]$$

In the case of NN controller, although general expression of the state space equations is same, number of the state variables is less than the case of conventional controller because ΔP_{ref} is taken out from the equations. Therefore, the state variables and inputs for single-area system in the case of using NN controller are

$$x^T = [\Delta f\ \Delta P_R, \Delta P_G, \Delta x_E, \Delta E_d, \Delta I_d] \quad ; \; u^T = [\Delta P_D, u_S]$$

where u_S is the output of NN controller In this case, the terms of the deviation of load is given in vector G at (11).

III. LOAD-FREQUENCY CONTROL BY USING NEURAL NETWORK CONTROLLER

The system equations given in Section Two for single-area system are non-linear state-space equations. A non-linear control strategy will be imposed by using back propagation-through-time algorithm given for multilayer perceptrons. So a non-linear adaptive controller will be used to control this non-linear system [11,14]. Since the system is well modelled and the problem imposed is a control problem not a modelling one, there is no need for NN emulator [14,16].

When the whole system, controller and single-area system, is not modelled by NN, the problem is to find a way to backpropagate the error, because the desired values are given a priori for the single-area system state values, not for the NN controller's output. This problem is solved by defining a new error, which is a linear combination of errors obtained at the output of the single-area system. This new error is then used in backpropagation algorithm.

As explained in introduction, to cope with the dynamic nature of the phenomena to be controlled, the behaviour of the power system is spread out in time and backpropagation through time is used. While this process is done, the continuous time power system is sampled with 0.02 second periods and during each period the dynamical system behaviour is obtained by solving state space equations using Euler method. So 100 blocks of controller and system are used to model the system behaviour of 600 iterations in Figure 5 [14].

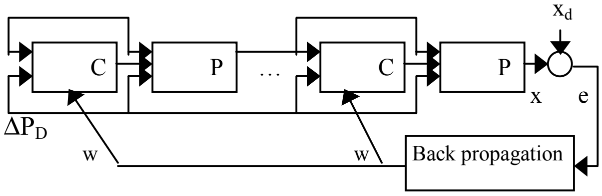

Figure 5. NN controller and plant model of the power system

The inputs of NN are six state variables and one input ΔP_D and the output is one, which becomes the control input of the power system. In the hidden layer there are 20 neurons and in the output layer there is only one neuron. The activation function is the sigmoid with unsymmetrical unipolar representation.

The backpropagation rule defines how to change the weights in the NN in order to minimize the error function given by $E = \frac{1}{2} e^T e$. The adaptiveness of NN is due to this process of weight change, which mimics the change of synaptic weights in human brain during, supervised learning process[14,16]. Due to backpropagation rule the weights change according to gradient descent method of optimization as follows :

$$\Delta w^l_{ij} = -\mu \frac{\partial E}{\partial w^l_{ij}} \tag{11}$$

where w^l_{ij} is the weight connecting neuron i in layer l to the neuron j in the next layer. For the NN controller used in this work there are two layers, one hidden layer and output layer, so l is one or two. The positive real number μ is the learning rate, which corresponds to step size in gradient-based optimization methods. The gradient of the error function is easy to calculate at the output layer; i.e. second layer and it is equal to:

$$\delta^2_j = -e_j f^{2'}_j \tag{12}$$

Here, $f^{2'}_j$ is the derivative of the activation function of the neuron j at the output layer. The gradient of energy function for the hidden layer; i.e. first layer is as follows:

$$\delta^1_j = \sum_m \delta^2_m w^2_{jm} \tag{13}$$

So the weights are changed according to the following rule for the output and hidden layers respectively:

$$\Delta w^2_{ij} = -\mu \delta^2_j f^1(v^1_j) \tag{14}$$

$$\Delta w^1_{ij} = -\mu \delta^1_j x_i \tag{15}$$

In the following section, the simulation results using the above given NN controller for single-area system will be given and these will be compared with the results obtained by integral controller.

IV. SIMULATIONS

The simulation results are obtained by using Matlab metafiles. It is not possible to benefit from NN toolbox of Matlab since backpropagation through time algorithm is used without emulator for the system as mentioned before. Instead of NN emulator for the plant the system equations are used directly. These state space equations with six states and two inputs are solved by using Euler method. One of the inputs is from the NN control output; the other is ΔP_D namely, a step load perturbation. In calculation related with the power system, the boiler effects and the deadband of governor are neglected, and the limits on the rate of generating power and the reheater in the turbine are considered. These mentioned aspects give rise to the nonlinearities in the equations. The parameter values belonging to the power system used during the simulation are given in Table-1. The parameter values related to NN are as follows: the learning rate μ=0.1, α which is a positive constant that controls the slope of the sigmoid function is taken to be 10, so the slope is a steep one. In order to model the non-linear dynamical behaviour of the power system 100 blocks formed by NN controller and power system equations are used. It is well- known that a criterion has to be imposed in order to stop back-propagation algorithm. In this work, step size and an error criterion both considered to stop the algorithm. In the beginning, the initial values of the state variables are taken to be zeros; the input ΔP_D considered is 0.01 p.u.MW. These values are applied both to the input of the NN controller and to the power system. The weights of the NN controller are chosen as random values.

TABLE 1 The Parameter Values

K_P	120	T_G	0.2s.	ΔP_D	0.01puMW
T_P	20s.	K_{AF}	0.5	K_I	0.05
T_s	0.002s.	R	2.4	I_{dmin}	4.05 kA
K_R	0.333	ω_0	3.14	I_{dmax}	6.21 kA
T_R	10s.	T_{dc}	0.026	E_{dmin}	-1.3 kV
T_E	0.3s.	L	2 H	E_{dmax}	3 kV
K_o	50	I_{do}	4.5 kA	E_{do}	0
K_{Id}	0.2				

The simulation results are summarized in the figures. In Fig. 6, the deviation of the frequency obtained using conventional controller against to step load fluctuation during 2000 iterations is given. In Fig. 9, the same deviation is given using NN controller during 600 iterations in the same case. The response of the turbine output power is given at the same case by using PI controller in Fig. 7 and by using NN controller in Fig. 10. In Fig. 8 and 11, the current of the SMES unit is shown in the cases of PI and NN controller, respectively. It has to be noted that the duration to reach the steady state is very short with NN controller. As a result, better performance is achieved by using NN controller than PI controller.
Compared with the results shows that, with the NN controller, the output variables reach to the steady state values in very shorter time and with less oscillation than with PI controller.

V. CONCLUSIONS

In this work, load-frequency control for both single-area and two-area power systems having SMES units are simulated for the case of an unexpected load deviation, which is in the first area in the case of two-area system.

The model of each area in the system includes steam reheat turbines and generation rate constraints. Also, the state space equations of SMES unit are included in the model. According to the deviation of power system energy demand, the SMES unit release to the needed energy or absorb residue energy from power system. The model including generating unit and SMES unit together represents realistic performance of the power system.

For comparison, both conventional PI controller and NN controller are used for LFC in both cases. For the case of two-area system, only one NN controller having two outputs is proposed. One of the outputs is the input of first area and the other is the input of second area. The non-linear state space equations of the power system are used directly during the control of the power system by NN. This is not a usual method with NN controllers. When an NN controller is used in order to back-propagate the error, NN emulator is used. So back-propagation NN configuration is only used as controller and the power system is modelled by its state space equations, in this work. As a result, in the study, during operation, both the effect of SMES and the effect of NN are together investigated. It is shown that the results obtained using NN controller outperform the results of the conventional controller. Furthermore, it can be to use a recurrent NN controller instead of multilayer perceptron with back-propagation through time algorithm to LFC.

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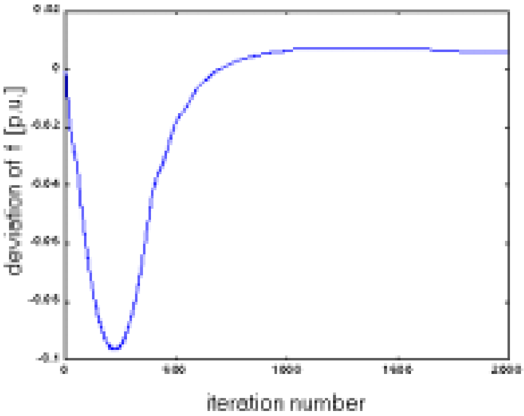

Figure 6. Deviation of the frequency by using PI controller

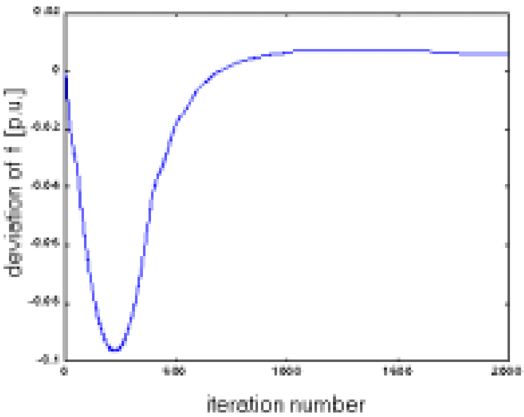

Figure 7. Deviation of the turbine output power by using PI controller

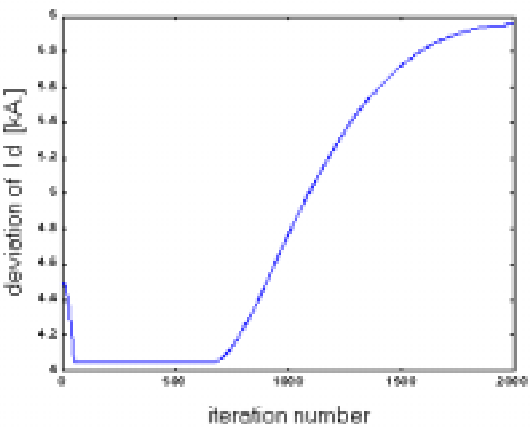

Figure 8. Current of the SMES unit by using PI controller

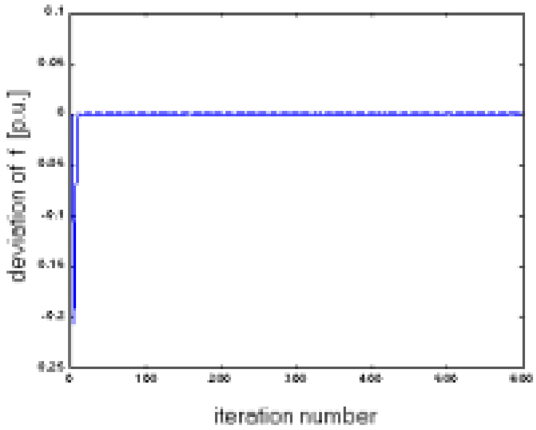

Figure 9. Deviation of the turbine output power by using NN controller

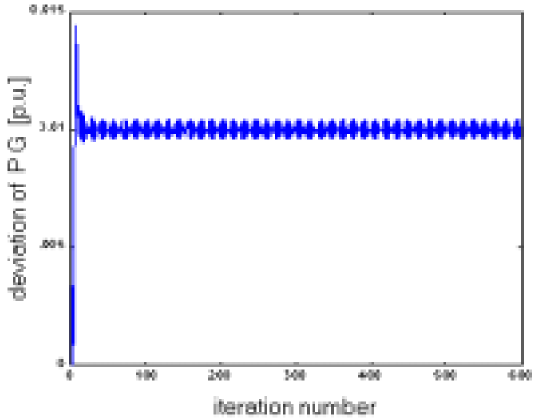

Figure 10. Deviation of the turbine output power by using NN controller

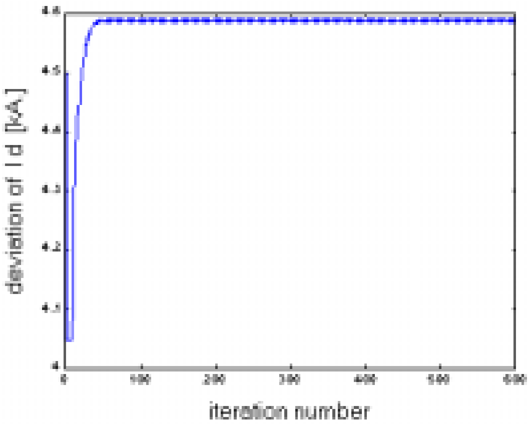

Figure 11. Current of the SMES unit by using NN controller