Introduction a Novel Approach for Power System Load-Frequency Control

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Abstract: - In this paper a novel approach design for load-frequency control (LFC) of power systems is proposed. In this approach, artificial neural network (ANN) trained with the real-time recurrent learning (RTRL) algorithm is used to control power systems. This algorithm works on real time. So it is the best algorithm for training the ANN controller in comparison with other neural network algorithms for LFC of power systems. The superiority of the proposed method over conventional integral controller is verified from simulations and comparisons. The proposed controller provides faster responses with lower overshoots. With this controller, steady state error of frequencies and interchanges of tie-lines are maintained in desired values.

Keywords: - Power system, Load frequency control, ANN, RTRL.

1 Introduction

One of important subjects in electric power system design and operation is Load frequency control. Several control designs have been proposed for LFC problem of power systems. Examples are PI controller, modified PI controller, fuzzy controller and ANN controller. But PI controller is the most widely applied controller because of its simple structure and convenient usage. PI controllers are based on classical linear control theory and designed at nominal values [1]. But in real power systems, load demands are changed during the day, so PI controllers with a fixed gain are not suitable in all operating conditions.

Therefore, PI controllers should be replaced with modern controllers such as artificial neural network controller. These controllers can cope with the inherent nonlinearity character of power systems and are efficient against load changes. This approach has been used for load-frequency control of power systems [2,3]. In mentioned works, back-propagation through time (BPTT) algorithm is used as neural network learning rule. The main deficiency of BPTT is the memory required to store the state of the network at each iteration. In this paper, a real-time recurrent neural network (RTRNN) is used as a LFC controller and it is for the first time that recurrent neural network with RTRL algorithm is used for LFC problem of power systems. This method is completely on-line and simple to implement. So it seems to be a very good candidate for LFC of power systems [4].

For simulations, power systems with single and two control areas have been considered. Each system is controlled by conventional integral controller and ANN controller. Only one ANN is enough to control the multi-area power systems. For each system a step load increasing is applied. The model of nonlinear power systems is given by discrete-time state space equations. From comparison the simulation, it can be seen that the proposed control approach achieves better control results than fixed integral controller. It can cope with the nonlinear nature of power systems and has much better performance.

2 Conventional Integral Controller

In this study single and two-area power systems with steam turbines have been considered. Single-area power system consists of similar generators works together and are assumed as a single generator. A two-area power system consists of two single-area power systems connected through a tie-line. When load perturbation in one of areas occurs, the control system should detect the load variations and produce suitable command immediately to compensate the transients produced by this perturbation. In conventional systems, the reference power of each area is set by an integral controller which acts as a secondary controller. The input of the integral controller in each area of power system is linear compound of local frequency variations and tie-line power variations and is shown by $B_i\Delta f_i + \Delta P_{tiei}$ for ith area.

In fig.1 the simplified block diagram of a single-area power system with an integral controller is shown.

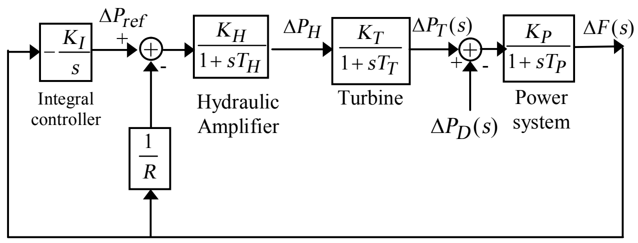

Fig.1 Single-area power system

For simplicity, the hydraulic amplifier, the turbine and the generator are modeled by a first- order transfer function. Power systems have dynamic and nonlinear nature and are described by state equations. The discrete-time state space equations of the single-area power system are as follows:

$$\Delta f(nT_s + T_s) = \Delta f(nT_s) + \frac{T_s}{T_P}[K_P \Delta P_T(nT_s) - K_P \Delta P_E(nT_s) - \Delta f(nT_s)] \quad (1)$$

$$\Delta P_T(nT_s + T_s) = \Delta P_T(nT_s) + \frac{T_s}{T_T}[K_T \Delta P_H(nT_s) - \Delta P_T(nT_s)] \quad (2)$$

$$\Delta P_H(nT_s + T_s) = \Delta P_H(nT_s) + \frac{T_s}{T_H}[K_H \Delta P_{ref}(nT_s) - \frac{K_H}{R}\Delta f(nT_s) - \Delta P_H(nT_s)] \quad (3)$$

$$\Delta P_{ref}(nT_s) = \Delta P_{ref}(nT_s - T_s) - T_s K_I \Delta P(nT_s) \quad (4)$$

where

$\Delta f(nT_s)$: Generator frequency variation

$\Delta P_T(nT_s)$: Turbine power variation

$\Delta P_H(nT_s)$: Hydraulic amplifier power variation

$\Delta P_{ref}(nT_s)$: Reference power variation

$\Delta P_E(nT_s)$: Load variation

T_s : Sampling time

n : discrete-time index

Δ : Deviation from nominal values

T_P , T_T , T_H : Time constants of the generator, the turbine and the hydraulic amplifier

K_P , K_T , K_H : Gains of the generator, the turbine and the hydraulic amplifier

R : Regulation parameter

A critical gain for integral control is the best value of the integral gain which makes fast response with low overshoot and is tuned based on trial and error approaches. The critical gain for integral controller of the single-area power system in this study is $K_I = K_{critical} = 0.2$.

To obtain the discrete-time state space equations of the two-area power system, it is assumed that the hydraulic amplifier and turbine time constants are negligible compared to the generator time constant. The state space equations are as follows:

$$\Delta f_i(nT_s + T_s) = \Delta f_i(nT_s) + \frac{T_s}{T_{Pi}}[K_{Pi}\Delta P_{refi}(nT_s) - (\frac{K_{Pi}}{R_i} + 1) \Delta f_i(nT_s) - K_{Pi}\Delta P_{Ei}(nT_s) - K_{Pi}\Delta P_{12}(nT_s)], i = 1,2 \quad (5)$$

$$\Delta P_{12}(nT_s + T_s) = \Delta P_{12}(nT_s) + T_s[2\pi T^0(\Delta f_1(nT_s) - \Delta f_2(nT_s))] \quad (6)$$

where

$\Delta P_{ij}(nT_s)$: Variation in tie-line power between areas i and j

T^0 : Tie-line synchronizing coefficient

The values of the parameters in these equations are given in appendix.

The critical gains for integral controllers of two areas are $K_{I1,2} = K_{critical} = 0.05$.

An integral controller with a fixed gain has not suitable performance in power systems with various load demands during a daily cycle. Also its dynamic response is very slow and has a large overshoot. In order to overcome this drawback, ANN controller with RTRL algorithm is proposed. In the next section, the design of this method is introduced.

3 Neural Network Controller

This study presents an application of real-time recurrent neural network to overcome the deficiency of other methods in load-frequency control of power systems. A power system has a dynamic nature and is described by its state equations. So a dynamic recurrent neural network with RTRL algorithm, which can cope with its dynamic behavior, is a suitable LFC controller for it. In fact capability of proposed approach in coping with the dynamic, nonlinear and time variant nature of power systems is one of its benefits over the integral controller with fixed gain which dose not have this property. The system behavior is obtained by solving the state space equations in discrete domain. In real systems, load-frequency areas are far from the control centers. Therefore, information of the system, frequency and tie-line power are sampled with a period of time and sent to the control center. As a result, the discrete-time control of a power system which has continuous character is one of the advantages of implementing the proposed approach for load-frequency control of power systems. Fig.2 shows a real time recurrent neural network [5].

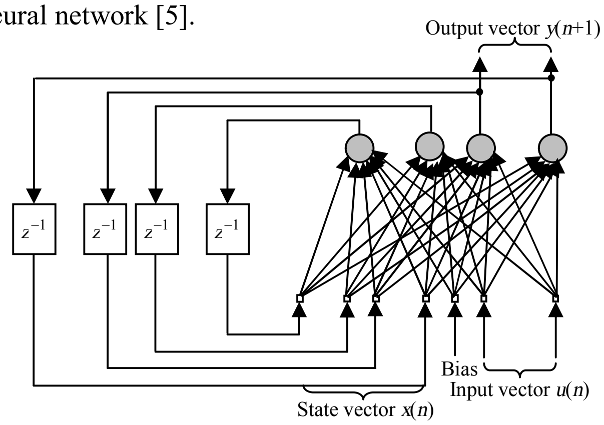

Fig.2 Real-time recurrent network

It consists of q neurons with m external inputs. State variables of different areas at time *n* and load perturbations are the inputs of neural network. State variables in the next period of time (n+1) are its outputs. These outputs are feedbacks to state variables of the inputs. There is a desired state vector that power systems must converge to by means of LFC controller. A desired vector consists of the values of the power system state variables at steady state. The power system controlled by an integral controller converges to this desired vector gently. So the ANN controller should make this convergence faster and also it must limit the duration and magnitude of transients.

There is a weight matrix in the recurrent neural network with RTRL algorithm. Its elements are selected by random at first. Then by use of an error vector, weights are changed to modify the output vector. The error vector is the difference between output vector and desired vector and is shown as follows:

$$e(n)=d(n)-y(n) \tag{7}$$

where $d(n)$ is the desired vector at time n, and $y(n)$ is the output vector at this time.

The important advantage of the proposed approach is its real-time behavior. In this way, error vector is calculated in real time. So weights are modified in real time and as a result, additional inefficient calculations are avoided. In fact, the learnable parameters of the system may be updated only after a part of a time step. This is one of the important advantages of RTRL algorithm in applications which need online learning. So the usage of this network causes faster responses.

According to mentioned descriptions, RTRNN is the most convenient approach for the purpose of load-frequency control of power systems in comparison with other neural networks algorithms, and has the fastest performance [6, 7]. In this work, only one neural network is used for LFC of multi-area power systems which is one of the advantages of using ANN.

To simplify the presentation of RTRL algorithm, three matrices are introduced as follows [8]:

$$\Lambda_j(n)=\frac{\partial x(n)}{\partial w_j} \tag{8}$$

where $x(n)$ is an index for the power system state vector and w_j denotes the weight vector. $\Lambda_j(n)$ is a q-by-(q+p+1) matrix described as the partial derivative of the state vector with respect to the weight vector.

$$U_j(n)=\begin{bmatrix}0\\ \zeta^T(n)\\ 0\end{bmatrix},\zeta(n)=\begin{bmatrix}x(n)\\ u(n)\end{bmatrix} \tag{9}$$

where $U_j(n)$ is a q-by-(q+p+1) matrix its rows are all zero, except for the jth row that is equal to $\zeta^T(n)$.

$$\Phi(n)=diag(\varphi'(w_1^T\zeta(n)),...,\varphi'(w_j^T\zeta(n)),...,\varphi'(w_q^T\zeta(n))) \tag{10}$$

where $\Phi(n)$ is a q-by-q diagonal matrix its kth diagonal element is the partial derivative of the activation function with respect to its argument, evaluated at $w_j^T\zeta(n)$. Index j denotes one of q neurons and $\varphi(0)$ is the activation function for all q neurons. In this work a tangent hyperbolic function is considered as activation function. So, the following recursive function is achieved:

$$\Lambda_j(n+1)=\phi(n)[W_a(n)\Lambda_j(n)+U_j(n)] \tag{11}$$

that describes the nonlinear state dynamics of the RTRL algorithm. The objective of the learning process is to minimize a cost function. The cost function is calculated in the time n and is shown as follows:

$$E_{total}=\sum_n E(n)=\sum_n \frac{1}{2}e^T(n)e(n) \tag{12}$$

To minimize this function, the gradient matrix is used. For this method, the gradient matrix is:

$$\nabla_W E_{total}=\frac{\partial E_{total}}{\partial W}=\sum_n \frac{\partial E(n)}{\partial W}=\sum_n \nabla_W E(n) \tag{13}$$

Weights are updated using the modification determined by:

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This modification is applied to the weight vector of neuron *j*, where μ is the learning-rate parameter which is set to 0.1 in this study. Weights are obtained by following equation:

$$w_j(n+1) = w_j(n) + \Delta w_j(n) \tag{15}$$

In the following section, simulation results for different power systems with both integral controller and ANN controller are shown and compared.

4 Simulation Results

In this paper, single-area and two-area power systems are considered. Parameters of the power systems are mentioned in appendix and used for simulations. For the regulator gain (R), maximum and minimum values are used for simulating the systems. All systems are hit by a 10 per cent increase in load demand.

For each system, both integral and ANN controllers are used for the purpose of LFC and responses are compared. For simulating the power systems and achieving dynamic responses, MATLAB software has been used. As mentioned, RTRL algorithm is used as neural network learning rule to cope with continuous dynamics of power systems and only one ANN controller is needed for LFC of a two-area power system. In fact, for the first time RTRL algorithm has been used for training the recurrent neural network for LFC of power systems. Continuous single-area power system is sampled with a 0.025 seconds period of time and discrete-time state space equations are solved during this period. So dynamic behavior of the power system is obtained.

Fig.3 shows frequency variations of the single-area power systems with R=6 and R=2.4 to 10 per cent increase in load demand.

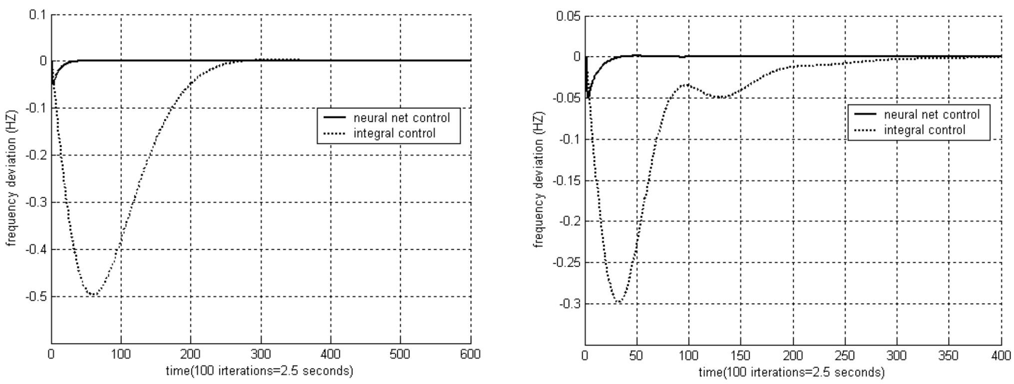
The two-area power system is sampled with a 0.1 seconds period of time. In Fig.5 dynamic response of the two-area power system for R=6 to a 10% step load increase in area 2 is shown. In Fig.4 frequency variations of the first area, frequency variations of the second area and tie-line power variations are shown respectively. Fig.5 shows dynamic response of the two-area power system for R=2.4 to the mentioned perturbation in area 2.

In all figures, the performance of ANN controller is shown by solid line and the performance of integral controller is represented by doted line.

From the comparison between simulation results of the two-area power systems with the results of the single-area power systems, it can be seen that settling time increases. But it is also seen that the proposed method responses are fast and desirable. So this approach is a powerful controller for LFC of multi-area power systems.

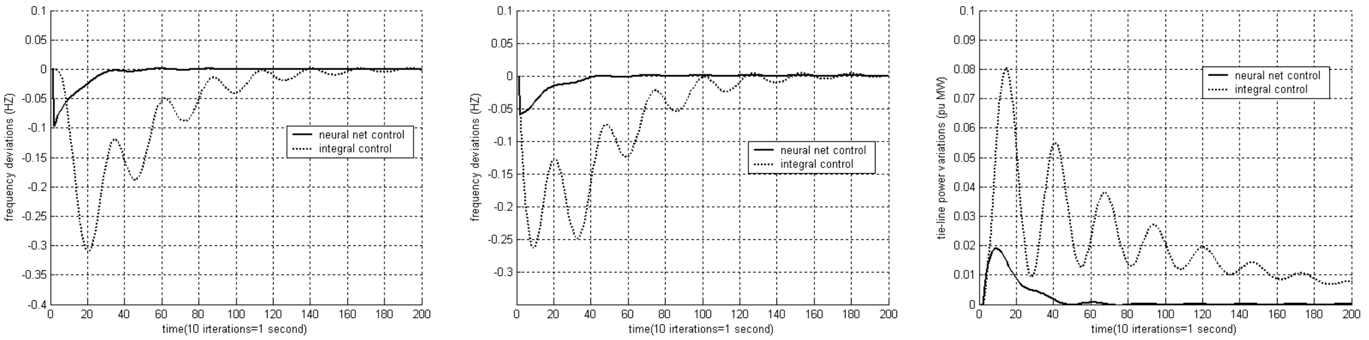
The simulation results demonstrated the effectiveness of the proposed method for load-frequency control of single and two-area power systems. Responses of recurrent neural network in all systems with various regulator gains are incredibly faster and have lower swings. Also it has a reliable performance for actual uses.

In RTRL algorithm, calculation and presentation of the error vector in real-time is possible. Fig.6 shows the variations of error in the frequency of the single-area power system. In Fig.7 the error variations of the frequency of the first area, the error variations of the frequency of the second area and the error variations of the tie-line power in the two-area power system are shown respectively.



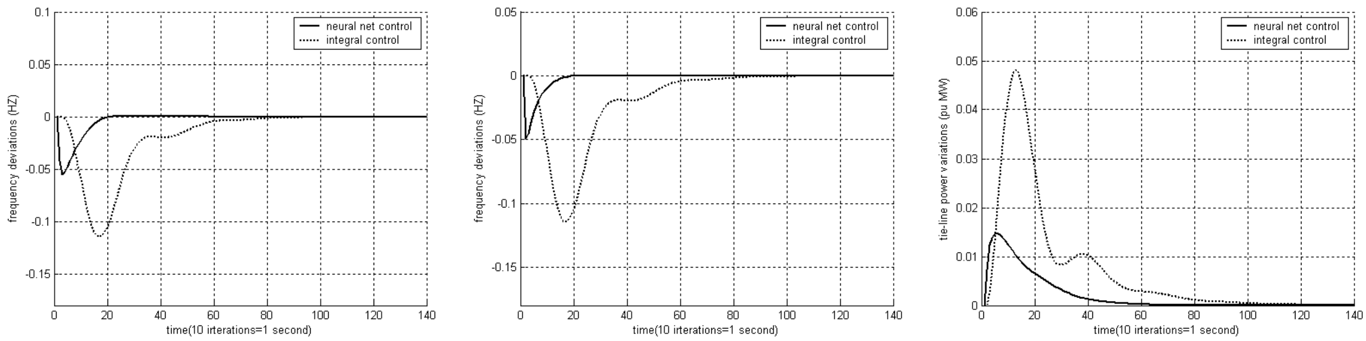
(a) (b)

Fig.3 Frequency variations of the single-area power system for (a) R=6 to a 10% step load increase (b) R=2.4 to a 10% step load increase



(a) (b) (c)

Fig.4 Dynamic response of the two-area power system for R=6 to a 10% step load increase in area 2: (a) Frequency variations in area 1; (b) Frequency variations in area 2; (c) Tie-line power variations.



(a) (b) (c)

Fig.5 Dynamic response of the two-area power system for R=2.4 to a 10% step load increase in area 2: (a) Frequency variations in area 1; (b) Frequency variations in area 2; (c) Tie-line power variations.

It can be seen that error variations for each state variable of each power system against load perturbation, become to zero very fast using neural network with RTRL algorithm. So this approach is very useful for the purpose of LFC of power systems which need fast responses and zero convergence.

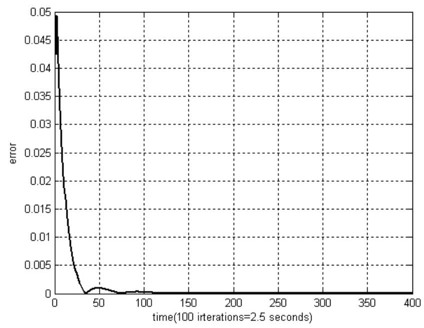
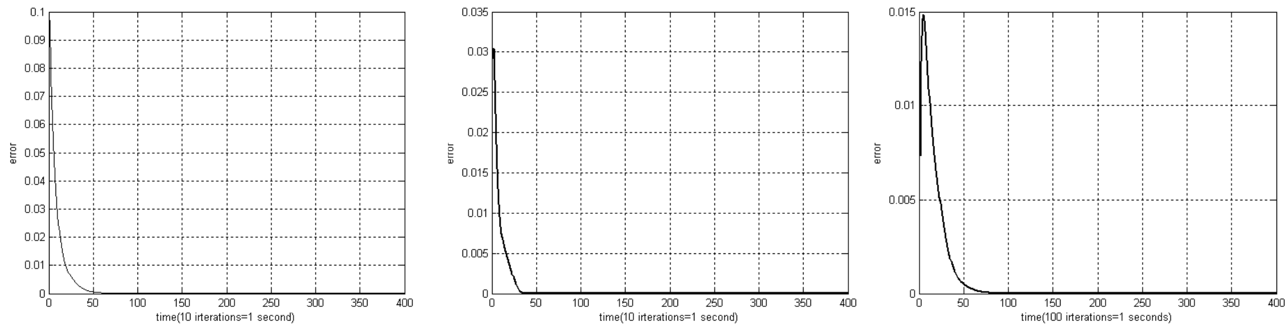


Fig.6 Error variations of the frequency in the single-area power system for R=2.4.

5 Conclusion

In this paper, a novel approach for load-frequency control of power systems is shown. This controller is an ANN which is trained with the real-time recurrent learning (RTRL) algorithm. Only one ANN is required for LFC purpose of two-area power systems. Recurrent neural network with RTRL algorithm is an adaptive controller which can cope with the inherent dynamic nature of power systems. ANN with RTRL algorithm modifies its weights in real time, so the convergence to the desirable response is much faster and it has suitable performance in real power systems. Discrete-time control of a power system which has continuous character is another advantage of implementing the proposed approach for load-frequency control of real power systems with large dimension. Dynamic behavior of the power system is obtained by solving the nonlinear discrete-time state space equations during a period of time. From these points, it can be seen that proposed method is a useful approach for LFC of real power systems.



(a) (b) (c)

Fig.7 Error variations of (a) the frequency of the first area (b) the frequency of the second area c) the tie-line power in the two-area power system for R=2.4.

Simulation results show the priority of RTRNN than conventional integral controller in LFC of power systems. Dynamic responses of the proposed method are much faster and have lower fluctuations.

Appendix

Parameter values of the power systems which are used for computer simulations are shown in the following table.

Parameter values of single-area and two-area power systems

Single-area power system
$K_T = 1$ $K_P = 120$ $K_H = 1HZ/puMW$
$T_T = 0.3s$ $T_P = 20s$ $T_H = 80ms$
$R = 6HZ/puMW$
Two-area power system
$K_{P1} = K_{P2} = 120$ $T_{P1} = T_{P2} = 20s$
$R_1 = R_2 = 6$ $B_1 = B_2 = 0.425\,puMW/HZ$
$T^0 = 0.0707MW/rad$

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