Comparative Analysis and Effect of CES on AGC by Using ANN

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Abstract—This paper presents an application of layered ANN controller to study load frequency control problem in power system. The objective of control scheme guarantees that steady state error of frequencies and inadvertent interchange of tie-lines are maintained in a given tolerance limitation. The proposed controller has been designed for a two-area interconnected power system. Only one ANN, which controls the inputs of each area in the power system together, is considered. In this study, back propagation-through-time algorithm is used as ANN learning rule. The performance of the power system is simulated by using conventional integral controller and ANN controller, separately. For the first time comparative study has been carried out between SMES and CES unit separately. By comparing the results for both cases, the performance of ANN controller with CES unit is found to be better than conventional controllers with SMES, CES and ANN with SMES.

Index Terms—Artificial neural network, capacitive energy storage, stability analysis, superconducting magnetic energy storage.

I. INTRODUCTION

Automatic generation control (AGC) is one of the most important issues in electric power system design, operation, and control. The successful operation of interconnected power system requires the matching of total generation with total load demand and associated system losses. With time, the operating point of a power system changes, and hence, these systems may experience deviation in nominal system frequency and scheduled power exchanges to the areas, which may yield undesirable effects [1].

There are two variable of interest, namely, frequency and tie-line power exchanges. These variables are weighted together by a linear combination to a single variable called the area control error (ACE). The AGC problems have been augmented with the valuable research contribution from the time to time, like AGC regulator designs incorporating parameter variations/uncertainties. The most recent advancement in this area is the application of concepts like neural network, fuzzy logic, and genetic algorithms to tackle the difficulties associated with the design of AGC regulators for the power system with non linear models and/or insufficient knowledge about the system required for its accurate modeling.

The AGC problem has been dealt with extensively for more than three decades. The major part of work reported so far has been performed by considering linearized models of multi area power system [2], [3].

The controllers based on classical control theories are employed in [4], [5] are insufficient because in operating points while the loads changes continuously during daily cycle, while an inherent characteristics of power system. The variable structure controllers proposed in [6], [7] are used to overcome this problem. Due to the requirement of the perfect model, which has to track the state variable and specify the system constraints, it is rather difficult to apply these adaptive control techniques to AGC in practical implementation. These controllers are considerably slow because the estimation of parameter is needed and more computing time is required.

Most of the solution proposed so far for AGC has not been implemented practically due to system operational constraints associated with thermal power plants. The main reason is the non availability of required power other than the stored in the generator rotor, which can be improved the performance of the system, in the wake of sudden increased load demands. A fast acting capacitive energy storage (CES) and superconducting magnetic energy storage (SMES) can be effectively damp out the electromechanically oscillations in a power system, because they provide storage capacity in addition to the kinetic energy of the generator rotor, which can share the sudden changes in the power requirement.

The application of SMES to electric power system can be grouped into two categories. (i) Large scale energy storage like conventional pumped hydro plant storage to meet for sudden load leveling applications. (ii) Low capacity storage to improve the dynamic performance of power system. In first case large sized (hundreds of meters in diameter) high capacity super conducting magnetic energy storage capable of storing 108 MJ is necessary [8]-[10], for the second application, very small sized SMES units with storage capacity of the order of 102 MJ or even less would be sufficient for a small load disturbances and with the optimized gain for the integral controller, the power frequency oscillation and the tie line deviation persist for a long duration, the addition of a small capacity SMES unit to the system sufficiently improves this situation and the oscillations are practically damped out.

In [11]-[13] the improvement in AGC with the addition of a small capacity SMES unit is studied, and time domain simulations used to study the performance of the power system dynamics are analyzed. Their applications in real power have invited problems form the view points of operation, maintenance, cost but the only advantages of SMES is, and that is very much useful for high power applications.
The CES for power system dynamic performance improvement has been widely and vividly reported as in [14], [15]. CES is an alternative choice to damp out the power frequency oscillation, following any perturbation in the power system. CES is, practically, maintenance free. Unlike magnetic energy storage units, CES does not impose any environmental problem. The operation is quite simple and less expensive, compared to SMES. SMES requires a continuously operating liquid helium system. In magnetic storage systems, continuous flow of current is required but CES does not demand so. Thus, as a corrective measure against power system perturbation, CES plays an important role to damp out local mode power system oscillations.

In this paper, ANN controller is used because this controller provides faster control than the others using conventional, adaptive control techniques. ANN controller gives a short settling time and eliminates the necessity of parameter estimation time required in conventional adaptive control technique. The model of nonlinear controller which is the most suitable model to represent the real system is given by a set of differential equations, which is the most suitable model to represent the real system. As ANN configuration will be used to control the non linear system. So back propagation through time algorithm is preferred in the ANN controller to cope with the continuous time dynamics [16]-[18]. This algorithm in a way gives control rule. Even though multi layer perception is non recurrent, when more than one of this structure is used with back propagation through time algorithm, it can be perceived as a recurrent ANN. Thus this study, as the system equations are used to model the system, there is no need to train ANN to obtain system model.

In this simulation, ANN technique is considered to control interconnected power system with two area is connected with tie line to each other to supply different consumers. As the load varies at any area considered in power system, the local frequency of this area is primary affected due to this variation and frequencies of other areas are affected through the tie lines. To return back to steady state value it is well known that AGC system conventionally includes an integral controller as a secondary controller. It is well known that AGC system conventionally includes an integral controller as secondary controller. The integral gain set to level the compromise between fast transient recovery and low overshoot in dynamic response of the system [19]. Unfortunately, this type of controller even if its gain is optimized is considerably slow and therefore the recovery of transient in the power system with respect to load perturbation takes very long time.

To damp out the oscillations as fast as possible, both the effect of SMES and CES based ANN using back propagation through time algorithm are investigated altogether. For the simulation, step disturbance is included in both areas, the considered power system is controlled by using: (i) Conventional integral controller, (ii) ANN using back propagation through time algorithm.

For the case mentioned above. In this study, that ANN controller with CES gives better dynamic response for load perturbation compared to conventional integral controller, AGC with ANN controller, ANN based AGC with SMES Units presented in [18] and [20] respectively.

The objectives of the proposed works are:
(i) To obtain the transient performance of the coordinated action of two areas AGC loop with various load conditions.
(ii) To investigate the further impact of SMES on the same transient performance, control system using SMES has been presented as one of the powerful stabilizers for damping out the power system oscillations.
(iii) To investigate the impact of CES on the same transient performance, Control system using CES has been presented as one of the powerful stabilizers for damping out the power system oscillations.
(iv) To compare the coordinated action of the transient performance of AGC and ANN with SMES and without SMES.
(v) To compare the coordinated action of the transient performance of AGC and ANN with CES and without CES.
(vi) Finally comparative analysis has been carried between AGC and ANN with coordinated action of SMES and CES.

The organization of the paper documented in the following headings. Section II provides two area power system investigations. While Sections III & IV deal with mathematical modeling of SMES and CES, Section V incorporates ANN in AGC. Section VI includes stability analysis comparison with PI, SMES, and CES. Section VII deals with results analysis being followed by concluding remarks.

II. AGC IN TWO AREA POWER SYSTEM

The two area power system, including two single areas connected through a tie-line is considered. Each area supplies its user pool, and tie-line allows electric power to flow between areas. So, both areas affect each other. Because of this, the control system of each area needs information about the transient situation in both areas to bring the local frequency to its steady state value. As the information about each area is found in its output frequency, the information about the other area is in the perturbation of the tie-line power. So, tie-line power flow is needed in order to feed back the information in both areas. While the electric load increases in one area, the frequency of the same area decreases, and power transmitted from the other area to this area increases. In conventional systems, the turbine reference power of each area is tried to be set to its nominal value by an integral controller. The input of the integral controller of each area is $B_i \Delta f_i + \Delta P_{tie}$ ($i=1,2$), and it is called ACE. The parameters of $B_i$ may be optimized, but here, they are chosen as $1/K_{p_i} + 1/R_{i}$ as generally taken. The equations are

$$\Delta f_i(k+1) = \Delta f_i(k) + \left( T_{i1}/T_{i1} \right) \times \left( K_{p_i} \times \Delta P_{i1}(k) - K_{p_i} \times \Delta P_{i1}(k) - K_{p_i} \times \Delta P_{i1}(k) \right)$$  \hspace{1cm} (1)

$$\Delta P_{i1}(k) + \left( T_{i1}/T_{i1} \right) \times \left( K_{p_i} \times \Delta P_{i1}(k) - \Delta P_{i1}(k) \right)$$  \hspace{1cm} (2)
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Fig. 1. Transfer function model of SMES.

\[
\Delta P_{31}(k+1) = \Delta P_{31}(k) + (T_{1} / T_{S1}) \times \\
(KE_{1} \times \Delta \theta_{11}(k) - (K_{e1} / R_{1}) \times \Delta f(k) - \Delta P_{31}(k))
\]

(3)

\[
\Delta P_{21}(k+1) = \Delta P_{21}(k) + (T_{1} / T_{S2}) \times \\
(K_{e2} \times \Delta \theta_{21}(k) - \Delta P_{21}(k))
\]

(4)

\[
\Delta P_{32}(k+1) = \Delta P_{32}(k) + (T_{1} / T_{S3}) \times \\
(K_{e3} \times \Delta \theta_{32}(k) - \Delta P_{32}(k))
\]

(5)

\[
\Delta P_{22}(k+1) = 2 \times p_{1} \times T_{12} \times T_{i} \times \\
(\Delta f(k) \times \Delta \theta_{22}(k)) + \Delta P_{22}(k)
\]

(6)

\[
\Delta P_{r21}(k+1) = \Delta P_{r21}(k) - (K_{e1} \times T_{S1}) \times \\
(\Delta P_{21}(k) + B_{1} \times \Delta f(k))
\]

(7)

\[
\Delta P_{r22}(k+1) = \Delta P_{r22}(k) - (K_{e2} \times T_{S2}) \times \\
(\Delta P_{22}(k) + B_{2} \times \Delta f(k))
\]

(8)

III. SMES SYSTEM

Fig. 1 shows the transfer function model SMES unit containing DC Superconducting coil and converter which are connected by Star-Delta/Delta-Star transformer. The control of the converter firing angle provides the DC voltage \(E_{d}\) appearing across the inductor to be continuously varying within a certain range of positive and negative values. The inductor is initially charged to its rated value \(I_{0}\), 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 since the coil is [9], [10] superconducting. Neglecting the transformer and the converter losses, the DC voltage is given by equation (11) where \(E_{d}\) is DC voltage applied to the inductor (kV), \(\alpha\) is firing angle (\(^{\circ}\)),

\[
E_{d} = 2V_{dc} \cos \alpha - 2I_{d}R_{c}
\]

(11)

\(I_{d}\) is the current flowing through the inductor (kA), \(R_{c}\) is the equivalent commutating resistance (\(\Omega\)) and \(V_{dc}\) is maximum circuit bridge voltage (kV). Charge and discharge of SMES unit are controlled through change of commutation angle. If \(\alpha\) is less than 90°, converter acts in rectifier mode and if \(\alpha\) is greater than 90°, the converter acts in inverter mode. In this study, as in recent literature, inductor voltage deviation of SMES unit of each area is based on error of the same area in power system. Moreover the inductor current deviation is used as a negative feed back signal in SMES control Loop. So the current variable of SMES unit is intended to be settling its steady state value. If the load demand changes suddenly, the feed back provide the prompt restoration of current. The inductor current must be restored to its nominal value quickly after system disturbances, so that it can respond to the next load disturbance immediately. As a result, the equations of inductor voltage deviation and current deviation for each area in Laplace domain are as follows

\[
\Delta E_{d}(s) = \frac{1}{1 + S T_{ac}} \Delta f(s) - \frac{1}{1 + S T_{ac}} \Delta I_{d}(s)
\]

(12)

\[
\Delta I_{d}(s) = \frac{1}{S T_{ac}} \Delta E_{d}(s)
\]

(13)

where \(K_{st}\) is the gain for feedback. \(\Delta I_{d}, T_{ac}\) is the change in increasing current, converter time delay respectively. \(K_{st}\) (kV/Unit) is gain constant and \(L_{p}\) (H) is the inductance of the coil. The deviation in the inductor real power of SMES unit is expressed in time domain as follows

\[
\Delta P_{ac}(t) = \Delta I_{d} \Delta E_{d} + \Delta I_{d} \Delta E_{d}
\]

(14)

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

\[
W_{ac}(t) = \frac{L_{p} I_{d}^{2}}{2} (MJ)
\]

(15)

A. Frequency Deviation as a Control Signal

The frequency deviation \(\Delta f\) of the power system is sensed and used to control the SMES voltage, \(E_{d}\). When power is to be pumped back in to the grid in the case of fall in the frequency due to sudden loading in the armature, the control voltage \(E_{d}\) is to be negative since the current through the inductor and thyristor cannot change its direction. The incremental change in the voltage applied to the inductor is expressed as

\[
\Delta E_{d} = \left[ \frac{K_{f}}{(1+ST_{dc})} \right] \times \Delta f
\]

(16)

where: \(i, j = 1, 2\), \(\Delta E_{ij}\) is the incremental change in converter voltage, \(T_{dc}\) is the converter time delay, \(K_{f}\) is the gain of the control loop and \(S\) is the Laplace operator \(d / dt\). If ACE is used as control signal then

\[
\Delta E_{d} = \left[ \frac{K_{f}}{(1+ST_{dc})} \right] \times \left\{ K_{ac}(\Delta f_{1} + \frac{1}{B_{1}} \Delta f_{2}) - K_{ac}\Delta f_{1} \right\}
\]

(17)

B. ACE as a Control Signal

In case where tie line power deviation signals are available, it may be desirable to use area control error as input to SMES control logic. This has certain disadvantages, which are desirable later, compared to frequency deviation derived controls. The area control error of two areas is defined as

\[
ACE_{i} = \Delta P_{i} + B_{i} \times \Delta f_{i}
\]

(18)
where, \( i, j = 1,2 \), \( \Delta f_i \) = Change in frequency of area \( i \).
\( \Delta P_{f_i} \) = Change in tie line power flow out of area \( i \) to \( j \).

If \( ACE \) is directly used for the control of SMES, The gains constant \( kA \) (kV/unit Area) would be totally different from \( KF \), the gain constant for frequency deviation as control signal. So a signal proportional to area control error \( (\Delta f_i + (1/B_i) \times \Delta P_{f_i}) \) is used in such a scheme. Then,
\[
\Delta E_{ai} = \frac{K_{ai}}{(1 + ST_{ai})} \left( \Delta f_i + \frac{1}{B_i} \times \Delta P_{f_i} \right)
\]

The discrete time equations for the two area AGC including SMES is solved in MATLAB using m-file and the results are presented here. The sampling time \( T_s \) is 0.001. The equations of SMES for two area in discrete form are
\[
\Delta E_{ai}(k+1) = \Delta E_{ai}(k) + (T_s/T_{ai}) \times (B_i \times \Delta f_i + \Delta P_{ui})
\times K_{ai} - \Delta I_{ai} - K_{ai} \times \Delta E_{ai}(k)
\]
(19)
\Delta I_{ai}(k+1) = \Delta I_{ai}(k) + \Delta I_{dio} \] (20)
\Delta P_{ui}(k+1) = \Delta E_{ai}(k+1) \times \Delta f_i + \Delta I_{dio} \] (21)
\[
\Delta I_{asio}(k+1) = \Delta E_{ai}(k+1) \times \Delta f_i + \Delta I_{dio} \] (22)

IV. CES SYSTEM

Capacitor is an electro chemical device consisting of two porous electrodes, an ion exchange membrane separating the two electrodes and a potassium hydroxide electrolyte. In many ways, an ultra capacitor is subject of same physics as a standard capacitor. That is the capacitor is determined by [14], [15] the effective area of the plates, the separation distances of the electrode and the dielectric constant of the separating medium.

Fig. 2 shows transfer function model of CES. The operation of CES units, that is, charging, discharging, the steady state model and the power modulation during dynamic oscillatory period, is controlled by the application of the proper voltage to the capacitor so that the desired current flows in to or out of the CES. This can be achieved by controlling the firing angle of the converter bridges. Neglecting the transformer and the converter losses, the DC voltage is given by
\[
E_d = 2V_{dc} \cos \alpha - 2I_dR\
\]
where: \( E_d \) = DC voltage applied to the capacitor (kV), \( \alpha \) = firing angle (degree), \( I_d \) = current through the capacitor (kA), \( R_{eq} \) = equivalent commutating resistance (ohm), \( V_{dc} \) = maximum open circuit bridge voltage of each 6-pulse converter at \( \alpha = 0 \) (kV). The capacitor is initially charged to its normal voltage, \( E_{do} \) by the PCS. Once the voltage of the capacitor has reduced \( E_{do} \), it is kept floating at this voltage by continuing supply from the PCS to compensate for the dielectric and other leakage losses of the capacitor. The energy stored at any instant
\[
W_s = \frac{CE_d^2}{2} \] (24)
where \( C \) = Capacitance of CES (Farad).

A. Frequency Deviation as Control Signal

The frequency deviation AF of the power system is sensed and used to control the CES current \( I_d \). The incremental change in CES current is expressed as
\[
\Delta I_{ai} = \left[ \frac{K_{ai}}{(1 + ST_{ai})} \right] \times \Delta f_i
\]
(25)
where, \( i = 1,2 \), \( \Delta f_i \) = Change in frequency of area \( i \).
\( \Delta P_{f_i} \) = Change in tie line power flow out of area \( i \) to \( j \). If \( ACE \) is directly used for the control of CES, The gains constant \( K_{ai} \) (kA/unit Area) would be totally different from \( K_{cf} \), the gain constants for frequency as control signal. So a signal proportional to area control error \( (\Delta f_i + (1/B_i) \times \Delta P_{f_i}) \) is used in such a scheme. Then,
\[
ACE_i = \Delta P_{f_i} + B_i \times \Delta f_i
\]
(26)

where, \( i, j = 1,2 \).

The capacitor voltage deviation can be sensed and used as a negative feed back signal in the CES control loop to achieve quick restoration of voltage then, that with frequency deviation as control signal,
\[
\Delta I_{ai} = \frac{K_{ai}}{(1 + ST_{ai})} \Delta f_i + \frac{B_i}{B_i} \Delta P_{f_i}
\]
(27)

where \( K_{ai} \) (kA/kV) is the gain corresponding to the \( ACE \) feedback. The block diagram representation of such a control scheme is shown in Fig. 2.

V. NEURAL NETWORK

The sequential updating of weights is the preferred method for on-line implementation of the back-propagation algorithm. For this mode of operation, the algorithm cycles through the training sample \( \{X(n),d(n)\}_{n=1}^{N} \) as follows:

The algorithm for the ANN controller and Plant for a LFC is given below.
1. Read the data’s for ANN parameters, plant parameters, change in load value. Initialize the NN weight matrices with random values and set the initial state vector of the plant and the desired target vector.

2. Set condition for exiting iteration loop (con = 0); and set the initial value for iteration counter (iter = 0).

3. Execute the forward run calculations for the neural network controller using the formulas given.

Forward Computation: Let a training example in the epoch be denoted by \((x(n), d(n))\), with the input vector \(x(n)\) applied to the input layer of sensory nodes and the desired response vector \(d(n)\) presented to the output layer of computation nodes. Compute the induced local fields and function signals of the network by proceeding forward through the network, layer by layer. The induced local field \(v_j^l\) for neuron \(j\) in layer \(l\) is

\[ v_j^l(n) = \sum_{i=1}^{n} w_{ji}^l(n) y_i^{l-1}(n) \]  

where \(y_i^{l-1}(n)\) is the output signal of neuron \(i\) in the previous layer \(l-1\) at iteration \(n\), \(w_{ji}^l(n)\) is the synaptic weight of neuron \(j\) in layer \(l\) that is fed from neuron \(i\) in layer \(l-1\). \(w_{ji}^l(n) = b_j^l(n)\) is the bias applied to neuron \(j\) in layer \(l\).

Assuming the use of sigmoid function, the output signal of neuron \(j\) in layer \(l\) is

\[ y_j^l = \sigma_j(v_j(n)) \]

if neuron \(j\) is in the first hidden layer (i.e. \(l=1\)), set

\[ y_j^1 = x_j(n) \]

where \(x_j(n)\) is the \(j\)th element of the input vector \(x(n)\). If neuron \(j\) is in the output layer, set

\[ y_j^l = o_j(n) \]

Compute the error signal

\[ e_j(n) = d_j(n) - o_j(n) \]

where \(d_j(n)\) is the \(j\)th element of the desired response vector.

4. Apply the output of the controller to the plant (i.e., in the plant equations). Find the error at the plant output at the final time \(K\).

5. Find the equivalent error at the controller output by multiplying the error matrix of the plant with the Jacobian matrix of the plant. The Jacobian matrix is the derivative of the plant outputs with respect to its inputs.

6. If the error is below the specified error criterion or maximum number of iteration is reached, then set \(con = 1\) (to exit the iteration loop).

7. If the above condition is not true, then execute the back-propagation calculations and calculate the local gradients as per the formulas given for static back-propagation algorithm for the final time instant of the controller.

Backward Computation: Compute the \(\delta_j\) (local gradients) of the network, defined by

\[ \delta_j(n) = \sum_{i} \delta_i^{l+1}(n) w_{ji}^{l+1}(n) \]

\[ \delta_j(n) = \nabla_j(v_j(n)) \]

where the prime in \(\Phi(\cdot)\) denotes differentiation with respect to the argument. Adjust the synaptic weights of the network in layer \(l\) according to the generalized delta rule

\[ w_{ji}^l(n + 1) = w_{ji}^l(n) + \alpha \left[ w_{ji}^l(n - 1) + \eta \delta_j(n) v_i^{l-1}(n) \right] \]

where \(\eta\) is the learning rate parameter and \(\alpha\) is the momentum constant.

8. Find the equivalent errors for the previous instants’ plant output and the controller, (say \(K - 1\)), in the same way as done in 7. Note that the plant error for this instant will be the local gradients at the input of the controller block which was previously calculated.

9. Find the change in weights for every instant controller blocks and add them together with the original weights of the network.

10. Repeat the steps 3 to 9 until the \(con = 1\). Plot the change in frequency in Hz vs. time in seconds from the plot find settling time and peak over shoot.

The internal architecture of the NN controller is shown in the above Fig. 3. The NN consists of one input layer, one hidden layer of 20 neurons, and one output layer. In case of two area system, two neurons in the output layer for getting separate control inputs to the individual areas, in the input layer, it has four nodes (in case of single area system). Three nodes are for the state inputs change in frequency (\(\Delta f\)), change in hydraulic power (\(\Delta P_h\)), change in turbine power (\(\Delta P_t\)) and fourth node for receiving the load estimate as input.

The output neuron generates the control input to the plant (\(U_c\)). The activation functions used are hyperbolic tangent functions for each neuron. The controller is a neural network. If the block containing the plant equations, \(P\), were replaced by a neural network copy, the unraveled system of Fig. 3 would become a giant layered neural network with inputs \(X_c(0)\) and \(\Delta P\), output \(X_c(K)\), and desired output \(X_c(K)\).

The back propagation algorithm could then be applied to train such a network. By doing so, the error gradient defined at the output of the network are back-propagated through the neural network copy of the plant and C blocks, from \(X_c(K)\) back to \(X_c(0)\); hence, the name back propagation through-time. This approach was first introduced by Nguyen and Windrow (1989), and was successfully applied to number of applications in the area of nonlinear neural control.

The paper adopts a slightly different approach by which we avoid the introduction and training of a neural network copy of the plant equations. The basic idea is that instead of building a neural network copy or emulator of \(P\), to
back-propagate error gradients through it, it is possible to directly back propagate the error gradients through the plant equations $P$. Building a neural network emulator of the plant and back propagating error gradients through it is nothing other than approximating the true Jacobian matrix of the plant using a neural network technique. Whenever the equations of the plant are known beforehand, they can be used to compute, analytically or numerically, the elements of the Jacobian matrix. The error gradient at the input of the plant is then obtained by multiplying the output error gradient by the Jacobian matrix.

The inputs for ANN in two area AGCs are the states of the plant.

$X_P = [\Delta f_1, \Delta P_{1f}, \Delta f_2, \Delta P_{2f}, \Delta P_{1d}, \Delta P_{2d}]$

$\Delta P'_{1f} = \Delta P_{1f}, \Delta P'_{2f} = \Delta P_{2f}$

where, $\Delta P_{1f}$ is the load perturbation in area 1, $\Delta P_{2f}$ is the load perturbation in area 2. For Training the vector $X_P$ was initially set to

$X_P = [0.0 \ 0.0 \ 0.0 \ 0.0 \ 0.0 \ 0.0]$

The target output states of the plant during steady state are

$x_d = [\Delta f_1 = 0, \Delta P_{1f} = (\Delta P'_{1f} + \Delta P_{1d}),$

$\Delta P_{1f} = (\Delta P_{1f} + \Delta P_{1d})/K_{f1},$

$\Delta f_2 = 0, \Delta P_{2f} = (\Delta P'_{2f} - \Delta P_{2d}),$

$\Delta P_{2f} = (\Delta P_{2f} - \Delta P_{2d})/K_{f2}, \Delta P_{1d} = 0]$}

VI. STABILITY ANALYSIS

The calculation of linearized system eigen values are done separately for the case where the SMES, or the CES control is active. The calculated eigen values are presented in Tables I-III. Table I, compares the calculated eigen values of two area power system with and without controller. The calculated eigen value shows that for open loop, the system unstable, the eigen values are in right half of S-plane and for the case of integral controller the system is stable. Table II shows that when the SMES loop is presence system is stable and it reduces settling time, peak over shoot, similarly Table III compares the calculated eigen values of power system with different cases, open loop, with SMES, with CES. The eigen values of Table III demonstrates the satisfactory behaviors of power system. For stability analysis eigen values for two area open loop eigen values, with integral controller without SMES, with SMES, CES have been calculated separately. From this analysis AGC for two area with CES is better than AGC with SMES.

VII. RESULT ANALYSIS

This study is an application of ANN controller for LFC in power system is investigated. For the purpose, the interconnected power system having single area, two areas consist of steam turbines are considered separately. First the LFC in power system is simulated by using both ANN and conventional controller to compare the behaviors of the controllers. In this simulation, a step load increasing in the first area of power system is considered, only one ANN controller, which controls the input of each area in power system together, is considered. Back propagation through time algorithm is used as neural network learning rule to cope with the continuous time dynamics.

The following controllers are designed individually for comparison studies.

i) Conventional PI controller.

ii) Conventional PI controller with SMES units.

iii) Conventional PI controller with CES units.

iv) ANN controller without SMES and CES units.

v) ANN controller with SMES units.

vi) ANN controller with CES units.

vii) Comparative analysis between SMES and CES with the presence of ANN controller.

The robustness of each controller against variations of system parameters is evaluated by the settling time and overshoot. These values are calculated under an occurrence different step load disturbances which are varied from ± 25% of the nominal values. Comparison results are shown in Figs. 4-8.

The system equations are given in Section II for a two area system with nonlinear state space equations. As the state space equation imply a non linear model, a non linear controller would be more proper than using a linear one such as conventional integral controller. The NN controller is indeed an adaptive nonlinear controller with control strategy denied by the learning rule used in changing the weights. This rule will be the back
The validity of SMES for power system dynamic performance improvement has been widely reported in Figs. 4 and 5. Their application in real power system have invited problems from the view point of operation, maintenance and cost involvement. But CES is a better choice to damp out power system oscillations, following any perturbation in power system. CES practically maintenance free, unlike other energy storage and it does not impose any environment problem, and its operation is quite simple and less expensive.

Figs. 6 and 7 show the performance evaluation of with CES under different load variations. Clearly, the setting time of the proposed SMES rarely changes while the variations in load. On the other hand, these indices of other controllers are larger and changes significantly. These results confirm that the robustness of the proposed ANN controller with SMES against load variations are superior to that of the other controllers.

VIII. CONCLUSIONS

(a). This study is an application of ANN to AGC, in a power system, with SMES and CES separately. In this
work, transient behaviors of the frequency of each area and tie line power deviation in the power system with two areas are considered, under any load disturbances in any area.

(b) In practice, power system generally has more than two areas, and each area is different from others. But, in this study, the power system, of two thermal areas, are considered. The nonlinear state space equation of power system is obtained and these equations are used directly during the control of power system by both integral controller and ANN controllers. This is not an usual method with ANN controller. When ANN used in order to back propagate the error, ANN emulator is used in most cases. But in this paper ANN with back propagation through time algorithm is used as controller and power system is modeled by its state space equations.

(c) Investigation reveals that the proposed ANN controllers gains are quite robust, i.e. ± 25% variation in system Load from their nominal values do not affect the system responses appreciably. Also this study reveals that the improved dynamic stabilization action of SMES and CES is always consistent.

(d) Performance of SMES and CES are close to each other in the context of transient analysis. But CES is practically maintenance free, it does not impose any environmental problem, and it is quite simple and less expensive. CES damping effects slightly better than SMES when variation in load.

(e) Finally, a number of studies have been performed with ANN controller in comparison with other controllers. Simulation results show that the performance of proposed controller is superior to the other controller in terms of settling time and over shoot.

(f) The ANN has been successfully implemented. Simulation results clearly confirms that the proposed controller is much superior to controllers in [18], [20] respectively in terms of load variations. It is found that this work may seem to be quite simple and easy to analyze in real power system. It has given very good result in terms of performance and stability.

REFERENCES


APPENDIX

AGC Data:

\[ P_i = P_f = 1200 \text{ MW}, \quad T_{r1} = 120 \text{ s}, \quad T_{r2} = 20 \text{ s}, \]

\[ K_{p1} = K_{p2} = 120 \text{ Hz/pu.MW}, \]

\[ T_{i1} = T_{i2} = 10 \text{ s}, \quad K_{i1} = K_{i2} = 0.5, \quad T_{i1} = T_{i2} = 0.3 \text{ s}, \]

\[ T_{d1} = 0.0866 \text{ s}, \quad T_{d2} = 0.08 \text{ s}, \]

\[ R_i = R_2 = 2.4 \text{ Hz/pu.MW}, \]

\[ D_1 = D_2 = 8.35 \times 10^3 \text{ pu.MW/Hz}, \]

\[ P_i = 0.01 \text{ pu/MW}, \quad P_f = 0.0 \text{ pu/MW}. \]

SMES Data:

\[ K_f = 100 \text{ kV/unit MW}, \quad K_{id} = 0.20 \text{ kV/kA}, \]

\[ K_v = 0.875, \quad L = 2.65 \text{ H}, \quad T_s = 0.03 \text{ s}, \]

\[ I_{do} = 4.5 \text{ kA}. \]

CES Data:

\[ C = 1 \text{ Farad}, \quad R = 100 \text{ Ohm}, \quad T_d = 0.05 \text{ s}, \]

\[ K_{aw} = 70 \text{ kV/unit MW}, \quad K_{vd} = 0.1 \text{ kA/kV}. \]

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