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Application of type-2 fuzzy logic system for load frequency control using feedback error learning approaches

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A B S T R A C T

In this paper, the type-2 fuzzy logic system (T2FLS) controller using the feedback error learning (FEL) strategy has been proposed for load frequency control (LFC) in the restructure power system. The original FEL strategy consists of an intelligent feedforward controller (INFC) (i.e. artificial neural network (ANN)) and the conventional feedback controller (CFC). The CFC acting as a general feedback controller to guarantee the stability of the system plays a crucial role in the transient state. The INFC is adopted in forward path to take over the control problem in the steady state. In this work, to improve the performance of the FEL strategy, the T2FLS is adopted instead of ANN in the INFC part due to its ability to model uncertainties, which may exist in the rules and measured data of sensors more effectively. The proposed FEL controller has been compared with a type-1 fuzzy logic system (T1FLS) – based FEL controller and the proportional, integral and derivative (PID) controller to highlight the effectiveness of the proposed method.

1. Introduction

One of the principle aspects of automatic generation control (AGC) of power system is the maintenance of frequency and power change over the tie-lines at their scheduled values. Therefore, it is a simultaneous load frequency control (LFC) [1]. In LFC problem, each area has its own generator(s), and it is responsible for its own load and scheduled interchanges with neighbouring areas. The tie-lines are utilities for contracted energy exchange between areas and they provide inter-area support in abnormal conditions. Area load changes and abnormal conditions lead to mismatches in frequency and scheduled power interchanges between areas. These mismatches have to be corrected by LFC, which is defined as the regulation of the power output of generators within a prescribed area [2–4]. Therefore, the LFC task is very important in interconnected and restructure power systems. It is well known that power systems are nonlinear and uncertain, where the parameters are a function of the operating point, and the loading in power system is never constant. To control these large scale power systems, the control algorithms must be able to deal with mechanical and electrical nonlinear dynamics and must be operated under imprecise and uncertain conditions, which are mainly caused by random load demands. It is obvious that the fixed gain controllers which are designed at nominal operating conditions fail to provide best control performance over a wide range of operating conditions. Thus, some classical adaptive controllers are presented for LFC in [5–8]. Despite the promising results achieved by these controllers, the control algorithms are complicated and require some on-line model identifications. Consequently, model-free approaches are generally preferred to both modelling and controlling purposes of these systems. The most common model-free approaches are using artificial neural networks (ANNs), fuzzy logic systems (FLSs) and fuzzy neural networks (FNNs) [9–14]. The FNN includes advantages of both FLS, in handling uncertain information, and ANN, in learning from process [14]. Although these controllers have shown promising results, they have not considered measurement noise and parametric uncertainties of the power system. The straightforward way to deal with these problems is using of type-2 FLSs (T2FLSs) [15]. The T2FLS is proposed as an extension of the T1FLS which is able to model the uncertainties that invariably exist in the rule base of the system [15]. In type-1 fuzzy sets, membership functions are totally certain, whereas in type-2 fuzzy sets membership functions are themselves fuzzy. In other words, a Type-2 fuzzy set can be visualized as a three dimensional, primary and secondary membership function. The primary membership is any subset in [0, 1] and there is a secondary membership value corresponding to each primary membership value that defines the possibility for primary membership. The advantage of the third dimension gives an

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extra degree of freedom for handling uncertainties [16,17]. In [18], Sepulveda and coworkers have shown that hardware implementations of T2FLS controllers are easier when high speed processing is required. But the important issue in the application of T2FLS is how to set the parameters of the consequent part as well as those of the antecedent part such as standard deviations and means. Therefore, a chemical optimization paradigm, particle swarm optimizations (PSO), an evolutionary method, simulated annealing and genetic algorithms (GA) have been employed to search for optimal values of these parameters [19–26]. In addition, the fuzzy Lyapunov synthesis method has been used to design the T1FLS and T2FLS controllers [27]. Although the aforesaid algorithms perform better, they are off-line and the parameters obtained by these approaches are optimal only at nominal operating points. In [28,29], the sliding mode control and the extended Kalman filter have been proposed for the on-line training of T2FLS. Furthermore, a decentralized controller based on T2FLS has been designed for LFC. But this controller has fixed structure and is very sensitive to noise effects [30]. However, the combinations of classic and intelligent controllers have become more attractive in recent years. In this case, the classic controller is used for stabilization and the intelligent part is designed to overcome the variations and uncertainties of the controlled system. The most important type of this controller is the feedback error learning approach (FEL) [31–34]. The original FEL strategy contains ANN controller in the feedforward path and a conventional feedback controller (CFC) (i.e. proportional–derivative (PD)) in the feedback path. This strategy can be considered as an adaptive and nonlinear controller. But as we know, the ANN controller is incapable of dealing with parameter uncertainties, noise and other sources of uncertainties. Therefore, the main contribution of this paper is to substitute the T2FLS controller in place of the multi-layer perceptron (MLP) neural network (or T1FLS) in the feedforward path. In the proposed FEL strategy, we have demonstrated that the performance of T2FLS is better than of its type-1 counterpart in the presence of higher levels of noise and uncertainties. Since uncertainty is inherent in the design of controllers for real world applications, in this work we have presented an approach to deal with this problem using T2FLS controllers. As they provide us with more parameters, they can handle uncertainties and measurement noise in a better way. In the proposed method, the CFC acts as a general feedback controller to guarantee the stability of the system and the output of this controller is used to train the T2FLS parameters. As the result, the information about the parameters of the controlled system (i.e. the Jacobean of the controlled system) is not needed to tune of the T2FLS parameters and this method consume less time in on-line applications. A two-area restructure power system is assumed for demonstration. The proposed controller has been compared with the T1FLS – based FEL approaches and PID controller through some performance indices. The integral of the square of the error (ISE), the integral of the time multiplied absolute value of the error (ITAE) and the integral of the time multiplied square of the error (ITSE) have been chosen as the performance indices. Simulation results indicate that the FEL strategy with T2FLS controller act better than T1FLS one in presence of uncertainties and measurement noise.

The remaining of the paper is organized as follows: the dynamic model of a two-area restructure power system is presented in Section 2. An on-line adaptive controller based on FEL approaches for two-area restructure power system is derived in Sections 3 and 4. The simulation results are presented in Section 5. Finally, the conclusion is given in Section 6.

2. Model description

In a traditional power system structure, the generation, transmission and distribution is owned by a single entity called a vertically integrated Utility (VIU), which supplies power to the customers at regulated rates. All such control areas are interconnected by tie lines. Following a load disturbance within an area, the frequency of that area experiences a transient change, and the feedback mechanism comes into play and generates an appropriate rise/lower signal to the turbine to make the generation follows the load. In steady state, the generation is matched with the load and the tie line power and frequency are enforced to zero.

In the restructured power systems, the VIU no longer exists, however, the common objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area are remained. In the vertically integrated power system structure, it is assumed that each bulk generator unit is equipped with secondary control and frequency regulation requirements, but in an open energy market, Gencos may or may not participate in the AGC problem. In that environment, Gencos sell power to various Discos at competitive price. Thus, Discos have the liberty to choose the Gencos for contract. The concept of a “generation participation matrix (GPM)” is used to make the visualization of contracts easier. The GPM shows the participation factors of each Genco in the considered control area and each control area is determined by a Disco. The rows of a GPM correspond to Genco and the columns correspond to control areas that contract power. For example, for a large scale power system with m control area (Discos) and n Gencos, the GPM will have the following structure:

$$\mathrm{GPM}=\begin{bmatrix} gpf_{11} & gpf_{12} & \cdots & gpf_{1(m-1)} & gpf_{1m} \\ gpf_{21} & gpf_{22} & \cdots & gpf_{2(m-1)} & gpf_{2m} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ gpf_{(n-1)1} & gpf_{(n-1)2} & \cdots & gpf_{(n-1)(m-1)} & gpf_{(n-1)m} \\ gpf_{n1} & gpf_{n2} & \cdots & gpf_{n(m-1)} & gpf_{nm} \end{bmatrix} \tag{1}$$

where gpf_{ij} refers to “generation participation factor” and it shows the participation factor of Genco i in load flowing of area j (based on a specified bilateral contract). The sum of all the entries in a column of this matrix is unity, i.e.

$$\sum_{i=1}^{n} gpf_{ij}=1 \tag{2}$$

To illustrate the effectiveness of the proposed control design and modelling strategy, a two control area power system is considered as a test system. It is assumed that each control area includes two Gencos and two Discos. A block diagram of the generalized LFC scheme for control area i will be obtained in a deregulated environment as shown in Fig. 1 [35].

The dashed lines show the demand signals based on the possible contracts between Gencos and Discos, which carry information as a Genco has to follow a load demand by the Disco.

These new information signals were absent in the traditional LFC scheme. As there are many Gencos in each area, the area control error (ACE) signals have to be distributed among them due to their ACE participation factor in the LFC task and $\sum_{j=1}^{n}\alpha_{ij}=1$. In the Fig. 1 we have:

Δfi frequency deviation,
ΔP_{gi} governor valve position,
ΔP_{ci} governor load set point,
ΔP_{ti} turbine power,
$\Delta P_{tie\text{-}i}$ net tie line power flow,
ΔP_{di} area load disturbance,
K'_{pi} proportional gain constant,
T_{pi} power system time constant,