Stabilization of Frequency Deviation in an AC-DC Interconnected Power Systems Using Supervisory Fuzzy Controller

S. Ramesh1* and A. Krishnan2

1Department of EEE, K.S.R. College of Engineering, Tiruchengode (TN), India
2Dean, K.S.R. College of Engineering, Tiruchengode (TN), India

Abstract

This paper presents a Supervisory Expert Fuzzy Controller (SEFC) for maintaining the system frequency in a parallel AC-DC interconnected thermal power system. In the proposed control scheme, the input scaling factor tuning of a direct expert controller is made using the area control error and power plant system input to obtain better performance for a different load disturbance. The control scheme will reduce the Area Control Error (ACE) and increase the system dynamic stability. The control scheme consists of a lower level direct fuzzy controller and an upper level supervisory fuzzy controller. The lower level controller provides the solution to a particular situation and the upper level controller provides a mechanism to the main goal of the system. The responses to various load changes in the multi area system are studied and the performance of the proposed expert controller is compared with the conventional integral controller and the fuzzy controller. The results prove that the SEFC performance is better in terms of stability and robustness than conventional control methods.

Key Words: Load Frequency Control, AC-DC Interconnected System, High Voltage Direct Current (HVDC) Link, Area Control Error, Direct Fuzzy Controller, Supervisory Expert Fuzzy Controller

1. Introduction

The control of power system is becoming increasingly complex due to large disturbance. In an electric power generation, disturbance caused by load fluctuation will result in changes of the desired operating frequency. The requirements for control of frequency in a multi area interconnected power system are implemented by the Automatic Load Frequency Control (ALFC). The ALFC provides automatic variation of generation set points on the speed governors to maintain system frequency within the specified limit [1–4]. Many investigations in the area of ALFC in interconnected power systems have been reported in the past decade. Recently, application of high power devices in AC power system provides better and attractive benefit of economics. In particular, in a parallel AC-DC interconnected power transmission system, a DC system can effectively cooperate with an AC system in improving system stability and frequency control quality of ALFC in an emergency [5–9]. It should be possible to simultaneously achieve the following objectives:

i. Minimize the Area Control Error (ACE) in AC system to avoid excessive governing system operation.

ii. The ability to enhance transient and dynamic stability in associated weak AC networks.

iii. Improve the overall performance of the power system during disturbance.

Modern power system networks require high perfor-
mance controller design and implementation to be simple for wide operating range. In the design of ALFC system, it is a usual practice to use conventional integral controller or Proportional plus Integral controller to reduce the ACE of the interconnected power system to zero state in order to obtain the better performance. However, the conventional integral controller performs only at a particular operating range and they need to be retuned if the operating range is changed. The performance of the conventional integral controller is not satisfactory for a sudden disturbance [10–15]. Considering effective tool for dealing with uncertainties, the performance of the conventional Fuzzy Logic Controller (FLC) is not up to the expected level for power system operation and control because the conventional fuzzy controller is designed only for a particular operating range of load disturbance. In many situations, under different operating conditions these controllers are not properly tuned and there is heuristic knowledge available on how to tune them while they are in operation. There is then opportunity to utilize supervisory expert fuzzy control that tunes or coordinates with the conventional direct fuzzy controller [16–19]. This paper addresses the design and implementation of a Supervisory Expert Fuzzy Controller (SEFC) structure with a knowledge based fuzzy controller as the supervisor for tuning input scaling factor of a direct fuzzy controller [20,21].

The remaining of this paper is organized as follows: In section 2 problem formulation and the practical motivation of the proposed control will be explained. Section 3 presents the design of direct fuzzy controller, SEFC and also describes the fuzzy rules, membership functions and defuzzification method. Result and discussion are presented in section 4.

2. Problem Formulation

In an interconnected network, a disturbance in one line, leads to affects on the neighboring systems to change in frequency causing severe problem in the entire power system network. ALFC is a very important in power system operation and control for supplying sufficient and adequate electric power with good quality. Power systems have not been designed for wide area power trading with daily varying load patterns where power flows do not follow the initial planning criteria of the existing network configuration. Most of the grids are already close to their limits. If the transmission of large power blocks through the interconnected system is needed, the problem can be solved by the interconnection of HVDC transmission system with an AC system and it can additionally enhance the system stability. The integration of HVDC transmission into an AC system started with the pacific intertie project. The second large HVDC, integrated into an AC system is Rihand-Dadri transmission in India, built to interconnect regional systems, to by – pass the weak AC system and to bring power directly from large power plant in the area of Rihand to load center of New Delhi under the system subjected to a sudden large disturbance. For the system study, a three area interconnected system through AC-DC link are considered as shown in the Figure 1. In this system the power demand is rapidly increased due to sudden change of load such as arc furnace, steel mills, etc., in area-1. These large load changes cause a serious problem of frequency oscillation in area-1. The capabilities of frequency control of governor in area-1 are not enough. The power exchange in the neighboring areas can be achieved by the interconnection.

The area-2 is not having sufficient reserve capacity to compensate the power required in area-1, since the interconnection between area-2 to area-1 is operating in parallel with a very weak AC system. On the other hand, by connecting long HVDC transmission line in parallel with AC line in area-3 having enough frequency capability to compensate the demand in area-1. The interconnections of AC and DC line, the DC tie line power modulation is capable to stabilize the frequency oscillation of associated AC networks and it can additionally enhance the system stability, especially when the connected AC line is weak and when there is no sufficient reserve capacity in the neighboring system available. The proposed

![Figure 1. Parallel AC-DC interconnected power system.](image-url)
control approach is able to offer the service for stabilizing frequency oscillations in the power system network under the different load disturbance in any area.

3. Controller Design

The objective of the proposed controller design is to improve the power system performance under the normal and different load disturbance. To maintain the frequency deviation in an interconnected power system, the controller has to be designed using an on-line tuning method to improve the power system stability and robustness.

A multi area interconnected power system with parallel AC-DC link is considered here [14,19]. The overall system can be modeled as a multi-variable system in the form of

\[ x = Ax + Bu + Ed \]  

where \( A, B \) and \( E \) are system state matrix, distribution matrix and disturbance matrix of appropriate dimensions respectively. Similarly \( x, u \) and \( d \) are the state, control and disturbance vector.

The prime objective is to minimize the ACE which stabilizes the system frequency for a sudden load disturbance. The objective function of the load frequency controller [19] is given by,

\[ ACE_i = \beta \Delta F_i + \Delta P_{tie,i} \]  

where \( i \) = Number of areas, \( \Delta F \) = Change in frequency, \( \Delta P_{tie} \) = Change in tie-line power and \( \beta \) = Biasing factor.

Lin and Huang [20] and N.Kanagaraj et al. [21] proposed some different method of designing the fuzzy supervisory controller. In most of the works [22,23], the error and change in error have been used for decision making in supervisory fuzzy system. These control parameters are not suitable for different load disturbances. To overcome such a problem, the error and plant input have been selected as the decision making input parameters of the supervisory fuzzy systems. The expert supervisory fuzzy systems determine the scaling factor for the direct fuzzy controller.

3.1 Direct Fuzzy Logic Controller

Based on the earlier research results the stabilization of frequency in a parallel AC-DC interconnected power systems, we design the direct fuzzy logic controller [10, 19]. Fuzzy set theory and fuzzy logic establish the rule of a nonlinear mapping. The use of fuzzy sets provides a basis for a systematic way for the application of uncertain and indefinite models. The design of direct fuzzy controller can be normally divided into three areas namely allocation of area inputs, determination of rules and defuzzifying of output into a real value.

The method of fuzzification has found increasing application in power system. In this FLC, membership function (MF) specifies the degree to which a given input belongs to a set. In the Power system network, the frequency is one of the sensitive parameter. By using triangle shape membership function even a small change in the input magnitude can be identified and the corresponding output will be applied to the plant to bring the system to stabilize quickly. Hence the triangular membership functions have been chosen for the inputs of Error (E), change in Error (\( \Delta E \)) and output (\( u \)).

The input range for the \( E, \Delta E \) and control output (\( u \)) are normalized based on the load disturbance from the normal operation. The linguistic descriptions of input membership functions are Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The output membership functions are Zero (ZE), Very Small (VS), Small (S), Medium (M), Large (L), Very Large (VL) and Very Very Large (VVL). The union minimum operation has been selected for the fuzzy implication. For the two-input fuzzy system, it is generally expressed as,

\[ \mu_{A_1(x_1) \cap A_2(x_2)} = \min \{ \mu_{A_1(x_1)}, \mu_{A_2(x_2)} \} \]  

where \( A_1(x_1) \) and \( A_2(x_2) \) are input fuzzy sets. The rule base of the fuzzy controller relates the premise (\( E \) and \( \Delta E \)) to consequent (\( u \)). Practically the load on the power system is time variant. The power demand is increased during peak load and reduced during light load. If the power demand is increased or decreased, it will affect the system frequency. By utilizing control techniques, the power demands are satisfied and the system frequency is maintained within the specified limit. Based on the system framework 49 linguistic fuzzy control rules are developed. Table 1 lists 49 linguistic fuzzy control rules.
rules for the fuzzy controller. The structure of the control rules of the fuzzy controller with two inputs and a one output is expressed as,

\[ \text{If (E is NS and } \Delta E \text{ is ZE) then control signal } u \text{ is VS} \] (4)

The centroid defuzzification has been made to find the crisp value of output. The centroid defuzzification is defined as,

\[ U_{\text{Crisp}} = \frac{\sum_{i=1}^{n} u_i \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)} \] (5)

where \( U_{\text{Crisp}} \) is the output of the fuzzy controller, \( u_i \) denotes the centre of the membership function of the consequent of \( i \)-th rule, \( \mu \) denotes the membership value for the rule’s premise and \( n \) represents the total number of fuzzy rules.

### 3.2 Supervisory Expert Fuzzy Controller

The rule base SEFC is developed to tune the direct fuzzy controller’s input scaling factor. These online scaling factor modifications, namely \( K_1 \) and \( K_2 \) values respectively, improve the controller performance and reduce the involvement of human operation. The structure of SEFC is shown in Figure 2. The universe of discourse of input and output of the SEFC is chosen based on the maximum allowable range of the power generation area.

The three triangular membership functions are used for the inputs and outputs. The area control error input membership functions are represented by N (negative), Z (zero) and P (positive). The input \( u \) and output membership functions are represented by L (low), M (medium) and H (high). The linguistic variables of supervisory fuzzy rules are given in Table 2. The rule base of the proposed SEFC system is expressed as:

\[ \text{If ACE is N and } u \text{ is L then } K_1 \text{ is L and } K_2 \text{ is H} \] (6)

### 4. Result and Discussion

In this paper, a three area non reheat interconnected AC/DC thermal power system has been considered for the system study. It is shown in Figure 3. The simulation tests were carried out to compare system dynamic response under similar conditions of operation of the power system.

For the system study, conventional integral control, conventional fuzzy control and SEFC control scheme have been applied for the three area interconnected AC/DC power system. The three area thermal power system data are given in the appendix. The system study is carried out by the MAT LAB software. The system is simulated for a step load disturbance of 10% (0.1 p.u.MW) occurring in area-1. Due to this, change in dynamics response of the system has been observed. Figures 4, 5, and 6 indicate the frequency deviations of area 1, 2, and 3 for

---

**Table 1. Fuzzy control rules**

<table>
<thead>
<tr>
<th>( \Delta E )</th>
<th>NL</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>VS</td>
<td>S</td>
<td>M</td>
</tr>
<tr>
<td>NM</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>ZE</td>
<td>S</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td>VS</td>
<td>VS</td>
<td>M</td>
<td>L</td>
<td>VL</td>
</tr>
<tr>
<td>E</td>
<td>ZE</td>
<td>ZE</td>
<td>VS</td>
<td>S</td>
<td>S</td>
<td>L</td>
<td>VL</td>
</tr>
<tr>
<td>PS</td>
<td>VS</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>VL</td>
<td>VVL</td>
<td>VVL</td>
</tr>
<tr>
<td>PM</td>
<td>S</td>
<td>M</td>
<td>L</td>
<td>L</td>
<td>VVL</td>
<td>VVL</td>
<td>VVL</td>
</tr>
<tr>
<td>PL</td>
<td>M</td>
<td>L</td>
<td>VL</td>
<td>VL</td>
<td>VVL</td>
<td>VVL</td>
<td>VVL</td>
</tr>
</tbody>
</table>

---

**Table 2. Supervisory expert fuzzy control rules**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>U</td>
</tr>
<tr>
<td>N</td>
<td>L</td>
</tr>
<tr>
<td>Z</td>
<td>M</td>
</tr>
<tr>
<td>P</td>
<td>L</td>
</tr>
</tbody>
</table>

---

**Figure 2. Structure of the SEFC scheme.**
a step load disturbance in area-1.

From Figure 4 we can infer that in conventional integral control, there is an overshoot and the frequency stabilization occurs only after 10 seconds. In conventional fuzzy logic control, overshoot is eliminated and the frequency stabilization occurs after 7 seconds. Whereas in SEFC there is no overshoot and the frequency stabilization occurs within 2.5 seconds. Figure 5 shows the frequency deviation in area-2 for a 10% disturbance in area-1. We can observe the same result except that the frequency stabilization takes place in 11.4 seconds for conventional integral control, in 7.6 seconds for conventional fuzzy logic control and in 4.5 seconds for SEFC. Similarly from Figure 6, which is the frequency deviation in area-3 for a 10% disturbance in area-1, we can observe the frequency stabilization as 11.2 seconds for conventional integral control, 6.5 seconds for conventional fuzzy logic control and 2.5 seconds for SEFC. Also the same study is done in the system’s response for a step-load disturbance of 30% (0.3 p.u.MW) occurring in area-1 and the frequency deviations of area 1, 2, and 3 are shown in Figures 7, 8 and 9 respectively.

From the comparison, we can observe that the proposed SEFC instantly responds to the step load disturbance and make the system stability within a short time. The effectiveness of the proposed control has been compared by using error criteria such as Integral Square Error (ISE), Integral of the Absolute value of Error (IAE) and settling time. The formulae of the ISE and IAE are

![Figure 4](image4.png)  
**Figure 4.** Frequency deviation in area-1 for a 10% disturbance in area-1.

![Figure 5](image5.png)  
**Figure 5.** Frequency deviation in area-2 for a 10% disturbance in area-1.
The performance by numerical comparison for a step load disturbance of 10% and 30% are presented in Table 3. From this table, we can observe that the ISE and IAE in SEFC are less compared to the conventional integral and conventional fuzzy controls. Also the settling time in SEFC is faster than the conventional integral and conventional fuzzy controls.

Practically load on the power systems are continuously varied from time to time. In order to test the robustness of the proposed controller, different step load disturbances have been applied for different time periods as shown in Figure 10.

It is seen from the Figure 10 that in SEFC, at the time of 10% load disturbance, the frequency stabilization occurs within 2.5 seconds. At 16 seconds, another 10% of load disturbance is applied. Frequency stabilization occurs within 3 seconds. At the time of 31 seconds the load disturbance is increased from 20% to 40%. During that

<table>
<thead>
<tr>
<th>Table 3. Performance comparison of different control techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of Control</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Integral Control</td>
</tr>
<tr>
<td>Fuzzy Control</td>
</tr>
<tr>
<td>Supervisory Expert Fuzzy Control</td>
</tr>
</tbody>
</table>

given as,

\[
ISE = \int_0^\infty ACE^2 \, dt \tag{7}
\]

\[
IAE = \int_0^\infty |ACE| \, dt \tag{8}
\]

Figure 6. Frequency deviation in area-3 for a 10% disturbance in area-1.

Figure 7. Frequency deviation in area-1 for a 30% disturbance in area-1.

Figure 8. Frequency deviation in area-2 for a 30% disturbance in area-1.

Figure 9. Frequency deviation in area-3 for a 30% disturbance in area-1.
condition, the frequency stabilization occurs within 3.2 seconds. Similarly, in the same system, if the load disturbance is reduced by 50% at a time of 46.5 seconds, the frequency stabilization occurs within 4.8 seconds. Even though the load has been suddenly reduced, the proposed SEFC reacts perfectly. The results of different load disturbances show that the robustness of the proposed SEFC technique is better than the conventional integral and conventional fuzzy control techniques.

5. Conclusion

Increasing power demand leads to more complexity and less reliability of interconnected power systems. Insufficient transmission capability of the interconnection leads to bottle necks in the system and reduce the system security. In this paper, the stability and robustness of different controllers have been studied to improve the dynamic performance of the interconnected AC/DC power system. The results are proved that the proposed SEFC stabilizes the frequency deviation with in short duration under sudden load disturbance especially when the connected AC links are weak and when there is no sufficient reserve power capacity in the neighboring areas. From the error criteria such as ISE, IAE and settling time, the proposed controller performance proved to be better than the conventional integral and fuzzy controllers.

From the results, the performance of the conventional integral and conventional fuzzy controllers were not up to the expected level in terms of eliminating disturbance, because these controllers are designed to operate in limited range. By means of online tuning concept, the proposed SEFC technique is very effective in suppressing the frequency derivation of parallel AC/DC multi area interconnected power systems.

Acknowledgements

We would like to thank our Dean-EEE Dr. K. Nallathambi and our Director Dr. N. Kanagaraj, Department of Electrical and Electronics Engineering, K.S.R. College of Engineering, Tiruchengode, Tamil Nadu, India, for their valuable suggestions throughout this work. We also thank the management of K.S.R. College of Engineering for the facilities provided to prepare this paper.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>Area Control Error</td>
</tr>
<tr>
<td>ALFC</td>
<td>Automatic Load Frequency Control</td>
</tr>
<tr>
<td>FLC</td>
<td>Fuzzy Logic Control</td>
</tr>
<tr>
<td>HVDC</td>
<td>High-Voltage Direct Current</td>
</tr>
<tr>
<td>K_ps</td>
<td>Power system gain</td>
</tr>
<tr>
<td>LFC</td>
<td>Load Frequency Controller</td>
</tr>
<tr>
<td>R</td>
<td>Speed regulation of the governor</td>
</tr>
<tr>
<td>SEFC</td>
<td>Supervisory Expert Fuzzy Controller</td>
</tr>
<tr>
<td>T_ps</td>
<td>Power system time constant</td>
</tr>
<tr>
<td>T_g</td>
<td>Speed governor time constant</td>
</tr>
<tr>
<td>T_t</td>
<td>Turbine time constant</td>
</tr>
<tr>
<td>T_DC</td>
<td>HVDC modulation time constant</td>
</tr>
</tbody>
</table>

Figure 10. Performance comparison of frequency deviation in area-1 for a different load disturbance.
\[ \beta \quad \text{Biasing Factor} \]
\[ \Delta F \quad \text{Incremental Frequency Deviation} \]
\[ \Delta P_{dc} \quad \text{Incremental change in tie line power} \]
\[ \Delta P_d \quad \text{Incremental load demand change} \]
\[ \Delta P_{AC} \quad \text{Incremental change in AC tie line power} \]
\[ \Delta P_{DC} \quad \text{Incremental change in DC tie line power} \]
\[ \Delta P_c \quad \text{Incremental change in speed changer position} \]
\[ \Delta P_g \quad \text{Incremental change in generation demand change} \]
\[ \Delta X_e \quad \text{Incremental change in valve position} \]

**Appendix**

**System Data**
Three area thermal non reheat power systems
Rating \( P_{r1} = 1000 \text{ MW} \), \( P_{r2} = 500 \text{ MW} \) and \( P_{r3} = 2000 \text{ MW} \)
\( \beta_1 = \beta_2 = \beta_3 = 0.425 \text{ p.u. MW/Hz} \)
\( T_{t1} = T_{t2} = T_{t3} = 0.3 \text{ sec} \)
\( T_{g1} = T_{g2} = T_{g3} = 0.08 \text{ sec} \)
\( K_{ps1} = K_{ps2} = K_{ps3} = 120 \text{ Hz/p.u. MW} \)
\( 2\pi T_{t1} = 2\pi T_{t2} = 2\pi T_{t3} = 0.545 \)
\( T_{ps1} = T_{ps2} = T_{ps3} = 20 \text{ sec} \)
\( R_1 = R_2 = R_3 = 2.4 \text{ Hz/p.u MW} \)
\( K_M = -0.3201 \)
\( K_{APAC} = -2.144 \)

**References**


[16] Juang, C.-F. and Lu, C.-F., “Power System Load Fre-


