NONLINEAR CONTROLLER DESIGN FOR POWER SYSTEM USING NOVAL MATHEMATICAL TECHNIQUE

Rekha
Research Scholar, Electrical Engg. Dept., NIT Jamshedpur

A.K. Singh
Professor, Electrical Engg. Dept., NIT Jamshedpur

ABSTRACT

In this paper design of nonlinear controller for power system is considered. Due to effects like sudden fault, electric equipment failure, severe storms etc. the parameters of electric power system does not maintain the fixed value which results in the parametric uncertainties. To overcome these parametric uncertainties, different control techniques have been analyzed by different researchers. The objective of this paper is to design controller to achieve transient stability improvement and voltage regulation.

Different techniques for designing controller have been discussed and the mathematical tool used for carrying out the linearization is direct feedback linearization technique. In this paper different controllers like voltage regulator, excitation controller, co-ordinated controller and fuzzy controller has been discussed and the simulated results for co-ordinated and fuzzy controller has been compared. The fuzzy controller has been found to be simple and more adaptive compared to other controllers.

Keywords: linear quadratic regulator (LQR), direct feedback linearization (DFL), automatic voltage regulator (AVR), genetic algorithm (GA).

1. INTRODUCTION

When a sudden fault occurs in a power system, the post fault voltage value is no longer maintained equal to the pre-fault voltage value. Considering the practical point of view, voltage quality is known as a key index of power supply in power system operation. Thus, the post fault value should reach the normal value as soon as possible. Over the years, complex system’s control
has been carried out by experts using the conventional control technique like PID controller. Tuning of PID controller parameter is done by ZieglerNichol’s method [1] and the modification to the conventional controller to overcome the shortcomings has been done by Ramos et al [2] and Gurrala [3]. Several tuning methodology based on robust and optimal control techniques were introduced to the design of PI/PID controllers and auto tuning PID controller, adaptive PID controller and other unconventional techniques [4-8] have been carried out by different researchers. However these methods have limitations that they are applicable mostly for linear systems and not suitable for complex systems. To overcome the demerits of above methods, new techniques like neural network and fuzzy logic systems [9-11] have been found to be particularly powerful tools to control nonlinear systems because of their universal approximation properties. Instead of using a single controller for control of complex system, a switching control strategy has been suggested by Wang and Hill [12] to increase the transient stability and voltage regulation. The solution of switching time considerably affects the performance of this method. To overcome this drawback, a global control scheme was proposed [13] and a fuzzy based co-ordinated controller has been proposed in [14] to mitigate the power system oscillations as well as to regulate the terminal voltage of generator. In case, where the state of the nonlinear system is unmeasured, adaptive output feedback control method [15] may be an effective way to control the system.

Automatic voltage regulator (AVR) systems and conventional power system stabilizer (PSS) contribute to the stability of power system but their independent use does not necessarily guarantee the best performance in the system stability. Therefore, they are mixed together and an integrated control strategy is used to stabilize power system.

The layout of the paper is as follows. The general overview of the process and controller is discussed in section 2. In Section 3, the theoretical background of the nonlinear controller design for power system has been presented. Linearization based on different techniques has been discussed which includes direct feedback method. The modeling of the system for different orders has been done here. Design of fuzzy based controller and its modeling has been presented in section 4. In section 5, simulated results for excitation, steam valve control and fuzzy controller based performance are presented to support the theoretical formulations. And finally the paper is concluded by brief remarks in section 6.

2. SYSTEM MODELING

The dynamical model for the power system consists of a single generator connected through the two parallel transmission lines to a very large network approximated by an infinite bus.

Block diagram consisting of system under consideration and controller is given in figure 1 where r (t) is the reference input which may be electrical excitation, u(t) is the controlled input and y(t) is the output.

![Figure 1: Block diagram representation for controller design](image)

Controller may be a conventional controller, robust controller, adaptive controller, fuzzy controller or genetic algorithm (GA) based controller. Here different controllers are implemented on single machine infinite bus (SMIB) power system. The proposed fuzzy controller uses speed
deviation and deviation in terminal voltage as inputs which are measurable signals and produce the signal required to control the power system.

**Figure 2:** Schematic diagram for SMIB system

Figure 2 presents schematic diagram for the system whose modeling has been carried out. The governing equations for the system discussed above (figure 2) is given below with significance of the terms mentioned in the appendix.

Mechanical equations for system are given as:

\[
\Delta \delta(t) = \omega(t) \\
\omega(t) = \frac{-B}{H} \omega(t) - \frac{\omega_0}{H} \Delta P_e(t)
\]  

2.1

2.2

Generator Electrical Dynamic equation is given as:

\[
\dot{E}_q(t) = \frac{1}{T_{do}} (E_f(t) - E_q(t))
\]

2.3

Turbine Dynamics and turbine valve control equations are given below as:

\[
P_m(t) = -\frac{1}{T_q} P_m(t) + \frac{K_T}{T_q} X_E(t)
\]

2.4

\[
\dot{X}_E(t) = -\frac{1}{T_g} X_E(t) + \frac{K_g}{T_g} \left[ P_c(t) - \frac{1}{R_w} w(t) \right]
\]

2.5

Electrical Equations for the above power system consisting of turbine, generator and controls are given as:

\[
E_q(t) = \frac{x_{ds}}{x_{ds}} E_q'(t) - \frac{x_{d} - x_{dq}'}{x_{ds}} V_s \cos \delta(t)
\]

2.6

\[
E_f(t) = K_e u_f(t)
\]

2.7

\[
P_e(t) = \frac{V_s E_q(t)}{x_{ds}} \sin \delta(t)
\]

2.8

\[
l_q(t) = \frac{V_s}{x_{ds}} \sin \delta(t) = \frac{P_e(t)}{x_{ad} f(t)}
\]

2.9

\[
Q_e(t) = \frac{V_s}{x_{ds}} E_q(t) \cos \delta(t) - \frac{V_s^2}{x_{ds}}
\]

2.10

\[
E_q(t) = x_{ad} l_f(t)
\]

2.11

\[
V(t) = \frac{1}{x_{ds}} \left( x_s^2 E_q^2(t) + V_s^2 \frac{x_s^2}{2} + 2x_s x_d x_{ds} P_e(t) \cot \delta(t) \right)^{1/2}
\]

2.12

### A. Category of fault

The fault considered in this paper is three phase short circuit fault occurring on one of the transmission line.
Different types of fault considered in this paper are:

Case 1: Permanent fault
(i) Fault occurred at 0.1 sec.
(ii) Fault removed by opening breaker of faulted line at t = 0.25 sec.
Note: The system is in post-fault stage.

Case 2: Temporary fault
(i) Fault occurred at 0.1 sec.
(ii) Fault removed by opening breaker of the faulted line at t = 0.25 sec.
(iii) Transmission lines are restored at t = 1.4 sec.
Note: The system is in post-fault stage.

3. NONLINEAR CONTROLLER DESIGN FOR POWER SYSTEMS

A power system network is a complex system with various specifications, which is difficult to control practically. For these reasons, many a times controller are developed omitting some insignificant parameters to partially satisfy the specifications.

To analyze the nonlinear problem, linearization is done to apply linear control techniques. Different linearization techniques such as Jacobian, Carleman, linearization using Lie series, iterative technique, feedback linearization and linearization via changes of variables are used as reported in the literature.

In this section direct feedback linearization (DFL) technique to linearize the system is considered. By this technique, compensation schemes are adopted to partially or totally cancel non-linearities present in input-output relationship, so that output or state dynamics are transformed into equivalent linear time invariant dynamics.

3.1 Linearization based on Direct feedback linearization

The model of the generator assuming mechanical power and valve excitation as fixed parameter are considered first so that the order of the system reduces to three. We use direct feedback linearization (DFL) to design a nonlinear controller for the power system.

Since $E_q(t)$ (as given in appendix) is physically immeasurable, we eliminate $E_q(t)$ by differentiating equation number 2.8 and using 2.1 to 2.8. The detail of process is given below:

$$P_e(t) = \frac{V_s E_q(t)}{x_{ds}} \sin \delta(t) \quad \text{3.1}$$

Taking derivative of equation 2.8, we have

$$\frac{dP_e}{dt} = \frac{V_s E_q(t)}{x_{ds}} \cos \delta(t) \frac{d\delta(t)}{dt} + \frac{V_s}{x_{ds}} \sin \delta(t)$$

$$= \frac{V_s}{x_{ds}} \left[ E_q(t) \cos \delta(t) \omega(t) \right] + \frac{V_s}{x_{ds}} \sin \delta(t) \left[ \frac{x_{ds} dE_q}{dt} + \frac{x_d - x_d'}{x_{ds}} V_s \sin \delta(t) \omega(t) \right]$$

$$= \frac{V_s}{x_{ds}} \left[ E_q(t) \cos \delta(t) \omega(t) \right] + \frac{V_s \sin \delta(t)}{x_{ds}} \left[ \frac{x_{ds} E_f(t) - E_q(t)}{T_{do}} + \frac{(x_d - x_d')}{x_{ds}'} V_s \sin \delta(t) \omega(t) \right]$$
The model (1) to (3) is therefore linearized and the model is given below:

\[
\frac{-P_e(t)}{T_{do}} + \frac{1}{T_{do}} \left\{ \frac{V_s \sin(t)}{x_{ds}} \left[ K_c u_f(t) + T_{do} (x_d - x_d') \frac{V_s}{x_{ds}} \sin(t) \omega(t) \right] + \frac{T_{do}'}{x_{ds}} V_s E_q(t) \cos(t) \omega(t) \right\}
\]

We have: \( \Delta P_e = P_e - P_m \)

\[
-\frac{P_e(t)}{T_{do}} + \frac{1}{T_{do}} \left\{ \frac{V_s \sin(t)}{x_{ds}} \left[ K_c u_f(t) + T_{do} (x_d - x_d') \frac{V_s}{x_{ds}} \sin(t) \omega(t) \right] + \frac{T_{do}'}{x_{ds}} V_s E_q(t) \cos(t) \omega(t) \right\} - \frac{P_m}{P_m}
\]

Therefore

\[
\frac{d\Delta P_e}{dt} = \frac{-\Delta P_e(t)}{T_{do}} + \frac{v_f(t)}{T_{do}}
\]

where

\[
v_f(t) = \frac{v_s \sin(t)}{x_{ds}} \left[ K_c u_f(t) + T_{do} (x_d - x_d') \frac{V_s}{x_{ds}} \sin(t) \omega(t) \right] + T_{do}' \frac{V_s}{x_{ds}} E_q(t) \cos(t) \omega(t) - P_m
\]

The model (1) to (3) is therefore linearized and the model is given below:

\[
\frac{d\delta(t)}{dt} = \omega(t)
\]

\[
\frac{d\omega(t)}{dt} = -\frac{D}{2H} \omega(t) - \frac{\omega_0 \Delta P_e(t)}{2H}
\]

\[
\frac{d\Delta P_e}{dt} = -\frac{\Delta P_e(t)}{T_{do}} + \frac{v_f(t)}{T_{do}}
\]

where \( v_f(t) \) is the new input; the inverse mapping of equation 3.7 gives

\[
u_f(t) = \frac{1}{K_c} \left\{ \frac{x_{ds}}{V_s \sin(t)} \left[ v_f(t) - T_{do}' \frac{V_s}{x_{ds}} E_q(t) \cos(t) \omega(t) + P_m \right] - T_{do} (x_d - x_d') \frac{V_s \sin(t) \omega(t)}{x_{ds}} \right\}
\]

which is defined except when \( \sin(t) = 0 \)

\[
\frac{1}{K_c \ell_q(t)} \left\{ v_f(t) - T_{do}' \left[ Q_e(t) + \frac{V^2_s}{x_{ds}} \omega(t) + P_m \right] - \frac{(x_d - x_d')}{K_c} T_{do} \omega(t) \ell_q(t) \right\}
\]

Equation 3.9 is independent of \( \delta(t) \) that is not measurable. For the linearized model obtained, \( v_f(t) \) is the new input which acts as controller for this power system problem.

**Case 1: Third order system**

The third order linearized model after carrying out linearization as given in previous section is given by equation 3.8-3-10.

\[
\begin{align*}
\dot{\delta}(t) &= \omega(t) \\
\dot{\omega}(t) &= -\frac{D}{2H} \omega(t) - \frac{\omega_0 \Delta P_e(t)}{2H} \\
\Delta P_e(t) &= -\frac{1}{T_{do}} \Delta P_e(t) + \frac{1}{T_{do}} v_f(t)
\end{align*}
\]

(A)
where \( \Delta P_e = P_e - P_{m0} \)

\[
T'_d = \frac{x ds}{x ds} T_{do}
\]

\[
v_f = \frac{V_s}{x ds} \sin \delta \left[ kcf u + Tdo'(xd - x'd) \frac{V_s}{x ds} \sin \delta w \right] + T' \frac{V_s}{x ds} Eq \cos \delta w - P_{m0}
\]

\( v_f(t) \) is the new input, which is given by equation (3.4). This implies that it depends on system parameters. After carrying out the linearization by using DFL, we see that the linearized model is independent of the operating point of the system which makes the nonlinear controller more flexible compared to linear controller.

The first order differential equations can be represented using state model as

\[
\dot{x}(t) = Ax(t) + Bu(t)
\]

where

\[
x(t) = [\delta(t) \ w(t) P_e(t)]^T
\]

\( A \) and \( B \) are the matrices containing the system parameter obtained from model.

The simulation results for the above controllers have been presented in the simulation section. It is inferred from the analysis of above controllers that excitation controller is not able to keep system transiently stable in all fault conditions. When fault is very near to generator bus, then the system is not transiently stable.

**Case 2: Fifth order system**

While designing the model, so far mechanical behavior of the system was not considered. In this section, the model of the system is modified to include the mechanical behavior of the system which has been assumed as constant previously for simplifying the analysis.

In the previous controller design, mechanical parameters were taken as constant whereas for obtaining stabilized response under all possible fault conditions, mechanical parameters cannot be assumed constant, so the model is further modified to a fifth order system. Mechanical power and valve excitation (given by equation 2.4 and 2.5) are also considered here which has been discussed by Wang, Hill and Guo. \[12, 13\].
And the inputs are:
\[ u(t) = [v_f(t)P_c(t)]^T \]

3.17

Mechanical behavior of steam valve comes into action during transient period. To achieve overall system stability, the feedback control law is structured as:
\[
\begin{bmatrix}
  v_f(t) \\
  P_c(t)
\end{bmatrix} = -\begin{bmatrix}
  k_{\theta 1} & k_{\omega 1} & k_{e 1} & 0 & 0 \\
  k_{\theta 2} & k_{\omega 2} & k_{e 2} & k_{m 2} & k_{x 2}
\end{bmatrix} x(t)
\]

3.18

Where \( v_f(t) \) is the new input to the system which depends on electrical parameters and \( P_c(t) \) is the input which is depending on both electrical as well as mechanical system parameters. So the controller design using the above structure can be realized as:

\[
\begin{align*}
  v_f(t) &= f(\delta(t), \omega(t), P_c(t)) \\
  P_c(t) &= f(\delta(t), \omega(t), P_c(t), P_m(t), X_e(t))
\end{align*}
\]

3.19

3.20

4 FUZZY DYNAMICAL MODEL

Fuzzy control is a family of methods for expressing and applying control laws, using fuzzy sets to provide several benefits. First, they provide the ability to express and use incomplete knowledge of the system being controlled and of the control law itself. Second, they allow one to specify a complex control law as the composition of simple components; third, fuzzy set membership functions provide smooth transitions from region to region.

Fuzzy control consists of two distinct approaches:

1. Fuzzy logic control determines the control action by a combination of fuzzy logic rules.
2. Heterogeneous control determines the control action as the weighted average of classical control law.

Instead of using the controllers discussed above, the system can be realized with the help of fuzzy controller which has been effectively used for many nonlinear systems which is discussed in Wang [10] paper.

The block diagram representation of how fuzzy is added to system has been shown in below figure (2). Majority of the research work on fuzzy PID controllers focuses on the conventional two-input PI or PD type controller proposed by Mamdani. However, fuzzy PID controller design is still a complex task due to involvement of large number of parameters in defining the fuzzy rule base.

![Figure 3: Implementation of fuzzy controller to nonlinear system](image)
4.1 Mathematical formulation for fuzzy controller

A general state model for nonlinear system is described below as:

\[ x(t) = f(x(t), u(t)) \]  \hspace{1cm} (4.1)

Where \( x(t) \in R^n \) is the state variable
\( u(t) \in R^p \) is the input of system

The state model equation can be simplified by using local operating regions. Linearization around several operating points of the system give:

\[ R_l : \text{If } x_1 \text{ is } F_1^l \text{ and } x_2 \text{ is } F_2^l \text{ and……. And } x_n \text{ is } F_n^l \]

Then
\[ \dot{x}(t) = A_l x(t) + B_l u(t) \text{ where } l = 1,2,3… n \]

\( R_l \) denotes the \( l \)th approximation inference rule, \((A_l, B_l)\) represents the \( l \)th local model of fuzzy system given by equation 4.2

\[ F^l = \pi^n_{i=1} F_i^l \text{ (l=1,2,…,m) denotes fuzzy sets in state space.} \]

\( M \) is the number of approximation inference rules, and
\( x(t) = (x_1(t), x_2(t), \ldots x_n(t)) \)

Let \( \mu_l(x(t)) \) is normalized membership function of the inferred fuzzy set \( F^l \) and it satisfies the condition \( \sum_{i=1}^{m} \mu_i = 1 \)

Using center average defuzzifier, product inference and singleton fuzzifier, the dynamical model can be expressed by the following global model.

\[ \dot{x}(t) = A(\mu(t))(x(t) + B(\mu(t))u(t)) \]  \hspace{1cm} (4.3)

Where \( A(\mu(t)) = \sum_{i=1}^{m} \mu_i A_i \), \( B(\mu(t)) = \sum_{i=1}^{m} \mu_i B_i \)
\( \mu(t) = (\mu_1(t), \mu_2(t), \ldots, \mu_n(t)) \)

The fuzzy global model given by equation 4.3 is smooth aggregation of the local linear models through nonlinear membership functions. So we infer that any continuous nonlinear function can be approximated to any degree of accuracy on any compact set.

The \( m \) local regions in state space are defined as:
\( S_l = \{ x \mid \mu_i(x) \geq \mu_i \quad i = 1,2, \ldots, m, i \neq l \} \)

The characteristic function of \( R_l \) is defined by

\[ n_l = \begin{cases} 1, & x \in S_l \\ 0, & \text{otherwise} \end{cases} \sum_{l=1}^{m} n_l = 1 \]

In every local region, the system can be expressed by following set of models:

\[ \dot{x}(t) = (A_i + \Delta A_i(\mu))x(t) + (B_i + \Delta B_i(\mu))u(t) \]  \hspace{1cm} (4.4)

Where \( \Delta A_i(\mu) = \sum_{l=1, l \neq i}^{m} \mu_i \Delta A_{il} \), \( \Delta B_i(\mu) = \sum_{l=1, l \neq i}^{m} \mu_i B_{il} \)
\( \Delta A_{il} = A_i - A_l \), \( \Delta B_{il} = B_i - B_l \)

The stabilizing control law can be chosen as
\( u(t) = K(\mu(t))x(t) \)  \hspace{1cm} (4.5)
As membership functions are nonlinear functions of $x(t)$, $K(\mu(t))$ is a nonlinear function of $x(t)$. The closed loop system is obtained from the feedback interconnection of equation 4.4 and 4.5, which is written as

$$\dot{x}(t) = A_{cl}(\mu)(x(t))$$  \hspace{1cm} \text{(4.6)}

Where $A_{cl}(\mu) = A_I + \Delta A_I(\mu(t))x(t) + [B_I + \Delta B_I(\mu(t))]K(\mu(t))x(t)$

To the above model obtained, all linear controller design methods can be applied in local region controller construction and global controller will be interconnection of local controllers which in turn become non-linear. For the system considered in this paper, the fuzzy controller is designed by using matlab-simulink tool. The model is prepared as shown in figure (3). The simulation result for the model is presented in the next section. The fuzzy controller thus designed gives smoother and stabilized output.

4.2 Modeling for fuzzy controlled system

The simulation model designed for the third order system using fuzzy controller has been shown in figure (3). The response for the terminal voltage and power angle has been shown, for the three phase fault occurring on one of the transmission line. The result can be further modified by using the fifth order system where the mechanical parameters are also considered as for practical system it cannot be ignored.

**Figure 4:** Modeling for fuzzy controller based power system

5 SIMULATION RESULTS

For carrying out the simulation for the different types of controller, different cases of fault are taken. The fault considered here is a three phase short circuit fault occurring on one of the transmission line. The location of the fault is represented by lambda value which is varying from 0 to
1. A value zero means fault is at the generator. Different values of lambda such as 0.2, 0.5 etc. are taken for doing simulation which represents location of fault.

**Case 1: Third order system**

For the third order system developed in section 3.2, MATLAB m-files have been written and the simulation results obtained so is presented in this section. Data assumed for carrying out the simulation is given in appendix which consists of generator, transformer and transmission line parameters. Here lambda which presents the fault location is taken as 0.2. Figure 4(a) and 4(b) shows the results for a third order system for the DFL-LQ controller, voltage regulator and excitation controller for initial power angle of 47 degree. Equation 3.13 to 3.15 shows the parameters on which the three controllers depend. Figure 4(a) shows the response for power angle for all the three controllers and figure 4(b) shows the terminal voltage for the three controllers.

![Figure 5(a): Power angle response for different controllers](image1)

![Figure 5(b): Terminal voltage response for different controllers](image2)

With change in fault location, the responses for power angle and terminal voltage changes. It is presented in figure 5(a) and 5(b). The simulation has been done for voltage regulator, \( \lambda = 0.2 \) for the lambda (fault location) value of 0.1 and 0.2 respectively.

![Figure 6(a): Power angle response for voltage regulator (different fault location)](image3)

![Figure 6(b): Terminal voltage response for voltage regulator (different fault location)](image4)
Table -1: Comparative results for different controllers

<table>
<thead>
<tr>
<th>Controller parameter</th>
<th>Power angle</th>
<th>Terminal voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFL-LQ controller</td>
<td>Reaches initial angle of $47^\circ$ after fault cleared</td>
<td>Steady state value not reached (1.05 p.u)</td>
</tr>
<tr>
<td>voltage regulator</td>
<td>Reaches value of $53^\circ$ after fault cleared</td>
<td>Reaches steady state value (1 p.u)</td>
</tr>
<tr>
<td>Excitation controller</td>
<td>Reaches value of $53^\circ$ after fault cleared</td>
<td>Reaches steady state value (1 p.u)</td>
</tr>
</tbody>
</table>

The comparative results for controllers have been presented in the above table 1. The response has also been obtained for different value of lambda for voltage regulator which shows that power angle overshoot increases with reduced value of lambda that implies that system becomes more unstable when fault is very nearer to generator bus.

Case 2: Fifth order system

Co-ordinated controller design has been done for fifth order system which is discussed in section 3.3. Here two new inputs $v_f(t)$ and $p_c(t)$ presents the controller input. The response of the system with and without power input control has been compared by plotting it on the same plane. Figure 6(a) and (b) presents the power angle and terminal voltage for co-ordinated controller where the system analyzed is of fifth order. It is compared with excitation controller presented in previous figures.

![Figure 7(a): Power angle response for excitation and co-ordinated controllers](image1)

![Figure 7(b): Terminal response for voltage excitation and co-ordinated controller](image2)

From the simulation results, we see that using excitation and co-ordinated controller, the post fault value of power angle is achieved equal to prefault value but regarding terminal voltage output, co-ordinated controller result is better than that of excitation controller as steady state error is eliminated. So it can be concluded that co-ordinated controller performs better in stabilizing the system.
Case 3: Fuzzy controlled system

For the model discussed in section 4 of fuzzy controller, the simulation results for power angle and terminal voltage for a fuzzy based controller is obtained which is presented in figure 7(a) and 7(b) respectively. Here while modeling fuzzy controller: speed, acceleration and terminal voltage are taken as input variables as these are the parameters which are to be monitored during the transient condition. During pre-fault and fault condition, speed and acceleration are taken as two inputs whereas during post-fault period, speed and terminal voltage are taken as input. This is due to the fact that steady state error in the terminal voltage is to be minimized in post fault period. In both the cases, the controlled output is produced which is given to the process.

![Figure 8: Response of system for fuzzy controller](image)

6 CONCLUSION

It can be concluded that by linearizing and reducing the order of the system, the system representation becomes simpler but it is seen that the system’s performance is not to the mark when dynamical system is considered. From the model obtained for the fifth order system, it has been observed that the two new inputs are $v_f(t)$ and $P_c(t)$. In this paper linear quadratic (LQ) regulator optimal control theory is used for designing. In later sections, instead of the LQ controller, it has been realized with the help of fuzzy controller.

The simulation results for the third order system with and without fuzzy controller has been obtained. The fuzzy controller has been found to be better optimized in case of parameter variation. There is a probability of improving the result of fuzzy controller if implemented for fifth order system. The result can be further modified by modifying the rule base and selecting different fuzzy inputs as fine tuning of fuzzy rules can be carried out either by human expert or by optimization tool such as GA.
APPENDIX

The following abbreviations are used while designing the model:

\[ \Delta \delta(t) = \delta(t) - \delta_0 \]

\[ \delta(t) = \text{Power angle of the generator} \]

\[ \delta_0 = \text{power angle of the generator at the operating point;} \]

\[ \omega(t) = \text{the relative speed of the generator} \]

\[ \Delta P_e = P_e(t) - P_m \]

\[ P_m = \text{mechanical input power} \]

\[ P_e = \text{active electric power delivered by the generator;} \]

\[ \omega_0 = \text{synchronous machine speed; } \omega_0 = 2\pi f_0 \]

\[ D = \text{per unit damping constant} \]

\[ H = \text{per unit inertia constant} \]

\[ E_q(t) = \text{the transient emf in the quadrature axis} \]

\[ E_f(t) = \text{the equivalent emf in the excitation coil;} \]

\[ T_{ds} = \text{the direct axis transient short circuit time;} \]

\[ Q_e(t) = \text{the reactive power} \]

\[ I_f(t) = \text{the excitation current} \]

\[ I_q(t) = \text{the quadrature axis current;} \]

\[ V_s = \text{the infinite bus voltage;} \]

\[ K_c = \text{the gain of the excitation amplifier;} \]

\[ u_f(t) = \text{the input of the SCR amplifier of the generator} \]

\[ x_{ds} = x_T + \frac{1}{2} x_L + x_d'; \]

\[ x_{ds}' = x_T + \frac{1}{2} x_L + x_d'; \]

\[ x_T = \text{reactance of the transformer} \]

\[ x_d = \text{direct axis reactance} \]

\[ x_L = \text{the reactance of transmission line;} \]

\[ \frac{1}{2} x_L \]

\[ x_{ed} = \text{the mutual reactance between the excitation coil and the stator coil;} \]

\[ V_s = \text{the infinite bus voltage;} \]

\[ X_E(t) = \text{steam valve opening} \]

\[ T_T = \text{the time constant of the turbine with typical numerical value of 0.2 to 2.0 sec} \]

\[ K_G = \text{the gain of the speed governor} \]

\[ K_T = 1 \]

The parameters of SMIB power system are as follows:

\[ x_d = 1.863, \ x_d' = 0.257, \ x_T = 0.127 \]

\[ T_{ds} = 6.9, \ x_L = 0.4853, \ H = 4, \ D = 5, \]

\[ K_c = 1, \ x_{ad} = 1.712, \ w_0 = 314.159 \]

The physical limit of excitation voltage is taken as

\[ -3 \leq K_c u_f \leq 6 \]

The operating point of the power system used in simulation is:

\[ \delta_0 = 47, 72 \text{ and } 79 \text{ degree, } P_{m0} = 0.45 \text{ p.u and } 0.9 \text{ p.u, } V_{t0} = 1.0 \text{ p.u.} \]
REFERENCES