TRANSIENT STABILITY IMPROVEMENT IN A THREE-MACHINE POWER SYSTEM USING SSSC WITH NOVEL CONTROL STRATEGY

KAUSHAL KAPADNIS
PG Student, “Veermata Jijabai Technological Institute, Mumbai, India.

MANISH PATIL,
PG Student, “Veermata Jijabai Technological Institute, Mumbai, India

J.O. CHANDLE,
Associate Professor of E.E.E, “Veermata Jijabai Technological Institute

ABSTRACT—Abstract-For controlling of transient stability in a three-machine power system here we proposed a novel sssc with fuzzy logic controller based technique is here. The proposed fuzzy controller combines the advantages good response than the conventional method, the conventional lead lag controller have some drawbacks like low accuracy and more computation time to overcome that we used the SSSC with fuzzy controller.

Index Terms—Multi-machine power system; Fuzzy controller; static synchronous series compensator (SSSC); transient stability.

I. INTRODUCTION

There are number of faults in transmission system like LL, LG, LLL and LLLG due to this faults there a chance of transient instability in power system to avoid that and to improve the stability of the power system proposed controller has been applied and tested under different disturbances for a multi-machine power system which gives the better results than the conventional methods.

To overcome the faults in the system and to increase the stability, Series capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and there by increase the transmittable power. Recent development of power electronics introduces the use of flexible ac transmission system (FACTS) controllers in power systems. Subsequently, within the FACTS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the lines and in improving stability. The voltage sourced converter based series compensator, called static synchronous series compensator (SSSC) provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line.

The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the system. Static synchronous Series Compensator (SSSC) is one of the important members of FACTS family which can be installed in series in the transmission lines. With the capability to change its reactance characteristic from capacitive to inductive, the SSSC is very effective in controlling power flow in power systems. An auxiliary stabilizing signal can also be super imposed on the power flow control function of the SSSC so as to improve power system oscillation stability[7]. The applications of SSSC for power oscillation damping, stability enhancement and frequency stabilization can be found in several references [8-11]. Methodology has captured the interest in a large number of applications in electrical power engineering. The applications include economical load dispatching, power system stabilizers (PSS), etc. The results have shown that fuzzy controllers have great potential in improving power system online and off-line applications.

The system consists of three generators divided into two subsystems and are connected via an intertie. The artificial neural network controller based on fuzzy control, i.e., is applied for series FACTS device, i.e., static synchronous series compensator (SSSC). For the design purpose, MATLAB/Simulink model of the power system with SSSC controller is developed. Simulation results are presented at different operating conditions and under various disturbances to show the effectiveness of the proposed controller. The results prove that the proposed SSSC-based fuzzy controller can improve the voltage profile and transient stability of the test system more efficient than the conventional lead-lag controller of above devices.
II. PROPOSED DG MODEL

Power system under study

The multi-machine power system with SSSC shown in Fig. 1 is considered in this study. The system consists of three generators divided into two subsystems and are connected through an inter-tie. The generators are equipped with hydraulic turbine and governor (HTG) and excitation system. The HTG represents a nonlinear hydraulic turbine model, a PID governor system, and a servomotor. The excitation system consists of a voltage regulator and DC exciter, without the exciter’s saturation function. Following a disturbance, the two subsystems swing against each other resulting in instability. To improve the stability the line is sectionalized and a SSSC is assumed on the mid-point of the tie-line. In Fig. 1, \( G_1, G_2 \) and \( G_3 \) represent the generators; \( T/F_1, T/F_2 \) and \( T/F_3 \) represent the transformers and \( L_1, L_2 \) and \( L_3 \) represent the line sections respectively. The relevant data for the system is given in Appendix.

![Figure 1. Three-machine power system with SSSC](image)

FUZZY CONTROLLER APPROACH

In this paper control is done by the fuzzy logic controller. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of the internal structure of the control circuit. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of reference currents and switching signals. The peak value of the reference current is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to the zero steady error in tracking the reference current signal. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed either by expert experience or with a knowledge database. Firstly, the input Error ‘\( E \)’ and the change in Error ‘\( 4E \)’ have been placed with the angular velocity to be used as the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current \( \text{Imax} \). To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in below fig

Rule Base: The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables, while in the steady state, small errors need fine control, which requires fine input/output variables. Based on this, the elements of the rule table are obtained as shown in below fig

<table>
<thead>
<tr>
<th>( \Delta E )</th>
<th>( E )</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NB</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PB</td>
</tr>
<tr>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

BLOCK DIAGRAM OF FUZZY CONTROLLER

A fuzzy inference system (or fuzzy system) basically consists of a formulation of the mapping from a given input set to an output set using fuzzy logic. This mapping process provides the basis from which the inference or conclusion can be made. A fuzzy inference process consists of the following steps:

Step 1: Fuzzification of input variables
Step 2: Application of fuzzy operator (AND, OR, NOT) in the IF (antecedent) part of the rule
Step 3: Implication from the antecedent to the consequent (THEN part of the rules)
Step 4: Aggregation of the consequents across the rules
Step 5: Defuzzification

The crisp inputs are converted to linguistic variables in
fuzzification based on membership function (MF). An MF is a curve that defines how the values of a fuzzy variable in a certain domain are mapped to a membership value $\mu$ (or degree of membership) between 0 and 1. A membership function can have different shapes. The simplest and most commonly used MF is the triangular-type, which can be symmetrical or asymmetrical in shape. A trapezoidal MF has the shape of a truncated triangle. Two MFs are built on the Gaussian distribution curve; a simple Gaussian curve and a two-sided composite of two different Gaussian distribution curves. The bell MF with a flat top is somewhat different from a Gaussian function. Both Gaussian and bell MFs are smooth and non-zero at all points. The implication step helps to evaluate the consequent part of a rule. There are a number of implication methods in the literature, out of which Mamdani and TS types are frequently used. Mamdani proposed this method which is the most commonly used implication method. In this, the output is truncated at the value based on degree of membership to give the fuzzy output.

Takagai-Surgeon-Kang method of implication is different from Mamdani in a way that, the output MFs is only constants or have linear relations with the inputs. The result of the implication and aggregation steps is the fuzzy output which is the union of all the outputs of individual rules that are validated or “fired”. Conversion of this fuzzy output to crisp output is defined as defuzzification. There are many methods of defuzzification out of which Center of Area (COA) and Height method are frequently used. In the COA method (often called the center of gravity method) of defuzzification, the crisp output of particular variable $Z$ is taken to be the geometric center of the output fuzzy value $\mu_{out}(Z)$ area, where this area is formed by taking the union of all contributions of rules whose degree of fulfillment is greater than zero. Here in this scheme, the error $e$ and change of error $ce$ are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as:

- NB (negative big)
- NM (negative medium)
- NS (negative small)
- ZE (zero)
- PS (positive small)
- PM (positive medium)
- PB (positive big)

The fuzzy controller is characterized as follows:

- Seven fuzzy sets for each input and output.
- Triangular membership functions for simplicity.
- Fuzzification using continuous universe of discourse.
- Implication using Mamdani's 'min' operator.
- Defuzzification using the 'height' method.

**Modeling of SSSC-based Fuzzy Controller**

The proposed fuzzy controller utilizes Sugeno-type Fuzzy Inference System (FIS) controller, with the parameters inside the FIS decided by the neural-network back propagation method. The fuzzy controller is designed by taking speed deviation & acceleration as the inputs, and the injected voltage by SSSC as the output. The output stabilizing signal, i.e., injected voltage is computed using the fuzzy membership functions depending on the input variables. The effectiveness of the proposed approach to modeling and simulation of SSSC controller is implemented in Simulink environment of MATLAB. FUZZY-Editor in MATLAB is used for realizing the system and implementation of the proposed fuzzy controller.

In a conventional fuzzy approach the membership functions and the consequent models are fixed by the model designer according to a prior knowledge. If this set is not available but a set of input-output data is observed from the process, the components of a fuzzy system (membership and consequent models) can be represented in a parametric form and the parameters are tuned by neural networks. The fuzzy controller uses 49 rules and 7 membership functions in each variable to compute output and exhibits good performance.

**APPENDIX**

- **Data generation:** To design the SSSC-based neuro Fuzzy controller, some data is needed, i.e., a set of two dimensional input vectors and the associated set of one-dimensional output vectors are required. Here, the training data has been generated by sampling input variables, i.e., speed deviation & acceleration uniformly, and computing the value of stabilized signal for each sampled point.

- **Rule extraction and membership functions:**

After generating the data, the next step is to estimate the initial rules. Then after applying Subtractive Clustering algorithm [28], rules are extracted. These rules are not so close to the identified system. Hence, there is a need of optimization of these rules. Hybrid learning algorithm is used for training to modify the above parameters after obtaining the Fuzzy inference system from subtracting clustering. This algorithm iteratively learns the parameter of the premise membership functions via back propagation and optimizes the parameters of the consequent equations via linear least squares estimation. The training is continued until the error measure becomes constant.

**Results:** The Fuzzy learning has been tested on a variety of linear and nonlinear processes. The objective here is to justify whether the neuro-fuzzy controller with less number of rules and membership functions can provide the same level of performance as that of the original one (system with 49 rules).

*Figure 2: Control surface of SSSC-based neuro-fuzzy controller*
System data: All data are in p.u. unless specified otherwise.

Generators:
Nominal powers: $SB1 = 4200$ MVA,  
$SB 2 = SB3 = 2100$ MVA,  
Nominal voltage: $VB = 13.8$ kV,  
Nominal frequency: $f = 60$ Hz,  
Reactance: $X d = 1.305$, $X' d = 0.296$,  
$X'' d = 0.252$, $X q = 0.474$, $X' q = 0.243$,  
$X q'' = 0.18$, Time constants: $T d = 1.01$ s,  
$T' d = 0.053$ s, $T'' qo = 0.1$ s, Stator resistance: $R = 0.252$ Ω/km,  
Inductance per unit length: $L = 3.7$ s, $p = 32$

Excitation Systems:
Low-pass filter time constant: $TLP = 0.02$ s, Regulator gains and time constants: $K A = 200$, $TA = 0.001$ s, Exciter gains and time constants: $Ke = 1$,  
$Te = 0$, Transient gain reduction: $Tb = 0$, $Tc = 0$
Damping filter gains and time constants: $K f = 0.001$, $Tf = 0.1$ s,  
Regulator output limits and gains: $E f min = 0$, $E f max = 7$, $K p = 0$

Hydraulic Turbine and Governor:
Servo-motor gains and time constants: $Ka = 3.33$, $Ta = 0.07$, Gate opening limits: $Gmin = 0.01$, $Gmax = 0.97518$,  
$Vg min = 0.1$ p.u./s, $Vg max = 0.1$ p.u./s,  
Permanent droops: $R p = 0.05$, PID regulators: $K p = 1.163$, $Ki = 0.105$, $Kd = 0$,  
$Tw = 2.67$ s

Transformers:
Nominal powers: $SB1 = 4200$ MVA, $SB2 = SB3 = 2100$ MVA, Winding connections: $D 1 Y g$
Winding parameters: $V1 = 13.8$ kV, $V2 = 500$ kV, $R1 = R2 = 0.002$, $L1 = 0$,  
$L2 = 0.12$, Magnetization resistance: $Rm = 500$
Magnetization reactance: $L m = 500$

Transmission lines:
Number of phases: 3-Ph, Resistance per unit length: $R1 = 0.02546$ Ω/km,  
$R0 = 0.3864$ Ω/km  
Inductance per unit length: $L1 = 0.9337 \times 10^{-3}$ H/km, $L0 = 4.1264 \times 10^{-3}$
$H/km$, Capacitance per unit length: $C1 = 12.74 \times 10^{-9}$ F/ km, $C0 = 7.751 \times 10^{-9}$ F/ km, Line lengths: $L1 = 175$ km, $L2 = 50$ km, $L3 = 100$ km.

SSSC:
Converter rating: $Snom = 100$ MVA, System nominal voltage: $Vnom = 500$ kV, Frequency: $f = 60$ Hz, Maximum rate of change of reference voltage ($V(\text{ref}) = 3$ p.u./s, Converter impedances: $R = 0.00533$, $L = 0.16$, DC link nominal voltage: $VDC = 40$ kV,  
DC link equivalent capacitance $CDC = 375 \times 10^{-6}$ F
Injected Voltage regulator gains: $KP = 0.00375$, $Ki = 0.1875$
DC Voltage regulator gains: $KP = 0.1 \times 10^{-3}$, $Ki = 0.97518$, $Tw = ± 0.2$

Loads:
Load1 = 7500 MW + 1500 MVAR,  
Load2 = Load3 = 25 MW, Load4 = 250 MW

SIMULATION RESULTS
The SimPowerSystems (SPS) toolbox is used for all simulations and SSSC-based neuro-fuzzy controller design [29]. In order to optimally tune the parameters of the SSSC based neuro-fuzzy controller, as well as to assess its performance, the model of example power system shown in Fig. 1 is developed using SPS block-set. The ratings of the generators are taken as 2100MVA each (G2 and G3) in one subsystem and 4200MVA (G1) in the other subsystem. The generators with output voltages of 13.8 kV are connected to an inter-tie through 3-phase step up transformers. All of the relevant parameters are given in the Appendix

Local control signals, although easy to get, may not contain the inter-area oscillation modes. So, compared to wide-area signals, they are not as highly controllable and observable for the inter-area oscillation modes. Owing to the recent advances in optical fiber communication and global positioning systems, the wide-area measurement system can realize phasor measurement synchronously and deliver it to the control center even in real time, which makes the wide-area signal a good alternative for control input. In view of the above, the speed deviation and acceleration of generators G1 and G2 are chosen as the control input of the SSSC-based fuzzy controller in this article. To assess the effectiveness and robustness of the proposed fuzzy controller, load flow is performed with Machine 1 as a swing bus and Machines 2 and 3 as PV generation buses. The initial operating conditions used are:

Machine 1 generation:
$Pe1 = 3480.6$ MW (0.8287 p.u.),  
$Qe1 = 2577.2$ MVAR (0.6136 p.u.)
Machine 2 generation:
$Pe2 = 1280$ MW (0.6095 p.u.),  
$Qe2 = 444.27$ MVAR (0.2116 p.u.)
Machine 3 generation: $Pe3 = 880$ MW (0.419 p.u.),  
$Qe3 = 256.33$ MVAR (0.1221 p.u.)
Simulation studies are carried out for the example power system subjected to various severe disturbances as well as small disturbances.

The simulation results are also compared with the result of lead-lag controller as given by ref. [13]. The original system is restored upon the clearance of the fault. A three-cycle, three-phase fault is applied at one of the line sections between Bus 1 and Bus 6, near Bus 6, at $t = 1$ sec. The fault is cleared by opening the faulty line, and the line is reclosed after three cycles.

The original system is restored after the fault clearance. Figs. 3(a)–3(d) show the variations of the inter-area and local mode of oscillation and the SSSC-injected voltage against time.

![Figure 3](image1.png)

**Figure 3.** Variation of inter-area and local modes of oscillations against time for a three-cycle, three-phase fault near Bus 6:
(a) And (b) Inter-area mode;
(c) Local mode; (d) SSSC-injected voltage, $V_q$

![Figure 4](image2.png)

**Figure 4.** Variation of tie-line power flow for a three-cycle, three-phase fault near Bus 6 cleared by a three-cycle line tripping
From these figures, it can be seen that the inter-area modes of oscillations are highly oscillatory in the absence of both SSSC-based damping controller as well as fuzzy controller, and the proposed fuzzy controller significantly improves the power-system stability by damping these oscillations. Furthermore, the proposed controller is also effective in suppressing the local mode of oscillations. The power flow through the tie-line (at Bus 1) for the above contingency is shown in Fig. 5, which clearly shows the effectiveness of the proposed controller to suppress power system oscillations. The effectiveness of the proposed controller on unbalanced faults is also examined by applying self-clearing type unsymmetrical faults, namely L-G, L-L-G, and L-L, each of three-cycle duration at Bus 1 at \( t = 1 \) sec. The inter-area and local modes of oscillations against time are shown in Figs. 5 and 6. It is clear from the figures that the power-system oscillations are poorly damped in the uncontrolled case, even for the least severe L-G fault, and the proposed SSSC-based fuzzy controller effectively stabilizes the power angle under various unbalanced fault conditions.

Figure 4. Variation of tie-line power flow for a three-cycle, three-phase fault near Bus 6 cleared by a three-cycle line tripping

From these figures, it can be seen that the inter-area modes of oscillations are highly oscillatory in the absence of both SSSC-based damping controller as well as fuzzy controller, and the proposed fuzzy controller significantly improves the power-system stability by damping these oscillations. Furthermore, the proposed controller is also effective in suppressing the local mode of oscillations. The power flow through the tie-line (at Bus 1) for the above contingency is shown in Fig. 5, which clearly shows the effectiveness of the proposed controller to suppress power system oscillations. The effectiveness of the proposed controller on unbalanced faults is also examined by applying self-clearing type unsymmetrical faults, namely L-G, L-L-G, and L-L, each of three-cycle duration at Bus 1 at \( t = 1 \) sec. The inter-area and local modes of oscillations against time are shown in Figs. 5 and 6. It is clear from the figures that the power-system oscillations are poorly damped in the uncontrolled case, even for the least severe L-G fault, and the proposed SSSC-based fuzzy controller effectively stabilizes the power angle under various unbalanced fault conditions.

Figure 5. Variation of inter-area mode of oscillations against time for three cycle unbalanced faults at Bus1:
(a) L-G fault; (b) L-L-G fault; (c) L-L fault
This article presents an SSSC-based fuzzy controller for transient stability improvement in a three-machine power system. The effectiveness of the proposed SSSC-based fuzzy controller in improving power-system stability is also demonstrated. The dynamic performance of proposed SSSC based controller under various loading and disturbance conditions are analyzed and compared. It is observed that the proposed SSSC-based fuzzy controller provides efficient damping to power system oscillations and greatly improves the system voltage profile. The inter-area and local modes of power system oscillations are effectively damped by using the proposed SSSC controller. The research work is intended to find the most suitable configurations of the fuzzy controller for the FACTS device. The superiority of fuzzy controller is evident from the simulation results for all types of disturbances.

**REFERENCES**

Kaushal Kapadnis is born in India. He is P.g. student, specialisation in Control System from “Veermata Jijabai Technological Institute, Mumbai” affiliated to University of Mumbai. He has done B.E. in Electronics Engineering from “Dr. D.Y.Patil Institute of Engineering & Technology, Pune” affiliated to University of Pune in 2012. Area of Interest is Control System, Digital Electronics, Power Electronics etc
Email id: kaushalpkapadnis@gmail.com

Manish Patil is born in India. He is P.g. student, specialization in Control System from “Veermata Jijabai Technological Institute, Mumbai” affiliated to University of Mumbai. He has done B.E. in Instrumentation Engineering from “Vidhyavardhini’s College of Engineering & Technology” affiliated to University of Mumbai. Area of Interest is Instrumentation & Control, Fuzzy Logic.Email id: manishptl57@gmail.com

Guide
J.O.Chandle is currently working as associate Professor in “Veermata Jijabai Technological Institute, Mumbai” affiliated to University of Mumbai. Area of Interest is Control System, Power System, Industrial Drives etc.
Email id: jochandle@vjti.org.in