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A NOVEL DESIGN OF A FUZZY COORDINATED SSSC CONTROLLER FOR INTEGRATED POWER SYSTEMS

A.S. Kannan[1] **R. Kayalvizhi**[2]

1. Department of Electrical & Electronics Engineering, Annamalai University, Tamil Nadu, India, askannan.aup@gmail.com
2. Department of Instrumentation Engineering, Annamalai University, Tamil Nadu, India, mithuvig.knr@gmail.com

Abstract- In this paper, a novel design and development of a fuzzy logic controller using static synchronous series compensators (SSSC) to damp out the swinging oscillations in a FACTS based integrated multi-machine power system when a three-phase line to line ground fault takes place at one of the generators in the power system is proposed. The multi-machine power system considered consists of three generators, three inductive transformers, nine buses, four loads and two POD based SSSC fuzzy coordinated controllers. Oscillations in power systems have to be taken a serious note of concern when the fault takes place in any part of the system; else this might lead to the instability mode and shutting down of the power system. The hybrid combination of a fuzzy coordination scheme with a static synchronous series compensator is proposed in this paper to suppress the swinging oscillations upon the occurrence of a fault at one of the generator side, say near the first generator (i.e. between the first generator and the three-phase load). Simulink models are developed with and without the fuzzy control by considering the occurrence of a fault. Three types of faults are considered, as LLLG (Line-Line-Line to Ground), LLG (Double Line to Ground) and LG (Line to Ground) faults. These faults are made to occur for a period of 0.2ms and then cleared. Simulations are performed with and without the fuzzy controller during the fault conditions. The results are compared for the effectiveness of the fault occurrence and the controller. Finally, the conclusions are given. The digital simulation results observed show the effectiveness of the method presented in this paper.

Keywords: SSSC, Fuzzy logic, Coordination, Controller, Oscillations, Damping, Stability, Simulink, State Space Model, Matlab, Simulink.

I. INTRODUCTION

Power systems is continuously expanding and upgrading to cater for the ever-growing power demands in the world. There has been considerable interest in the application of high-power semiconductor technology in designing controllers for the stability of large-scale power systems. Advanced power electronic devices, such as the SSSC, can now be used for the control of transmission line voltages, increasing power transmission capacity, and damping of power oscillations with increased flexibility. The FACTS controllers have the ability to control the interrelated parameters that govern the operation of transmission system including series impedance, shut admittance, current, voltage, phase angle and damping of oscillations at various frequencies below rated frequency. Furthermore, with increasing power transfers and heavier loading, power systems become more complex to operate and they may become less secure for riding out major power outages [1, 2]. As a result, large power flows with inadequate control may be observed and excessive reactive power and large dynamic swings may be experienced in different parts of the system which will prevent the transmission interconnections from being fully utilized [3].

Power system exhibits various modes of oscillations due to interaction among various components. Most of the oscillations are due to synchronous generator rotors swinging relative to each other. Stressed power systems are known to exhibit non-linear behavior. Load changes or faults are the main causes of power oscillations. If the oscillations are not controlled properly, it may lead to a total or partial system outage and blackening out of the entire world due to acute power shortage. If no adequate damping is available, these oscillations may sustain and grow to cause system separation or isolations [4-6].

In the past three decades, power system stabilizers (PSSs) have been extensively used to increase the system damping for low frequency oscillations. The power utilities world-wide are currently implementing PSSs as effective excitation controllers to enhance the system stability [7-16]. However, there have been problems experienced with PSSs over the years of operation. Some of these were due to the limited capability of PSS, in damping only local and not inter-area modes of oscillations. In addition, PSSs can cause great variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing system stability [17]. This situation has necessitated a review of the traditional power system concepts and practices to achieve a larger stability margin, greater operating flexibility, and better utilization of existing power systems.

A new concept of flexible AC transmission systems (FACTS) brought radical changes in the power system operation and control. A new technique using FACTS based devices linked to the improvements in semiconductor technology opened the new opportunities for controlling power and enhancing the usable capacity of existing transmission lines as damping the inter-area modes and enhancing PS stability using FACTS controllers have been extensively studied, researched and investigated. Generally, it is not cost-effective to install FACTS devices for the sole purpose of power system stability enhancement. Some FACTS devices can control both active and reactive power flows. For PS security enhancement, the active and reactive powers, both should be controlled. This can be performed with various FACTS based devices.

Various types of FACTS based controllers that could be used in the power system controller design are: SSSC, TCSC, STATCOM, UPFC (combination of SSSC + STATCOM). But, in the proposed research work, the controller design using SSSC to damp out the swinging oscillations in an integrated power system is considered. According to IEEE, SSSC - which is the abbreviation of Static Synchronous Compensator, is defined as "*a shunt device of the Flexible AC Transmission Systems* (*FACTS*) *family using power electronics and it regulates the voltage by generating or absorbing reactive power*". Dynamic reactive power compensation and damping power system oscillations can also be achieved using FACTS controllers. Injecting the series voltage phasor, with desirable voltage magnitude and phase angle in a line can provide a powerful means of precisely controlling the active and reactive power flows, by which system stability can be improved, system reliability can be enhanced while operating and transmission investment cost can be reduced.

It is possible to vary the impedance of specific transmission line to force power flow along a desired "*contract path*" in the emerging power systems, and to regulate the unwanted loop power flows and parallel power flows in the interconnected system. The FACTS controllers have been broadly developed on two different principles, one that alters the line series reactance or bus shunt reactance or voltage phase difference across a line and utilizes conventional thyristor switches for control. In general, FACTS controllers can be divided into four categories based on their connection in the power system network, viz., series, shunt, combined series-series, and combined series-shunt. In the proposed research work, the static series synchronous capacitor combination has been used.

FACTS devices enhance the stability of the power system with its fast control characteristics and continuous compensating capability. The fast progress in the field power electronics has opened new opportunities for the power industry via utilization of the controllable FACTS devices such as UPFC, TCSC and SVC which offer an alternative means to mitigate power system oscillations. Because of the extremely fast control action associated with FACTS-device operations, they have been very promising candidates for mitigation power system oscillation in addition to improve power system steady-state performance [13].

In the modern day power system stability, operation and control (PSOC), FACTS (Flexible AC Transmission Systems) plays a very important role. Usage of FACTS in the power systems not only enhances the dynamic performance, but also increases the stability of the power systems, enhances the controllability and increases its power transfer capability. Some of the devices used in the control of FACTS are the SVC, TCSC, SSSC, UPFC and the IPFC. The FACTS controllers utilize power electronics based technology and can provide dynamic control on line power flows, bus voltages, line impedance and phase angles. The FACTS initiative was originally launched in 1980's to solve the emerging problems faced due to restrictions on transmission line construction and to facilitate growing power export / import and wheeling transactions among utilities. The two basic objectives behind the development of FACTS technology; is to increase power transfer capability of the transmission systems and to keep power flow over designated routes, significantly increase the utilization of existing (and new) transmission assets and play a major role in facilitating contractual power flow in electricity markets with minimal requirements for new transmission lines.

FACTS devices have shown very promising results when used to improve the power system steady state performance. In addition, because of the extremely fast control action associated with FACTS-device operations, they have been very promising candidates for utilization in power system damping enhancement. The first generation (G1) FACTS devices include SVC, TCPS and TCSC. It has been found that SVCs can be effective in damping power system oscillations if a supplementary feedback signal is applied [9].

SSSC consists of a series Voltage Source Converter (VSC) which can inject a series voltage into the transmission line. As such the series VSC makes SSSC exchange the reactive power with the inserted line. If the DC side of the two VSC is connected together, then the active power as well as the reactive power can transfer in a bilateral and absolute way through the common DC link [10]. Many research efforts have been devoted to the control of TCSC. Chen et. al. designed a state feedback TCSC controller based on the pole placement technique [5]. Other TCSC optimal and non-linear control schemes are proposed in the literatures [4].

The control mechanism and the controller have an important effect on the performance of the static synchronous compensators. In the literature, several control mechanisms are used in the SSSC models. A novel fuzzy inference system described in matrix form was proposed and used to improve the dynamic control of real and reactive powers [4]. In recent years, the fast progress in the field of power electronics has opened new opportunities for the power industry via utilization of the controllable Flexible AC Transmission System devices like the SSSC's which offer an alternative means to mitigate power system oscillations.

A non-incremental method of optimal control of reactive power flows in an integrated power system was proposed by Zhuding Wang and et. al. Based on the decoupling principle, a non - incremental quadratic programming model for optimal control of reactive power flow in power systems was presented by them. In their model, the reactive powers through all lines were regarded as the unknown variables, which were to be evaluated, as well as the transformer tap positions, generator terminal voltages and switchable injected reactive powers and a characteristic linear approximation of power flow was formulated. Because of the characteristics of the non-incremental variables of the model, execution time and memory requirements and convergence properties were satisfactory; thus, it is particularly fit to improve voltage magnitudes and to minimize system losses under operating conditions. Real power economic dispatch was also accomplished by standard techniques.

But, nowadays, some critical problems in power systems that exist are; the power system oscillations, stability of power systems and the damping of electromechanical oscillations upon the occurrence of faults. These electromechanical oscillations occurring in power systems are generally in the oscillation frequency range of 0.2 Hz. to 2 Hz. These low frequency oscillations are the consequence of the development of interconnection of large power systems. A low frequency oscillation in a power system constrains the capability of power transmission, threatens system security and damages the efficient operation of the power system [10].

Damping of electromechanical oscillations between interconnected machines in an integrated power system is always necessary for a secured system operation. A FACTS controller always increases the transmission capability and the stability. Researchers have developed a number of methods for damping of power system oscillations using FACTS devices. However, majority of them are confined to single machine infinite bus systems.

Very few researchers have worked on multi-machine control of FACTS systems. Of course, this had yielded satisfactory results. But, excellent results can be obtained using the fuzzy logic concepts, neural network concepts and the genetic algorithms. This has been showed by few researchers in their papers [6]. In this paper, we make a modest attempt to simulate a fuzzy logic control scheme with a static series synchronous compensator for a FACTS power system to dampen the power system oscillations upon the occurrence of a fault.

The fuzzy logic control technique has been an active research topic in automation and control theory. Various researchers have worked on these concepts. To name a couple of them, being Mamdani and Zadeh. Zadeh proposed in 1965, a control strategy to deal with the problems in systems which are not easy to be modeled. Further, Mamdani used some of the concepts of Zadeh and proposed in 1974 a theory based on the fuzzy sets.

The concept of FLC is to utilize the qualitative knowledge of a system to design a practical controller. For a process control system, a fuzzy control algorithm embeds the intuition and experience of an operator designer and researcher. The control doesn’t need an accurate mathematical model of the plant and therefore, it suits well to a process where the systems are modeled with uncertain or complex dynamics. Of course, fuzzy control algorithm can be developed by adaptation based on learning and fuzzy model of the plant. The fuzzy control is basically non-linear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect [19].

In general, a fuzzy control algorithm consists of a set of heuristic decision rules and can be regarded as an adaptive and non-mathematical control algorithm based on a linguistic process, in contrast to a conventional feedback control algorithm [18]. Robust self-learning fuzzy controller for a class of non-linear MIMO systems was discussed in brief by Kim and Bien in their papers [5]. Fuzzy control using linguistic information possesses several advantages such as robustness, model-free, universal approximation theorem and rules-based algorithm [12].

Recent literature has explored the potentials of fuzzy control for machine drive applications [7]. It has been shown that a properly designed direct fuzzy controller can out-perform conventional proportional integral derivative (PID) controllers [19]. Note that fuzzy logic controllers are nothing but rule-based controllers in which a set of rules representing a control decision mechanism to adjust the effect of certain cases coming from power system is considered. Further, these FLCs do not require a mathematical model of the system and can cover a wide range of operating conditions with much robustness inherency. FLCs combined with SSSC’s can definitely reduce the swing oscillations in multi-machine systems.

In an interconnected power system, the synchronous generators should rotate at the same speed and power flows over tie-lines should remain constant under normal operating conditions. However, low frequency electro mechanical oscillations may occur when a disturbance is applied to the power system. These oscillations can be observed in most power system variables like bus voltage, line current, generator rate and power. Power system oscillations were first observed as soon as synchronous generators were interconnected to provide more generation capacity and more reliability to a power system. Originally, the fairly closely connected generators were observed to swing against each other at frequencies of around 1 to 2 Hz. Damper windings on the generator’s rotor were used to prevent the amplitude of oscillations from increasing. After fast excitation systems were introduced to prevent the generators from loosing synchronism following that when a system fault occurs, it was noticed that this kind of excitation system always tends to reduce the damping of the system oscillations.

The organization of the paper is as follows. Firstly, a brief introduction to the FACTS, its evolutions, applications, the background work done in the power system damping using SSSC’s was presented in the previous paragraphs. Section two presents a brief review of the SSSC. Section three presents the mathematical modeling of the multi-machine power system along with the parameters. In section four, the control strategy, the design of the controller is presented. Section five presents a brief review of the fuzzy logic concepts that is used in the development of the controller. Section six presents the development of the Simulink model for the damping of the power system oscillations with and without the fault that takes place near the first generator. Simulation results are presented in section seven. Conclusions are finally presented at the end in the section eight. This is followed by the references and the author biographies.

II. STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

The SSSC is a power electronic-based synchronous voltage source that generates three phase AC voltages of controllable magnitude and phase angle. This voltage, which is injected in series with the transmission line, is almost in quadrature with the supply voltage v_s and hence emulates an equivalent inductive or capacitive reactance in series with the transmission line. When the series injected voltage leads the line current, it emulates an inductive reactance causing the power flow and the line current to decrease. When the line current leads the injected voltage, it emulates a capacitive reactance thereby enhancing the power flow over the line [8]. The basic schematic diagram of the static synchronous series compensator with its test system is shown in Figure 1.

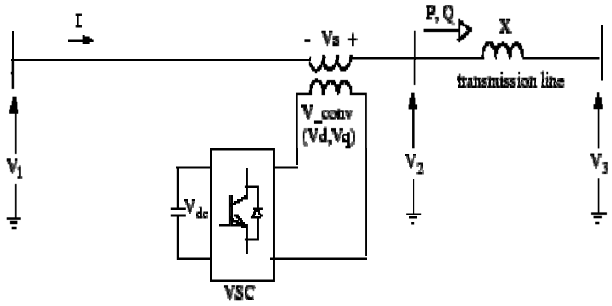


Figure 1. Schematic diagram of SSSC

The Voltage-Source Converter (VSC) is the basic building block of many of the modern FACTS devices such as STATCOM, SSSC, and UPFC. The voltage-source converter uses switching gates that have turn-on and turn-off capability such as Gate Turn-Off Thyristor (GTO), Insulated Gate Bipolar Transistor (IGBT), MOS Turn-Off Thyristor (MTO) and Insulated Gate-Commutated Thyristor (IGCT). The voltage-sourced converter generates AC voltage from a DC voltage. With a voltage-source converter, the magnitude, the phase angle and the frequency of the output voltage can be controlled. It has the capability to transfer power in either direction by just reversing the polarity of the current.

The SSSC using a VSC to inject a controllable voltage in quadrature with is able to rapidly provide both capacitive and inductive impedance compensation independent of the power line current. Moreover, an SSSC with a suitable designed external damping controller [18-19] can be used to improve the damping of the low frequency power oscillations in a power network. These features make the SSSC an attractive FACTS device for power flow control, power oscillation damping and improving transient stability.

The SSSC is one of the most recent FACTS devices for power transmission series compensation. It can be considered as a synchronous voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. The injected voltage is almost in quadrature with the supply voltage v_s or v_r. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. This variable reactance influences the electric power flow in the transmission line. The theory of operation of SSSC and its control fundamentals are presented extensively in a number of literatures [1-5].

III. MODEL OF THE 3-MACHINE, 9-BUS INTEGRATED POWER SYSTEM

The integrated multi-machine power system model consisting of three generators used for the simulation purposes is shown in the form of a one-line diagram (single line diagram) with and without the occurrence of a fault in the Figures 2, 3 and 4, respectively. The three generators are connected to buses one, eight and five. Static synchronous compensators are used for controlling and damping the power system oscillations in the integrated power system plant. Two such SSSC controllers are used. One is connected between the bus two and three and the other one is connected between the buses six and bus nine. Three transformers T1 to T3 are also used in the integrated power system near the generator buses for the power transmission purposes, i.e., for stepping up and stepping down purposes. Note that the loads considered are of R or RL type and the transformers are being considered as inductive. Transmission lines are connected between the buses three-nine-four-six. Since, we know that the power system is a dynamic one, definitely, it is a non-linear system [16], and the model is obtained from first principles and finally converted into a state space model form using some transformation techniques.

For modeling and simulation purposes in the Matlab-Simulink environment, a linearized numerical model about an operating point is needed. By linearizing about an operating point, the total linearized power system model (the plant model) is represented finally in the state space form as

$$\Delta x = A\Delta x + B\Delta u \tag{1}$$

$$\Delta y = C\Delta x + D\Delta u \tag{2}$$

where, Δx is the state vector of length equal to the number of states n, Δy is the output vector of length m, Δu is the input vector of length r, A is the system state matrix of size $(n \times n)$, B is the control input vector of size $(n \times r)$, C is the system output vector of size $(m \times n)$, D is the feed-forward matrix of size $(m \times r)$.

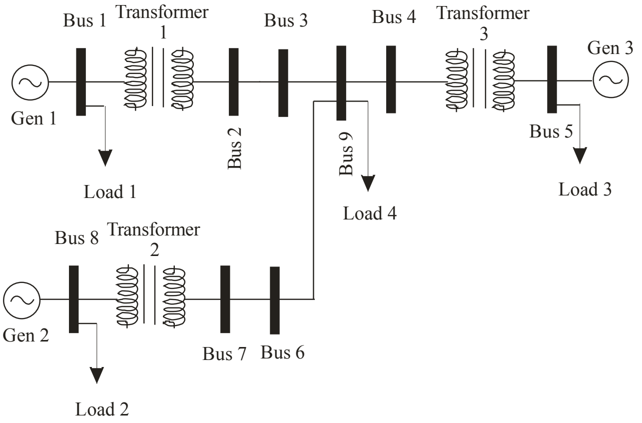


Figure 2. A three-machine, nine-bus interconnected power system model with four-loads without the controllers

Note that for this linearized power system model, controllers are designed and incorporated in loop with the plant model so that when there are any disturbances taking place like the faults, the oscillations are reduced quickly in no time, thus becoming a closed loop feedback control system [15]. The simulation parameters of the three-machine, nine-bus interconnected power system model with four loads L1 to L4 and the SSSC-fuzzy coordinated controller is given in the Table 1 [16].

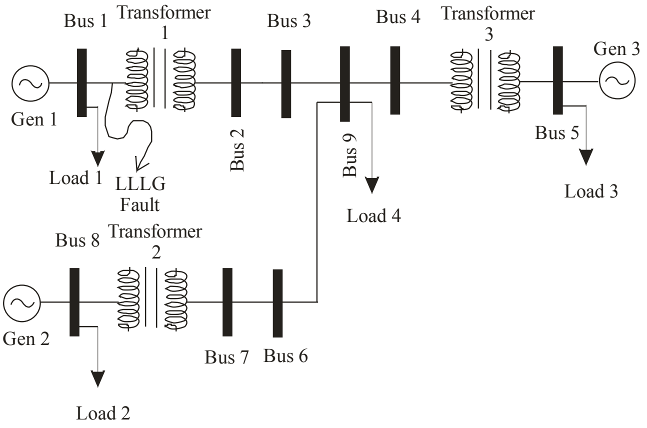


Figure 3. A three-machine, nine-bus interconnected power system model with four-loads without the controllers and a LLLG fault occurring near bus one

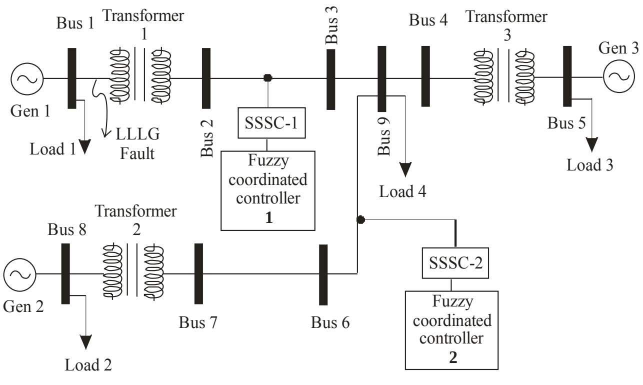


Figure 4. A three-machine, nine-bus interconnected power system model with four-loads with the SSSC based fuzzy coordinated controllers upon the occurrence of a LLLG fault occurring near bus one

Table 1. Machine parameter details

Base value	$V_B = 220\,\text{KV},\ S_B = 100\,\text{MVA}$
Generators	$2H_1 = 2H_2 = 8\,(\text{sec}),\ 2H_3 = 10$ $D_1 = D_2 = D_3 = 0.0,$ $T_{d01} = T_{d02} = 4.49\,(\text{sec}),\ T_{d03} = 6\,(\text{sec})$ $X_{d1} = X_{d2} = 1.56\,(\text{p.u.}),$ $X_{d3} = 2\,(\text{p.u.})$ $X_{q1} = X_{q2} = 1.06\,(\text{p.u.}),$ $X_{q3} = 1.9\,(\text{p.u.})$ $X_{d1} = X_{d2} = 0.17\,(\text{p.u.}),$ $X_{d3} = 0.25\,(\text{p.u.})$ $R = 0.001$
Transformers	$X_{T1} = X_{T2} = X_{T3} = j0.305\ (\text{p.u.})$
Transmission lines	$Z_{l1} = Z_{l2} = Z_{l3} = 0.2 + j0.25\ (p.u.)$
SSSCs	$V_{Oper} = 220\,\text{KV},$ $V_{se\max} = 0.1V_{Oper},$ $V_{se\min} = -0.1V_{Oper}$
Loads	$L_1 = L_2 = L_3 = 0.05\,(\text{p.u.}),$ $L_4 = 0.65\,(\text{p.u.})$

IV. DEVELOPMENT OF THE CONTROL STRATEGY

A controller is a device which controls each and every operation in the system making decisions. From the control system point of view, it is bringing stability to the system when there is a disturbance or a noise or a fault, thus safeguarding the equipment from further damages.

It may be hardware based controller or a software based controller or a combination of both. In this section, the development of the control strategy for damping the oscillations in FACTS based power systems is presented. The overall block-diagram of the controller and the controlled system (plant) is shown in the Figure 5.

V. REVIEW OF FUZZY LOGIC CONCEPTS USED IN THE DESIGN

Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables and emerged as a consequence of the 1965 proposal of fuzzy set theory by Lotfi Zadeh. Linguistic variables, defined as variables whose values are sentences in a natural language (such as large or small), may be represented by the fuzzy sets. Fuzzy set is an extension of a ‘crisp’ set where an element can only belong to a set (full membership) or not belong at all (no membership). Fuzzy sets allow partial membership, which means that an element may partially belong to more than one set.

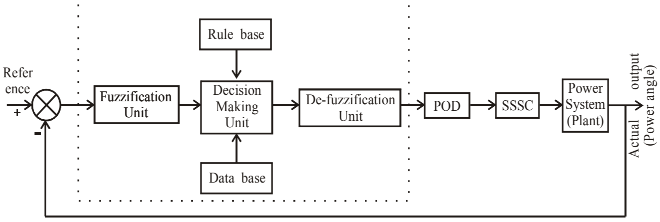


Figure 5. Diagrammatic view of a typical fuzzy logic controller used along with POD-SSSC for controlling the oscillations in a power system

A fuzzy set A of a universe of discourse X is represented by a collection of ordered pairs of generic element $x \in X$ and its membership function $\mu: X \rightarrow [0\ 1]$, which associates a number $\mu_A(x)$: $X \rightarrow [0\ 1]$, to each element x of X. A fuzzy logic controller is based on a set of control rules called as the fuzzy rules among the linguistic variables. These rules are expressed in the form of conditional statements. Our basic structure of the fuzzy logic coordination controller to damp out the oscillations in the power system consists of three important parts, viz., fuzzification, knowledge base - decision making logic (inference system) and the de-fuzzification, which are explained in brief as follows [22].

The necessary inputs to the decision-making unit blocks are the rule-based units and the data based block units. The fuzzification unit converts the crisp data into linguistic variables. The decision making unit decides in the linguistic variables with the help of logical linguistic rules supplied by the rule base unit and the relevant data supplied by the data base [19]. The output of the decision-making unit is given as input to the de-fuzzification unit and the linguistic variables of the signal are converted back into the numeric form of data in the crisp form. The decision-making unit uses the conditional rules of 'IF-THEN-ELSE' [21].

In the fuzzification process, i.e., in the first stage, the crisp variables $P_{\text{SSSC-1}}$ and $P_{\text{SSSC-2}}$ are converted into fuzzy variables or the linguistics variables. The fuzzification maps the two input variables to linguistic labels of the fuzzy sets. The fuzzy coordinated controller uses the linguistic labels: {(Small S mf_1), (Medium M mf_2), (Big B mf_3)}. Each fuzzy label has an associated membership function. The membership function of triangular type is used in the proposed research work and is shown in the Figure 4. The inputs are fuzzified using the three-fuzzy sets (S, M, B). The output of the fuzzy-converter will generate the pulses, which are further given as inputs to the plant.

The membership function of the small set is given by the Equation (3) as

$$\mu_{small}(x) = \begin{cases} 1 & x < (p-N) \\ {(-x+p)}/{N} & (p-N) \le x \le p \\ 0 & x > p \end{cases} \qquad (3)$$

where x, is the inputs to the fuzzy-SSSC controllers. From this equation, we see that when x is less than $(p-N)$, the value of the function is 1, when it is greater than p, the value is zero. In between the two inequalities, the value of the function is having a decreasing slope of −1. The membership function of the medium set is given by the Equation (4) as

$$\mu_{medium}(x) = \begin{cases} 0 & x < (p-N) \\ {(x+N-p)}/{N} & (p-N) \le x \le p \\ {(-x+N+p)}/{N} & p \le x \le (p+N) \\ 0 & x > (p+N) \end{cases} \qquad (4)$$

From this Equation (2), we see that when x is less than $(p-N)$, the value of the function is 0, when it is greater than $(p-N)$, the value is zero. In between the two inequalities, the value of the function is having an increasing and decreasing slope of +1 and −1.

The membership function of the big set is given by the Equation (5) as

$$\mu_{Big}(x) = \begin{cases} 0 & x < p \\ {(-x+N+p)}/{N} & p \le x \le (p+N) \\ 1 & x > (p+N) \end{cases} \qquad (5)$$

From this equation, we see that when x is less than p, the value of the function is 0, when it is greater than p, the value is 1. In between the two inequalities, the value of the function is having an increasing slope of +1.

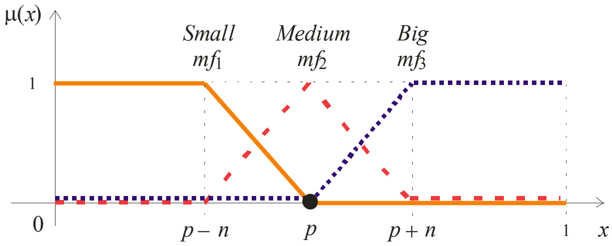


Figure 6. Membership function used in the fuzzification process.

Note that p is the parameter which can be determined on the basis of the rated values of the controllers, which is the starting of the curves and n is ending point of the curves. The whole concept of the membership functions as mentioned in the above Equations (1) to (3) which are used in generating the rule base for the fuzzification process is explained graphically in the Figure 6.

The developed fuzzy rules included in the fuzzy coordinated controller are given in the form of an algorithm.

- If (input_1 is mf1) and (input_2 is mf1) then (output_1 is mf3)
- If (input_1 is mf1) and (input_2 is mf2) then (output_1 is mf2)
- If (input_1 is mf1) and (input_2 is mf3) then (output_1 is s1)
- If (input_1 is mf2) and (input_2 is mf1) then (output_1 is mf3)
- If (input_1 is mf2) and (input_2 is mf2) then (output_1 is mf2)
- If (input_1 is mf2) and (input_2 is mf3) then (output_1 is s1)
- If (input_1 is mf3) and (input_2 is mf1) then (output_1 is mf3)
- If (input_1 is mf3) and (input_2 is mf2) then (output_1 is mf2)
- If (input_1 is mf3) and (input_2 is mf3) then (output_1 is s1)

The control decisions are made based on the fuzzified variables. The inference involves a set of rules for determining the output decisions. As there are two input variables and three fuzzified variables (S, M, B), the fuzzy logic coordination controller has a set of nine rules for the fuzzy based SSSC controller. To determine the degree of memberships for the output variables, the concept of min-max inference is used. Note that both the controllers use the same rule base system. The rule base for the decision-making unit for the POD based SSSC controller-1 is written as shown in the Table 2.

Now, the nine output variables of the inference system are the linguistic variables and they must be converted into numerical output, i.e., they have to be de-fuzzified. This process is what is called as de-fuzzification. De-fuzzification is the process of producing a quantifiable result in fuzzy logic. The defuzzifcation transforms fuzzy set information into numeric data information. This operation along with the operation of fuzzification is critical to the design of fuzzy systems as both of these operations provide nexus between the fuzzy set domain and the real valued scalar domain.

Table 2. The nine-fuzzy rules used for determining the output decisions (Inference table) rule base used for the control purposes

	Small set S mf_1	Medium set M mf_2	Big set B mf_3
Small set S mf_1	B	M	S
Medium set M mf_2	B	M	S
Big set B mf_3	M	S	S

There are so many methods to perform the de-fuzzification, viz., centre of gravity method, centre of singleton method, maximum methods, the marginal properties of the centroid methods and so on. In the proposed research work, the centre of gravity method is used to perform the de-fuzzification. The output of the fuzzy-coordination controller according to the CG method is given by the Equation (6) as

$$y = \frac{\sum_{i=1}^{9} \mu_c(u_i).u_1}{\sum_{i=1}^{9} \mu_c(u_i)} \tag{6}$$

where u_i corresponds to the value of the control output for which the membership values in the output sets are equal to unity.

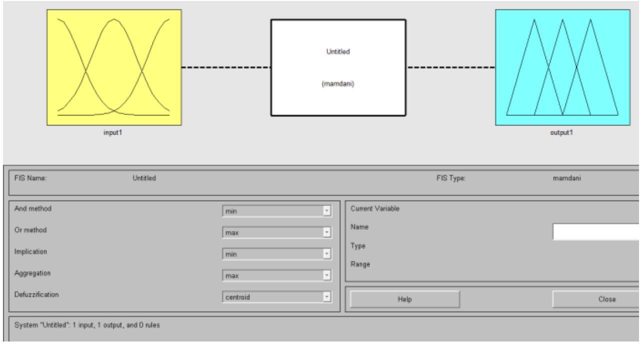
VI. DEVELOPMENT OF THE SIMULINK MODEL

In this section, we present the development of the Simulink model for the multi-machine FACTS based power system with and without the SSSC controller. The Figures 18 and 19 show the simulation models of the three-generator, nine-bus system with and without the two Fuzzy-SSSC controllers, i.e., first one between second and the third bus and second one is at sixth and seventh bus, when the fault takes place near the first generators. The entire system modeled in Simulink is a closed loop feedback control system consisting of the plants, controllers, comparators, feedback systems, the mux, de-mux, integrators, state-space models, sub-systems, transformers, the output sinks (scopes) and the input sources. The Simulink model is developed from the basic functions available in the Simulink library and from the various tool-boxes available. Note that the transformers are used for voltage step up and step down purposes.

VII. SIMULATION RESULTS

Digital Simulations are carried out in Matlab 7 and was run for 0.2 s with and without the controller for the fault at the first generator. The step size for the simulation was taken to be very small so that accurate results are obtained. For the software implementation purposes, we had taken a three-generator nine bus system with 220 KV line and 100 MW generators. The three phase to ground symmetrical LG, LLG and LLLG faults is made to occur near the first generator for a period of 2.00 ms from the first cycle to the tenth cycle, i.e., from 0.04 s to 0.08 s and is also simulated in the Simulink model. No fault is considered near the second and the third generators. The various performance characteristics curves were observed after running the simulation.

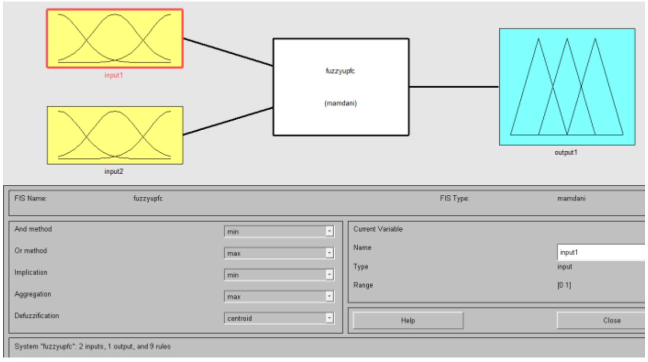
Simulink model for the damping of the power system oscillations when the fault takes place with and without the POD based SSSC controller was developed in Matlab 7 and shown in the Figures 18 and 19, respectively. In order to start the simulations, the fuzzy rule set has to be invoked first from the command window. Initially, the fuzzy file where the rules are written with the incorporation of the control strategy is opened in the Matlab command window (after typing the word, ‘fuzzy’ and then pressing enter), after which the fuzzy editor (FIS) dialogue box opens as shown in the Figure 7. The .fis file is imported using the command window from the source file and then opened in the fuzzy editor dialog box using the file open command. Once the file is opened, the fuzzy rules file gets activated as shown in the Figure 8.



FIS Name: Untitled
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
System "Untitled": 1 input, 1 output, and 0 rules

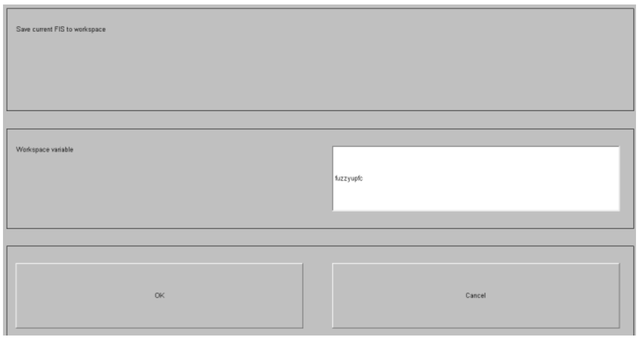
Figure 7. FIS editor window

Further, the data is exported to the workspace as shown in the Figure 9, i.e., the .fis variables are saved in the workspace after loading from the disk. The fuzzy membership function editor is then obtained using the view membership command from the menu bar and this is shown in the Figure 10. The rule viewer for the two inputs and one output can be observed pictorially in the Figure 11. The written fuzzy rules also can be viewed from the rule view command, which is presented in the Figure 12. The surface plot for the error speed and change in error with the output is shown in the Figure 13.



FIS Name: fuzzyupfc
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Name: input1
Type: input
Range: [0 1]
System "fuzzyupfc": 2 inputs, 1 output, and 9 rules

Figure 8. FIS Fuzzy editor with 2 inputs and 1 output, loading of data from the disk


Save current FIS to workspace

Workspace variable: fuzzyupfc

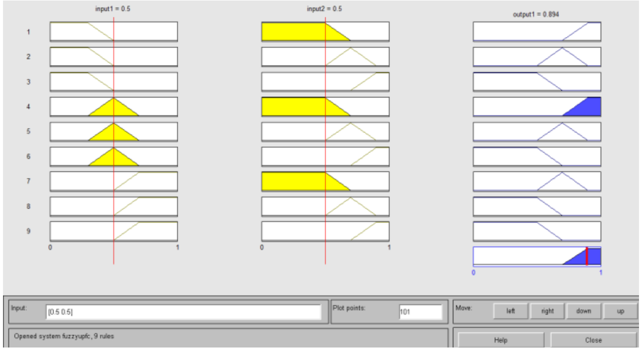
Figure 9. Saving current .fis file to the workspace

Now, after viewing all the preliminary results, the simulations are run for a period of 0.2 seconds in Matlab 7. While the simulation is run, the two fuzzy inputs are then given to the controller (fuzzy coordinated POD-SSSC) as shown in the Figure 14, where the controller output is obtained thereafter. Note that in this SSSC based fuzzy controller (which consists of three basic blocks viz., fuzzification, inference, and the de-fuzzification blocks) the set of nine fuzzy rules are called in the form of a file. After the simulation is run, the performance characteristics are observed on the respective scopes. The response curve of the power angle (delta) vs. time is observed on the respective scope and is shown in the Figures 15-17 with and without the controller, respectively.


Current Variable
Name: input1
Type: input
Range: [0 1]
Display Range: [0 1]

Current Membership Function (click on MF to select)
Name: mf1
Type: trapmf
Params: [0 0 0.3 0.5]

Figure 10. Developed membership function plots

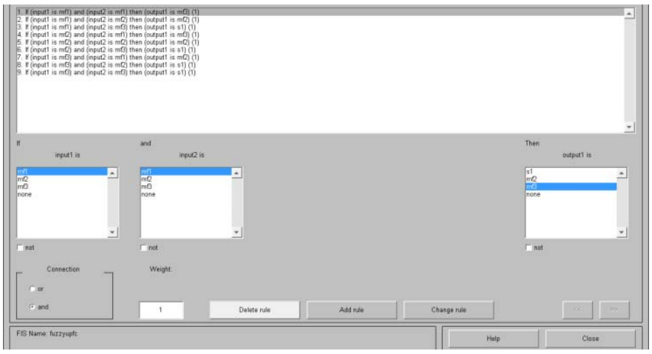

Input: [0.5 0.5]
Plot points: 101

Opened system fuzzyupfc, 9 rules

Figure 11. Rule viewer

VIII. CONCLUSIONS

A POD based SSSC-fuzzy coordinated controller was simulated and proposed for a multi-machine integrated power system comprising of three generators, nine buses, four loads. Simulink models were developed with and without the controller for the multi-machine model in order to damp out the swinging oscillations in the power angle characteristics. In the Simulink model, the fault takes place near the first generator for a certain period and then cleared.


1. If (input1 is mf1) and (input2 is mf1) then (output1 is mf3) (1)
2. If (input1 is mf1) and (input2 is mf2) then (output1 is mf2) (1)
3. If (input1 is mf1) and (input2 is mf3) then (output1 is s1) (1)
4. If (input1 is mf2) and (input2 is mf1) then (output1 is mf3) (1)
5. If (input1 is mf2) and (input2 is mf2) then (output1 is mf2) (1)
6. If (input1 is mf2) and (input2 is mf3) then (output1 is s1) (1)
7. If (input1 is mf3) and (input2 is mf1) then (output1 is mf2) (1)
8. If (input1 is mf3) and (input2 is mf2) then (output1 is s1) (1)
9. If (input1 is mf3) and (input2 is mf3) then (output1 is s1) (1)

Connection: ○ or ● and
Weight: 1

FIS Name: fuzzyupfc

Figure 12. Rules written in the rule editor

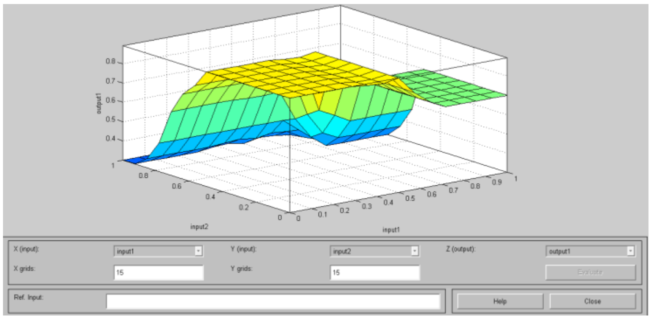

X (input): input1
Y (input): input2
Z (output): output1
X grids: 15
Y grids: 15
Ref. Input:

Figure 13. Surface plot

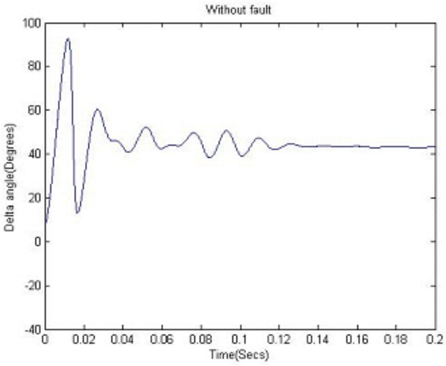


Figure 14. The simulation result of the plot of the power angle delta versus time without the use of SSSC based fuzzy controller for the without fault at the first generator

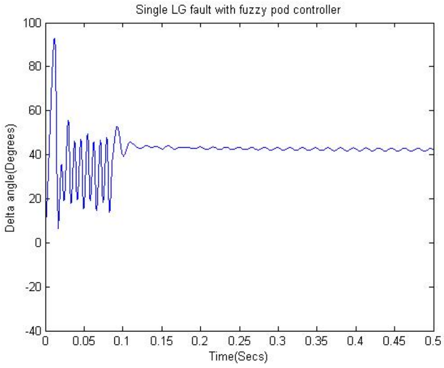


Figure 15. The simulation result of the plot of the power angle delta versus time with the use of SSSC based fuzzy controller for the L-G fault at generator 1

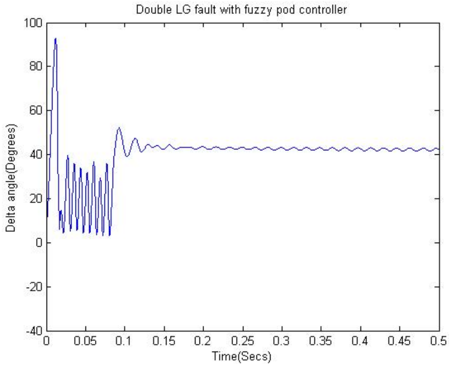


Figure 16. The simulation result of the plot of the power angle delta versus time without the use of SSSC based fuzzy controller for the LL-G fault at generator 1

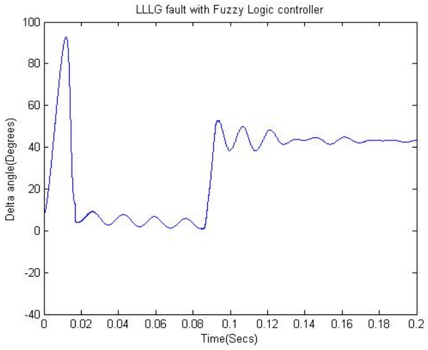


Figure 17. The simulation result of the plot of the power angle delta versus time with the use of SSSC based fuzzy controller for the LLL-G fault at generator 1

Table 3. Comparison of all faults with Fuzzy Pod Controller

SI No	Type of Fault	Initial Peak Over Shoot (degrees)	Distortion Range		Stabilized Power Angle (degrees)
			width (secs)	height (degrees)	
1	Without Fault	92.7	0.02 - 0.12	42 - 53	43
2	LG Fault	93	0.02 - 0.1	10 - 57	43
3	LLG Fault	92	0.02 - 0.12	5 - 40	43
4	LLLG Fault	92	0.02 - 0.12	5 -12	43

The control strategy was also developed by writing a set of fuzzy rules. Simulations were run in Matlab 7 and the results were observed on the scope. Graphs of power angle vs. time were observed with and without the controller for the model considered.

From the simulation results, it was observed that without the fuzzy controller, the three-machine nine-bus system will be having more disturbances, while we check the power angle on the first generator in model 1. There are lot of ringing oscillations (overshoots and undershoots) and the output takes a lot of time to stabilize, which can be observed from the simulation results. But, from the incorporation of the fuzzy coordination system in loop with the plant in the entire Simulink model, gave better results, thereby reducing the disturbances and the swinging oscillation in the power angle and also the post fault settling time also got reduced a lot.

The oscillations are less with fuzzy compared to w/o fuzzy. The system stabilizes quickly, thus damping the local mode oscillations and reducing the settling time immediately after the occurrence of the fault. The developed control strategy is not only simple and reliable, but also easy to implement in real time applications using dSPACE or NI-based TI DSP cards.

Note that during the fault when controller is not considered, the del angle is 10 degrees, while with the controller, during the occurrence of the fault, the del angle is improved to 40 degrees, as a result of which the power delivered will be maximum. During fault time, the del curve is smoothened and damped without being oscillatory. Also, lot of improvement can be seen from the power angle characteristics.

The performance of the developed method in this paper thus demonstrates the damping of the power system oscillations using the effectiveness of the SSSC based fuzzy coordination concepts over the damping of power system oscillations without the fuzzy coordination scheme.

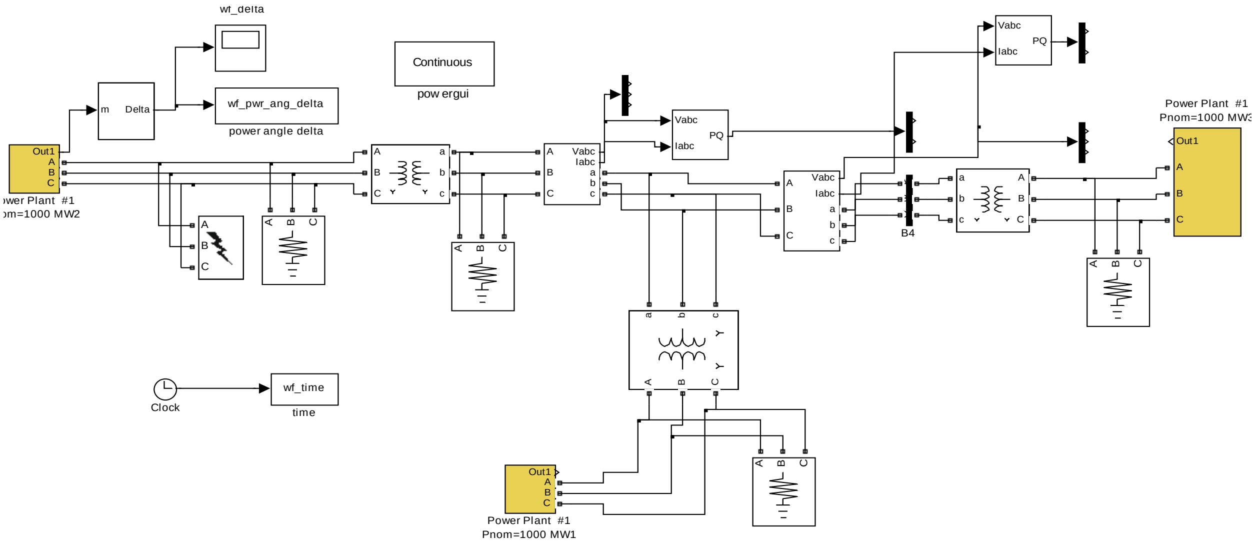


Figure 18. The developed Simulink model of a three-machine, nine-bus system without fuzzy controller based SSSC (with controller) and fault taking place near the generator 1

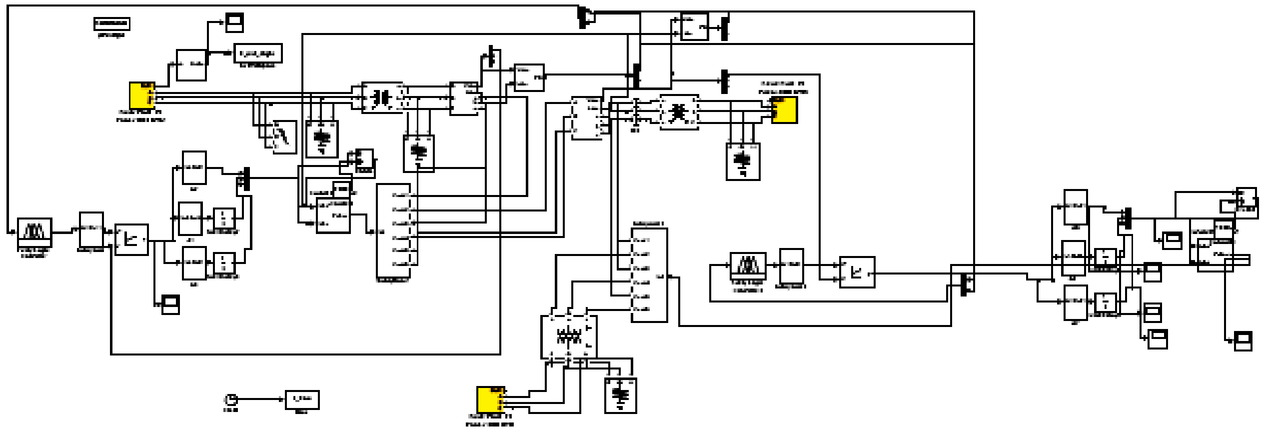


Figure 19. The developed Simulink model of a three-machine, nine-bus system with the POD based SSSC-fuzzy controller and fault taking place near the generator 1

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BIOGRAPHIES

Annamalainagar Subramanian Kannan received his B.E degree in Electrical and Electronics Engineering and M.E. degree in Power Systems Engineering from Annamalai University, Annamalai Nagar, Chidambaram, India. Currently, he is working as an Assistant Professor in the Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, Annamalai University, Annamalai Nagar, Chidambaram, India. He has got more than 11 years of teaching experience. He has also published three papers in international journals and one research paper published in national conference. He has attended ten seminars and workshops. His research interests are in power electronics and FACTS. He is presently pursing Ph.D. in Annamalai University in the Department of Electrical and Electronics Engineering, Annamalai University.

Ramanujam Kayalvizhi was born in Chidambaram, India in 1963. She obtained the B.E. degree in Electronics and Instrumentation and M.E. degree in Power Systems degrees from Annamalai University, Annamalai Nagar, Chidambaram, India with distinction in 1984 and 1988, respectively. She is presently a Professor in the Department of Instrumentation Engineering, Annamalai University where she has put in a total service of 21 years. Her four papers have been presented in IEEE conferences in Malaysia and Korea and she has also published two papers in national journals. Her research interests are in DCDC converters: modeling, simulation and implementation of intelligent control strategies. She is a life member of Indian society for Technical Education.