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DAMPING OF OSCILLATIONS IN MULTI-MACHINE INTEGRATED POWER SYSTEMS USING HYBRID FUZZY STRATEGIES

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ABSTRACT

The design & development of a fuzzy logic controller using UPFCs to damp out the oscillations in FACTS based integrated multi-machine power system when faults takes place at different buses (one fault at a time) is presented in this paper. The multi-machine system consists of 3 generators, 3 transformers, 9 buses, 4 loads & 2UPFCs. 3 Simulink models are developed with & without the hybrid controller by considering the occurrence of one fault at a time near each generator. The 3 phase to ground symmetrical fault is made to occur near the first generator for 200 ms in the model 1, next at the second generator in model 2 & finally at the third generator in model 3. Simulations are performed with & without the controller. The 3 models are compared for the effectiveness of the fault occurrence near each of the generators. The digital simulation results show the effectiveness of the method presented in this paper.

Keywords : *UPFC, POD, Fuzzy logic, Coordination, Controller, Oscillations, Damping, Stability, Simulink, State space model.*

I. INTRODUCTION

According to IEEE, FACTS - which is the abbreviation of Flexible AC Transmission Systems, is defined as "*alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and power transfer capability*". 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 network, viz., series, shunt, combined series-series, and combined series-shunt. In our work, we have used the series-shunt combination [2].

The organization of the paper is as follows. Firstly, a brief introduction to the FACTS, its evolutions, applications, the UPFC controller & the fuzzy logic controller was presented in the previous paragraphs. Section 2 presents the mathematical modeling of the multi-machine system along with the parameters. In section 3, the control strategy, the design of the controller for all the 3 models is presented. Section 4 presents the development of the 3 Simulink models for the damping of the power system oscillations when fault takes place near each generator, individually at a time. Simulation results are presented in section 5.

Conclusions are finally presented at the end in section 6. This is followed by the acronyms & the references.

II. MODELING OF THE 3-MACHINE, 9-BUS INTEGRATED POWER SYSTEM

The integrated multi-machine power system model consisting of 3 generators used for the simulation purposes is shown in the form of a one-line diagram (single line diagram) with & without the controllers in the Fig. 1 respectively. The generators 1, 2 and 3 are connected to buses 1, 5 and 8. Two UPFC's are used for controlling & damping the power system oscillations in the integrated plant [11]. One is connected between bus 2 & 3 and the other is connected between buses 6 and 7. 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 & stepping down purposes. Transmission lines are connected between the buses 3-9-4-6. Since, we know that the power system is a dynamic one, definitely, it is a non-linear system [10]. For modeling & simulation purposes in the Matlab-Simulink environment, a numerical model 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

$$\begin{aligned} \Delta\dot{x} &= A\,\Delta x + B\,\Delta u, \\ \Delta y &= C\,\Delta x + D\,\Delta u. \end{aligned} \tag{1}$$

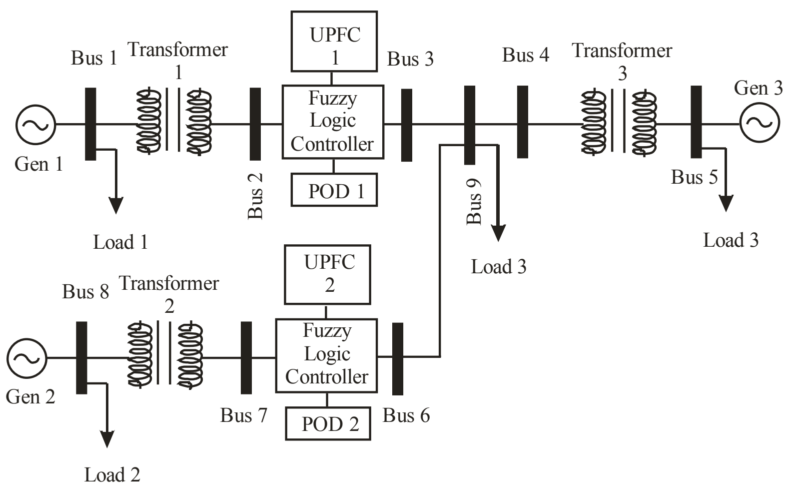

Fig. 1 : A 3-machine, 9-bus interconnected power system model with 4-loads & 2 POD-UPFC & the fuzzy controller

III. DEVELOPMENT OF THE CONTROL STRATEGY

A controller is a device which controls each & 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 unified power flow controller (UPFC) is one of the most promising device & most versatile controller device used in the FACTS family [1] - [4]. It is an electrical device for providing fast-acting reactive power compensation on high-voltage transmission networks & is generally used as a controller in loop with the plant. It has the capability to control voltage magnitude, line impedance and phase angle, and can also independently provide (positive or negative) reactive power injections, thus providing the voltage support, control of power flow, & can be used to control active and reactive power flows in a transmission line. [5]. The concept of UPFC makes it possible to handle practically all power flow control and transmission line compensation problems, using solid state controllers, which provide functional flexibility, generally not attainable by conventional thyristor controlled systems [13]. It has a capability of improving both steady-state and dynamic performances of a power system as they allow more accurate control of the power flow, better and faster control of voltage and system stability. [6]. It can be connected in series with a transmission line inside a system or in a tie-line connecting sub-systems in a large interconnected power system [7]. Moreover, UPFC further improves the dynamic performance of the power system in coordination with damping controllers [8]. As a result, one of their applications is the damping of power system oscillations using Power Oscillation Damping (POD), which recently has been attracting the interest of many researchers, including ours.

The heart of the UPFC is the power electronic devices, i.e., the silicon controlled rectifiers. It consists of two solid-state synchronous voltage source converters coupled through a common DC link capacitor as shown in Fig. 3, i.e., 2 voltage source inverters sharing a common DC storage capacitor. Two coupling transformers are used. As shown in Fig. 3, the UPFC consists of a boosting transformer and an excitation transformer linked by back-to-back converters 1 and 2. The first converter 1 is connected in shunt and the second one 2 in series with the line. The shunt converter is primarily used to provide active power demand of the series converter through a common DC link [14]. Converter 1 can also generate or absorb reactive power and thereby provide independent shunt reactive compensation for the line. Converter 2 provides the main function of the UPFC by injecting additional voltage with controllable magnitude and phase angle in series with the transmission line through series transformer [15]. The main task of the UPFC is to control the flow of power in steady-state conditions. In addition, high speed of operation of thyristor devices makes it possible to control real and reactive power flow. The UPFC can be employed to enhance power system damping by modulating the converter voltages. The UPFCs are used at certain locations in a integrated power system in between some buses [16]. In the Fig. 3 shown, the *i* and *j* represents the buses in the integrated power system model. In our work considered, we have taken the total number of buses to be 9 & Two UPFCs connected between bus 2, 3 and 6, 7.

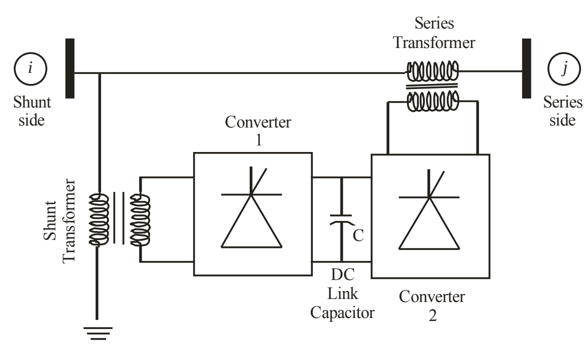

Fig. 3 : A block diagram of the UPFC scheme used in FACTS (single line diagram)

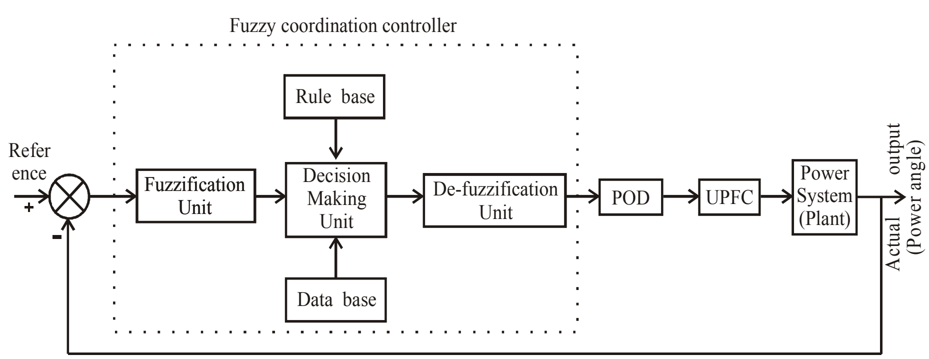

Fig. 5 : A diagrammatic view of a typicall fuzzy logic controller used along with POD-UPFC for controlling the oscillations in a power system

In the research work considered in this paper, fuzzy logic controller is used to coordinate between the various parameters of the multi-machine based FACTS power system along with the POD-UPFC as shown in the block diagram in the Fig. 5. These fuzzy controllers have got a lot of advantages compared to the classical (P, PI, PID) & the conventional controllers (POD-UPFC), such as the simplicity of control, low cost, high reliability, compactness of the hardware (since fuzzy logic controller just makes use of fuzzy rules) and the possibility to design without knowing the exact mathematical model of the process [22]. Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables & 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. 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 $\mu : X \rightarrow [\ 0 \quad 1]$, which associates a number $\mu_A(x) : X \rightarrow [\ 0 \quad 1]$, 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 [7]. 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 3 important parts, viz., fuzzification, knowledge base - decision making logic (inference system) and the de-fuzzification, which are explained in brief as follows [23].

The internal structure of the fuzzy coordination unit is shown in the Fig. 5. 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 [8, 5]. 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 [5]. The decision-making unit uses the conditional rules of 'IF-THEN-ELSE', which can be observed from the algorithm mentioned below [24].

The developed fuzzy rules included in the fuzzy coordinated controller is given below in the form of an algorithm as follows :

1. If (input_1 is mf1) and (input_2 is mf1) then (output_1 is mf3) (1)
2. If (input_1 is mf1) and (input_2 is mf2) then (output_1 is mf2) (1)
3. If (input_1 is mf1) and (input_2 is mf3) then (output_1 is s1) (1)
4. If (input_1 is mf2) and (input_2 is mf1) then (output_1 is mf3) (1)
5. If (input_1 is mf2) and (input_2 is mf2) then (output_1 is mf2) (1)
6. If (input_1 is mf2) and (input_2 is mf3) then (output_1 is s1) (1)
7. If (input_1 is mf3) and (input_2 is mf1) then (output_1 is mf3) (1)
8. If (input_1 is mf3) and (input_2 is mf2) then (output_1 is mf2) (1)
9. If (input_1 is mf3) and (input_2 is mf3) then (output_1 is s1) (1)

The control decisions are made based on the fuzzified variables. The inference involves a set of rules for determining the output decisions [28]. As there are 2 input variables $P_{\text{UPFC-1}}$ and $P_{\text{UPFC-2}}$ & three fuzzified variables (S, M, B), the fuzzy logic coordination controller has a set of 9 rules for each POD based UPFC 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 [29]. The rule base for the decision-making unit for the POD based UPFC controller-1 is written as shown in the table II as follows :

$P_{UPFC1} \rightarrow$ / $P_{UPFC2} \downarrow$	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

Table II : The 9-fuzzy rules used for determining the output decisions (Inference table) rule base used for the control purposes

Now, the 9 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 [30]. This process is what is called as de-fuzzification. Defuzzification is the process of producing a quantifiable result in fuzzy logic. The defuzzifcation transforms a fuzzy set information into a 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 [31]. There are so many methods to perform the deffuzification, viz., centre of gravity method, centre of singleton method, maximum methods, the marginal properties of the centroid methods & so on. In our work, we use the centre of gravity method [32].

The output of the fuzzy-coordination unit is further given as the input to the POD, which in turn is given as input to the UPFC controller. The POD (Power Oscillation Damping) uses 5 individual blocks, viz., the amplification block, the wash out link, 2 stage of lag-lead blocks and a limiter. The modeling of this is done in Simulink and is shown in the Fig. 9. Note that the inputs to controller ($P_{\text{UPFC-1}}$ and $P_{\text{UPFC-2}}$) are the active power flow through the UPFCs. The output signal of the fuzzy-POD combination is the command signals to the UPFCs [33]. Thus, in this way, the conventional POD controllers are tuned by making use of the fuzzy-coordination controllers. The control signal generated from this combined fuzzy-POD-UPFC is given to the multi-machine model which is further used to dampen the oscillations [34]. The main advantage of putting the fuzzy coordination controller before the UPFC-POD in modeling is the amplification part of the conventional controller being modified by the fuzzy coordination unit, thus increasing the power system stability. The overall structure of the fuzzy-coordination controller used in the work is shown in the block-diagram in the Fig. 8.

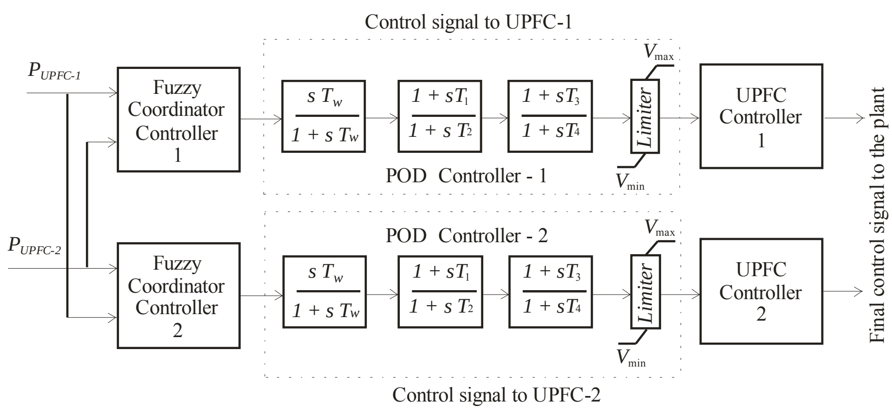

Fig. 8 : The Fuzzy-POD-UPFC fuzzy-cordinator controller

IV. 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 controller. The Figs. 10 - 12 show the 3 simulation models of the 3-generator, 9-bus system installed with two Fuzzy-POD-UPFC controllers, i.e., first one between 2nd and the 3rd bus and second one is at 6th and 7th bus when the fault takes place near generators 1, 2 & 3. 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) & the input sources [39]. The Simulink model is developed from the basic functions available in the Simulink library & from the various tool-boxes available. Transformers are used for voltage step up & step down purposes. The sub-system shown in the 3 Simulink models consists of FACTS POD controller and it involves a 3-stage first order transfer function consisting of an amplification block, a wash-out block and m_c stages of lead-lag blocks & the limiters [35].

The output signal of the Fuzzy coordinated POD is amplification signal adjusted to the UPFC POD controller & given as input to the UPFC. In this way, the conventional POD controllers are coordinated dynamically by means of fuzzy-logic & the amplification part of the conventional controller is modified by the fuzzy coordination controllers, thus acting as a pre-amplifier [38]. Fuzzy coordinated controller consists of 3 basic blocks viz., fuzzification, inference, and the de-fuzzification blocks. A set of 9 fuzzy rules are written and called in the form of a file in the developed Simulink model with the controller. The 3 phase to ground symmetrical fault is made to occur near the first generator for 200 ms from the first cycle to the tenth cycle. In the work considered shown in the Fig. 10, the combined effect of Fuzzy-POD-UPFC is mainly used for power system oscillation damping [37]. The Figs. 13 - 15 show the simulation model of 3-generator, 9-bus system installed without the controllers for all the 3 models. This system is thus, an open loop control system because of the absence of the controller [40]. The 3 phase to ground symmetrical fault is also made to occur near the first generator for 200 ms from the first cycle to the tenth cycle like in the model with the controller in all the 3 cases. This is done in order to compare the effectiveness of the incorporated controller in the model when the fault takes place with the model without the controller when the fault takes place [36].

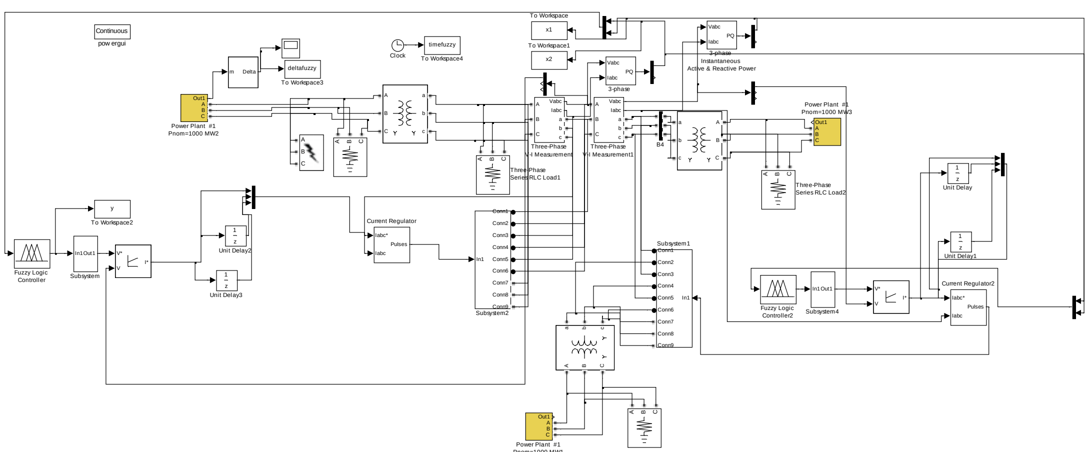

Fig. 10 : The developed Simulink model of a 3-machine, 9-bus system with Fuzzy-POD-UPFC (with controller) fault taking place at generator 1 in model 1

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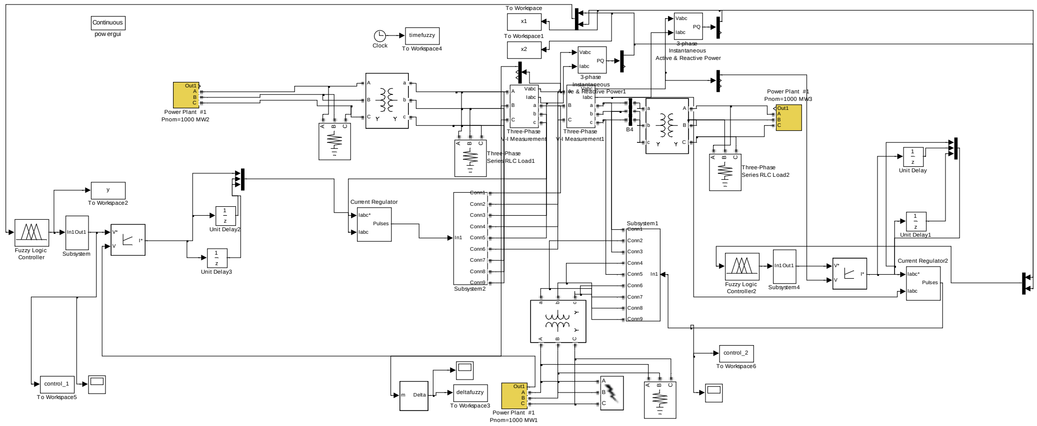

Fig. 11 : The developed Simulink model of a 3-machine, 9-bus system with Fuzzy-POD-UPFC (with controller) fault taking place at generator 2 in model 2

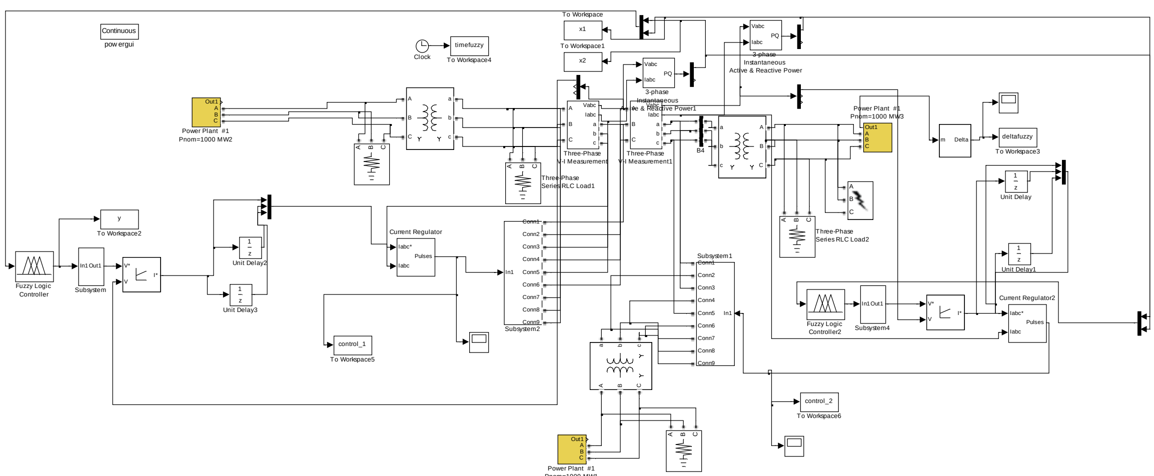

Fig. 12 : The developed Simulink model of a 3-machine, 9-bus system with Fuzzy-POD-UPFC (with controller) fault taking place at generator 3 in model 3

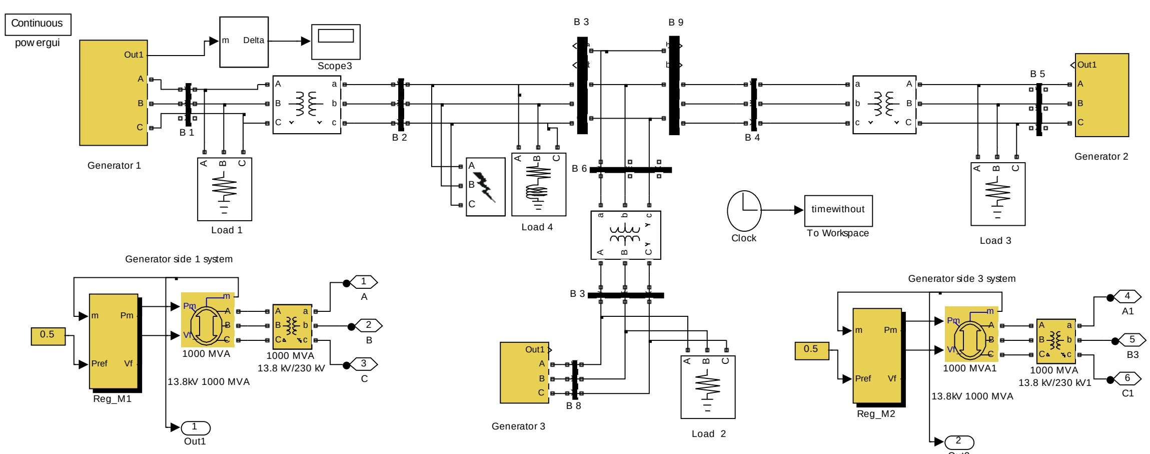

Fig. 13 : The developed Simulink model of a 3-machine, 9-bus system without Fuzzy based UPFC-POD (without controller) & fault taking place at generator 1 in model 1

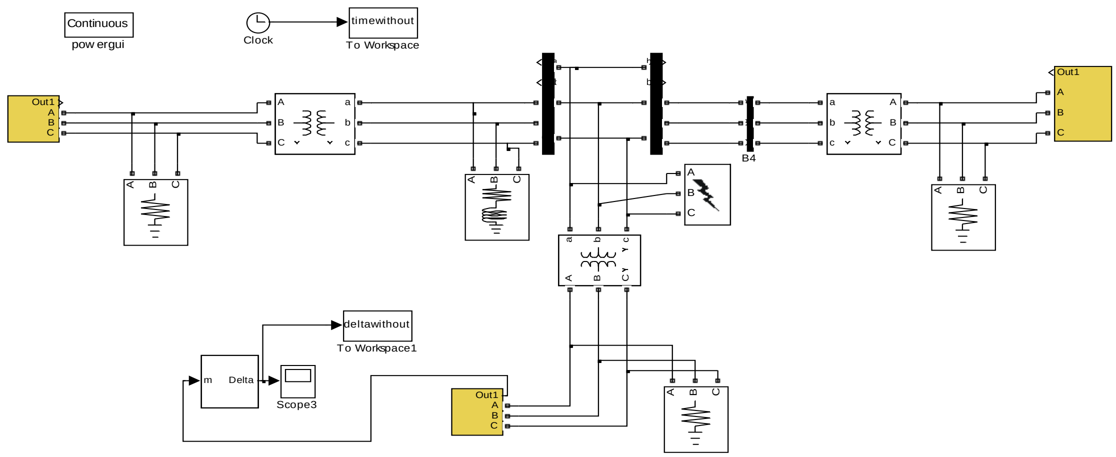

Fig. 14 : The developed Simulink model of a 3-machine, 9-bus system without Fuzzy based UPFC-POD (without controller) & fault taking place at generator 2 in model 2

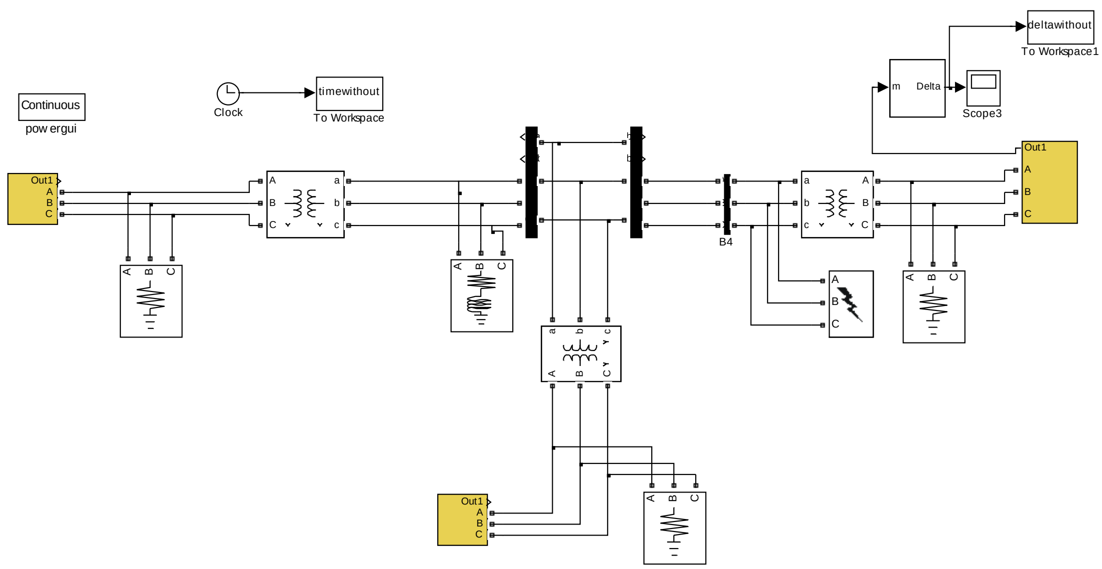

Fig. 15 : The developed Simulink model of a 3-machine, 9-bus system without Fuzzy based UPFC-POD (without controller) & fault taking place at generator 3 in model 3

V. SIMULATION RESULTS

Digital Simulations are carried out in Matlab 7 & was run for 2 s with & without the controller for all the 3 models, viz., fault at generator 1 (model 1), fault at generator 2 (model 2), fault at generator 3 (model 3). The step size for all the 6 simulations (3 with controller & 3 without controller) was taken to be very small so that we get very accurate results. For the software implementation purposes, we had taken a 3-generator nine bus system with 220 KV line and 100 MW generators. The 3 phase to ground symmetrical fault is made to occur near the first generator for 200 ms from the first cycle to the tenth cycle & & is also simulated in the Simulink model. Similarly, the 3 phase to ground symmetrical fault is made to occur near the second generator for 200 ms from the first cycle to the tenth cycle & & is also simulated in the Simulink model. Again, the 3 phase to ground symmetrical fault is made to occur near the first generator for 200 ms from the first cycle to the tenth cycle & & is this also simulated in the Simulink model. Due to the occurrence of the fault, the simulation results were observed with & without the controller for all the 3 models after the occurrence of the fault. The fuzzy editor with 2 inputs & 1 outputs is shown in the Fig. 16. The membership function with the 9 fuzzy rules used in the development of the fuzzy logic

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coordination scheme for the model 1 is shown in the Fig. 17 only for convenience. The set of fuzzy rules is shown in Fig. 18. This remains the same for the remaining 2 models (model 2 & 3) & is not shown here in this context.

The response curve of power angle in degrees vs. time is obtained without the controller for all the 3 models & is shown in the Figs. 19 - 21 respectively & without the controllers for all the 3 models in the Figs. 22 - 24 respectively. It is clearly observed from the comparative simulation results that with the developed controller, the dynamic performance of the power system is quite improved with the incorporation of the fuzzy coordination scheme for all the 3 individual models. It is also observed that with the controller, the power angle characteristics curves exhibit very less overshoots & undershoots. The oscillations are also damped out in a lesser time. The response characteristics take less time to settle & reach the final steady state value in all the 3 cases. Without the controller, the response characteristics take a lot of time to settle which can be observed from the simulation results in the Figs. 19 - 21 respectively. One thing to observe is that since we have used only 2 fuzzy-POD-UPFCs, one near the generator 1 & the other near the generator 2 & no UPFC near the generator 3. Because of this reason (absence of fuzzy-POD-UPFC), the output near the generator 3 with the control effect is more oscillatory, of course it settles & stability is maintained & takes a lot of time to stabilize. The output near the generator 2 is less oscillatory compared to the output at generator 3 and stabilizes very quickly compared to the previous counterpart. The output near the generator 1 does not exhibit oscillations & are damped out very quickly compared to the power angle characteristics near the generator 2 & 3. Hence, it can be concluded that upon the occurrence of the fault near the respective generators, the fault at generator 1 has less effect on the system dynamics than the others. Here, the comparative statements of the settling times with and without the controllers is presented in the form of a table in the table IV.

	Without controller	With controller
Model 1	4.33	0.53
Model 2	5.42	0.72
Model 3	9.22	5.73

Table IV : Comparative statements of the settling times of the power angle curves

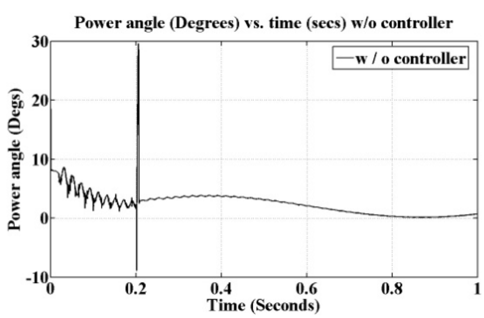

Fig. 19 : Simulation result of power angle v/s time (without UPFC) for model 1, fault at generator 1

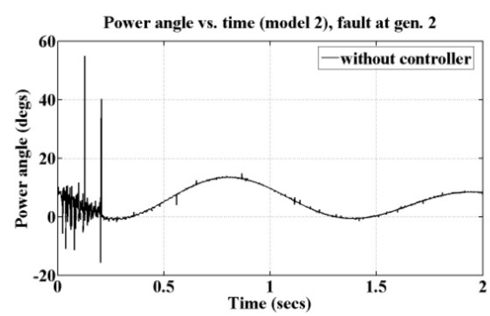

Fig. 20 : Simulation result of power angle v/s time (without UPFC) for model 2, fault at generator 2

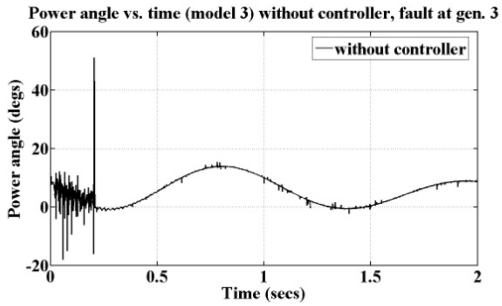

Fig. 21 : Simulation result of power angle v/s time (without UPFC) for model 3, fault at generator 3

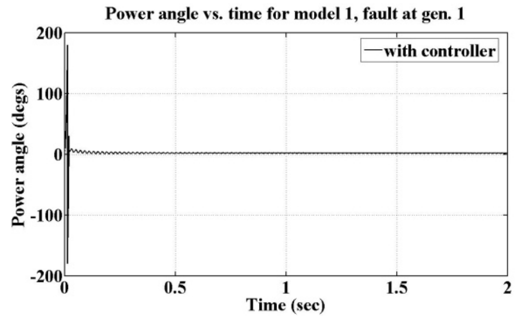

Fig. 22 : Simulation result of power angle v/s time (with UPFC & fuzzy control), fault at generator 1 for model 1

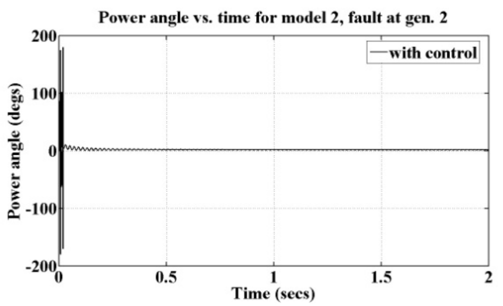

Fig. 23 : Simulation result of power angle v/s time (with UPFC & fuzzy control), fault at generator 2 for model 2

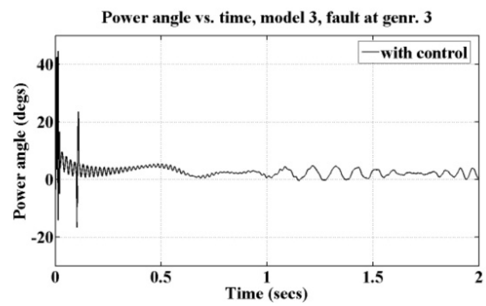

Fig. 24 : Simulation result of power angle v/s time (with UPFC & fuzzy control), fault at generator 3 for model 3

VI. CONCLUSION

A FACTS based multi-machine power system comprising of 3 generators, 9 buses, 3 loads with and without the 2 Fuzzy-POD-UPFC controllers was considered in this paper by developing 3 Simulink models. Simulink models were developed in Matlab 7 with & without the Fuzzy-POD-UPFC controllers for the considered multi-machine model in order to damp out the oscillations. 3 models were developed. In the 1st model, fault takes place near generator 1. In the 2nd model, fault takes place near generator 2. In the 3rd model, the fault takes place near generator 3. The control strategy was also developed by writing a set of fuzzy rules. The fuzzy control strategy was designed based on the conventional POD-UPFC controller & put before the POD-UPFC in the modeling. The main advantage of putting the fuzzy coordination controller before the POD-UPFC in modeling is the amplification part of the conventional controller being modified by the fuzzy coordination unit, thus increasing the power system stability. Simulations were run in Matlab 7 & the results were observed on the scope. Graphs of power angle vs. time were observed with and without the controller for all the 3 models. From the simulation results, it was observed that without the Fuzzy-POD-UPFC controller, the nine bus system will be having more disturbances, while we check the power angle on the first generator in model 1, second generator in model 2, third generator in model 3. There are lot of ringing oscillations (overshoots & undershoots) & the output takes a lot of time to stabilize, which can be observed from the simulation results. But, from the incorporation of the Fuzzy-POD-UPFC coordination system in loop with the plant in all the 3 models, gave better results there by reducing the disturbances in the power angle and also the post fault settling time also got reduced a lot. 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, reliable, and may be easy to implement in real time applications. The performance of the developed method in this paper thus demonstrates the damping of the power system oscillations using the effectiveness of Fuzzy-POD-UPFC coordination concepts over the damping of power system oscillations without the Fuzzy-POD-UPFC coordination scheme. Finally, it was concluded that the generator 2 (model 2) is less stable and takes a lot of time to stabilize as the UPFC is not being used near it. Generator 1 stabilizes very quickly, whereas generator 2 takes some time and generator 3 time a lot of time to stabilize compared to the other two models.

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