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Application of SSSC and IPFC for Stability Enhancement for SMIB and MMIB using FUZZY Logic Controller

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Abstract:
In this dissertation, a static synchronous series compensator (SSSC) and Internal Power Flow Controller (IPFC) independently are used to improve small signal stability in a series compensated transmission system. SSSC is applied for both Single Machine Infinite Bus (SMIB) system and IPFC is applied for Multi Machine Infinite Bus (MMIB) system to enhance power oscillations such as power angle, stator terminal voltage. Further enhancement can be achieved by using MAMDANI based FUZZY Logic Controller (FLC). Complete stability analyses, including voltage, small perturbation and transient stability studies, and the associated models and controls of a SSSC and IPFC with 7 rules Mandeni based FLC are studied in this work. It is shown that the SSSC and IPFC improve the synchronizing power coefficient for SMIB and MMIB and further ensures increased damping of small signal oscillations. It is also shown through detailed simulations that the SSSC and IPFC independently is a competitive device against series power-flow controllers and it might be a better option for similar purposes where space and costs are at premium. Hence, a full comparative evaluation of this controller with respect to controllers used mainly for oscillation control in transmission corridors, namely, SSSC, IPFC is also presented. The results obtained show that the SSSC and IPFC have better oscillation damping characteristics with FLC than conventional PI controller, hence making these types of controllers a competitive alternative against existing series flexible ac transmission sys(FACTS)controllers for dynamic series compensation of transmission lines.

Key words: *AVR, Transient Stability, Fuzzy Logic Controller, Membership Function, FACTS, SSSC, IPFC, Series Compensation*

1. Introduction

Power system synchronous stability is usually studied by a single mass turbine-generator shaft Machine infinite bus system or multi-machines power systems are usually used .Power system oscillations can be classified in local oscillations between a unit and the rest of a generating station in the order of (0.8 to 4.0) Hz, interplant oscillations occur between two electrically close generation plants of the order (1.0 to 2.0) Hz and inter-area oscillation between two major groups oscillations of frequency (0.2 to 0.8) Hz In this study using a IPFC with power system stabilizer(PSS), the SSSC is a series device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids. The IPFC regulates power at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low,

the ipfc generates reactive power . When system voltage is high, it absorbs reactive power (IPFC inductive). It can be used in three-phase power systems together with synchronous generators, motors, and dynamic loads to perform transient stability studies and observe impact of the IPFC on electromechanical oscillations and transmission capacity. This model does not include detailed representations of the power electronics, the measurement system, or the synchronization system. These systems are approximated rather by simple transfer functions that yield a correct representation at the system's fundamental frequency. Results showed superior results using such power system stabilizer than conventional power system stabilizers using (MB-PSS) or that using the (dPa-PSS), as input signals.

In most modern power systems the Automatic Voltage Regulator (AVR) is widely used to sense the generator output voltage and then initiates corrective action by changing the exciter control in the desired direction. The AVR is so designed as to be able to respond quickly to a disturbance endangering the transient stability [1, 2, 3]. Also, it should be able to damp low frequency oscillations of power angle (8) and thereby contribute in improving the small signal stability of the system. Because of the high inductance of the generator field winding, it is difficult to make rapid changes in field current. This introduces a considerable lag in the control function and is one of the major obstacles to be overcome in designing the regulating system.

To fulfill the above requirements of an excitation control system and to avoid the growing difficulties faced by the conventional control schemes while handling complex and highly non-linear systems, Artificial Intelligence (AI) techniques are being used. Among various AI techniques, the major advantage of fuzzy logic control is its lower computational burden and robustness [4]. Moreover, in the design of fuzzy logic controllers, unlike most conventional methods, a mathematical model is not required to describe the system under study.

This paper reports on the design and validation of a fuzzy-based AVR to enhance the stability of power systems considerably and emphasizes its easy implementation. The effectiveness of the proposed fuzzy AVR in single-machine and multi-machine systems is demonstrated by digital computer simulation. It is shown that, by application of fuzzy AVR to the power systems commendable dynamic performance can be obtained.

Flexible AC Transmission Systems (FACTS), based on either Voltage or Current Source Converters (VSC/CSC), can be used to control steady-state as well as dynamic/transient performance of the power system. Converter-based FACTS controllers, when compared to conventional switched capacitor/reactor and thyristor- based FACTS controllers such as Static Var Compensator (SVC) and Thyristor-controlled Series Capacitor (TCSC), have the advantage of generating/absorbing reactive power without the use of ac capacitors and reactors. In addition, converter-based FACTS controllers are capable of independently controlling both active and reactive power flow in the power system [1].

Series connected converter-based FACTS controllers include Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), and Interline Power Flow Controller (IPFC). A SSSC is a series compensator with ability to operate in capacitive/inductive modes to improve system stability [3,4]. The UPFC includes a Static Synchronous compensator (STATCOM) and a SSSC that share a common dc-link. The IPFC consists of two or more SSSC with a common dc-link; so, each SSSC contains a VSC that is in series with the transmission line through a coupling transformer, and injects a voltage – with controllable magnitude and phase angle - into the line. IPFCs provide independent control of reactive power of each individual line, while active power could be transferred via the dc-link between the compensated lines. An IPFC can also be used to equalize active/ reactive power between transmission lines, and transfer power from overloaded lines to under-loaded lines [2].

Since its introduction in 1998 [2], relatively only a few research papers exist about IPFC configurations as compared to other types of FACTS controllers. In [5,6,7], the control design and steady-state operation of an IPFC is presented. In [8,9], the utilization and steady-state operation of the ±200 MVA Convertible Static Compensator (CSC) installed by New York Power Authority at its Marcy 345 kV substation is described. The CSC is capable of controlling voltage, increasing power transfer and enhancing the dynamic performance of the power system. It includes two VSCs, and by means of different circuit configurations, can function either as a STATCOM, SSSC, UPFC or IPFC.

This paper presents EMTP-RV based models of the IPFC which are based on [1,2]. In section II, the model of a 3-level Neutral-Point-Clamped (NPC) VSC - used as the basic building block of an IPFC - is presented. In section III, the IPFC control scheme for two identical transmission lines is studied. The controller is designed to regulate the transmission line impedance (*R* and *X*) and balance the dc-link capacitor voltages of the IPFC. The simulation results are used to assess the ability of the IPFC to regulate the transmission line impedance in the power system and PSS produce oscillations in synchronous machine.

2. Multi–Band Power System Stabilizer

The need for effective damping of a wide range of electromechanical oscillations motivated the concept of the (MB-PSS). As its name reveals, the MB-PSS structure is based on multiple working bands. The main idea of the MB-PSS is that three separate bands are used, respectively dedicated to the low, intermediate, and high frequency modes of oscillations. The low band is typically associated with the power system global mode, the intermediate band with the inter-area modes, and the high band with the local modes. Each of the three bands is made of a differential band-pass filter, gain, and limiter as shows Fig. A. The outputs of the three bands are summed and passed through a final limiter producing the stabilizer output *Vstab* (Fig. A). This signal then modulates the set point of the generator voltage regulator so as to improve the damping of the electromechanical oscillations. Usually, a few of the lead-lag blocks should be used in MB-PSS circuits. Two different approaches are available to configure the settings during MB-PSS tuning process.

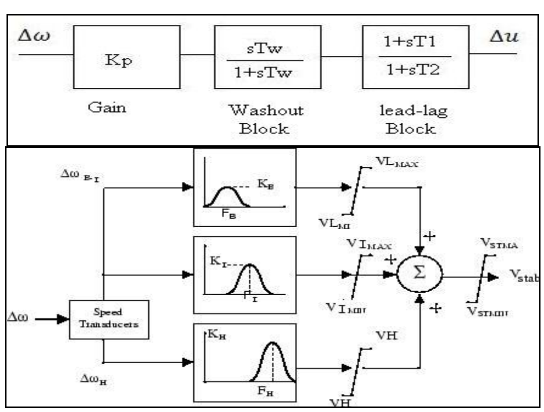
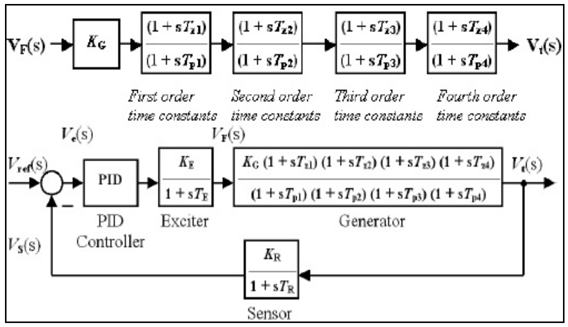


Fig.A.(a) PSS block parameters,(b)MB-PSS block diagram

2.1. Automatic Voltage Regulator(AVR)
In most modem power systems the Automatic Voltage Regulator (AVR) is widely used to sense the generator output voltage and then initiates corrective action by changing the exciter control in the desired direction The AVR is so designed as to be able to respond quickly to a disturbance endangering the transient stability . Also, it should be able to damp low frequency oscillations of power angle (Δ) and thereby contribute in improving the small signal stability of the system. Because of the high inductance of the generator denotes field winding,



fig(B).AVR with PID block diagram

It is difficult to make rapid changes in field current. fig(B).This introduces a considerable lag in the control function and is one of the major obstacles to be overcome in designing the regulating system block diagram shown in Fig(B).

3. Fuzzy Set Theory

3.1. Definition of a fuzzy set
Assuming that X is acollection of objects, a fuzzy set A in X is defined to be
a set of ordered pairs:
$A = \{(x,\mu_A(x))/x\epsilon X\}$ (1)
where $/\mu_A$ (x) is called the membership function of x in A. The numerical interval X is called Universe of Discourse [5]. The membership function $\mu_A(^x)$ denotes the degree to which x belongs to A and is usually limited to values between 0 and 1.

3.2. Fuzzy set operation
Fuzzy set operators are defined based on their corresponding membership functions. Operations like AND, OR, and NOT are some of the most important operators of the fuzzy sets. It is assumed that A and B are two fuzzy sets with membership Functions $\mu_A(x)$ *and* $\mu_B(x)$ respectively. Then, the following operations can be defined:

- *The AND operator or the intersection of two fuzzy sets:* The membership function of the intersection of these two fuzzy sets ($C = A \cap B$), is defined by $\mu_c(x) = min\{\mu_A\{x),\mu_B(x)\}, x \epsilon X$ (2)

- *The OR operator or the union of two fuzzy sets:* The membership function of the union of these two fuzzy sets ($D = A \cup B$), is defined by $\mu_D(x) = Max\{\mu_A(x), \mu_B(x)\}, x\epsilon X$ (3)

- *The NOT operator or the complement of a fuzzy set:* The membership function of the complement of A, A', is defined by: $\mu_A(x) = 1 - \mu_A(x), x \epsilon X$ **(4)**

- *Fuzzy relation:* A fuzzy relation R from A to B can be considered as a fuzzy graph and characterized by membership function $\mu_R(x, y)$, which satisfies the composition rule as follows: $\mu_B(y) = \underset{x\epsilon X}{Max}\{min[\mu_A(x), \mu_B(x)]\}$ (5)

4. Fuzzy-Based AVR

The first step in designing a fuzzy-based AVR is to choose which state variables, representative of system dynamic performance, must be taken as the input signals to the controller. Choice of proper linguistic variables formulating the fuzzy control rules is also an important factor in the performance of the fuzzy control system. These variables transform the numerical values of the input of the fuzzy AVR, to fuzzy quantities. Empirical knowledge and engineering intuition play an important role in choosing linguistic variables and their corresponding membership functions. In this paper, based on previous experience, deviation in terminal•
voltage (e) and its derivative (*e*) has been chosen as the input signals of the fuzzy-based AVR. The second step is to choose the linguistic variables, keeping in mind that the number of linguistic variables specifies the quality of the control. As the number of the linguistic variables increases, the computational time and required memory also increase. Therefore a compromise between the quality of control and computational time is needed to choose the number of linguistic variables. For the test systems, following seven linguistic variables for each of

the input and output variables are used to describe them: (i)LP (Large Positive), (ii) MP (Medium Positive), (iii)SP (Small Positive), (iv) ZE (Zero), (v) SN (Small Negative), (vi) MN (Medium Negative) and (vii) LN (Large Negative). The normalization of the input variables is done by dividing the input values by maximum of the corresponding value of the input variable obtained by open loop simulation [6]. Thirdly, it is required to determine the membership functions for the fuzzy sets. In this paper, the authors have used triangular membership functions to define the degree of membership as shown in Figure 2.

In designing the AVR, the rules are defined using linguistic variables. The two inputs, deviation of terminal voltage and its derivative, result in 49 rules for each machine. A proper way to show these rules is given in Table 1. A typical rule has the following structure:

- *Rule 1: IF voltage error is LN (Large Negative) AND derivative of error is LN (Large Negative) THEN V_{AVR} (Output of fuzzy AVR) is LP (Large Positive).*

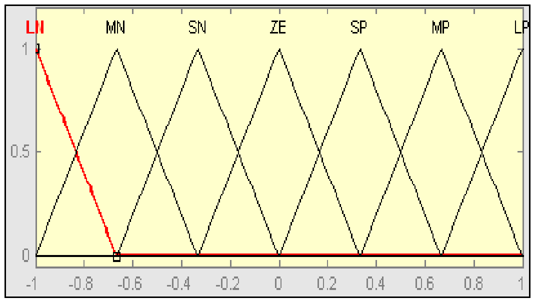


Figure 2: Triangular Membership Function of Input and Output Variables

$\Delta\dot{e}$	**LN**	**MN**	**SN**	**ZE**	**SP**	**MP**	**LP**
LN	*LP*	*LP*	*LP*	*MP*	*MP*	*SP*	*ZE*
MN	*LP*	*MP*	*MP*	*MP*	*SP*	*ZE*	*SN*
SN	*LP*	*MP*	*SP*	*SP*	*ZE*	*SN*	*MN*
ZE	*MP*	*MP*	*SP*	*ZE*	*SN*	*MN*	*MN*
SP	*MP*	*SP*	*ZE*	*SN*	*SN*	*MN*	*LN*
MP	*SP*	*ZE*	*SN*	*MN*	*MN*	*MN*	*LN*
LP	*ZE*	*SN*	*MN*	*MN*	*LN*	*LN*	*LN*

Table 1: Rules Table

In this paper, the Min-Max method is used to find the fuzzy region for each fuzzy rule. Fuzzy rules are connected using AND operator, where the AND operator means finding minimum between two membership functions. The AND operator is used to obtain the minimum between input membership functions. Later, the minimum between this result and the output membership function is found. Finally the output membership function of a rule is calculated. This procedure is carried out for all the rules and for every rule an output membership function is obtained. To find the output membership function due to all these rules, the maximum among all of these rules is calculated. Since a non-fuzzy signal is needed for the excitation system, by knowing the membership function of the fuzzy controller its numerical value is determined. This is called defuzzification and in this paper, the Centroid Method is used, where the weighted average of the membership function or the center of gravity of the area bounded by the membership function curve is computed to be the most typical crisp value of the fuzzy quantity

4.1. Power Circuit of IPFC

4.1.1. Power Circuit

An IPFC (Fig. 1) uses two or more VSCs that share a common dc-link. Each VSC injects a voltage – with controllable amplitude and phase angle - into the power transmission line through a coupling transformer. Each VSC provides series reactive power compensation for an individual line and it can also supply/absorb active power to/from the common dc-link. Thus, an IPFC has an additional degree of freedom to control active power flow in the power system when compared to a traditional compensator. This capability makes it possible to transfer power from over- to under-loaded lines, reduce the line resistive voltage drop, and improve the stability of the power system. Fig. 1 shows the scheme of an IPFC having two VSCs. In this scheme, a master control system is used to compensate both resistive and inductive impedances of the Line 1 power system, and the slave control system is used to regulate the reactance of Line 2 and maintain the common dc-link voltage.

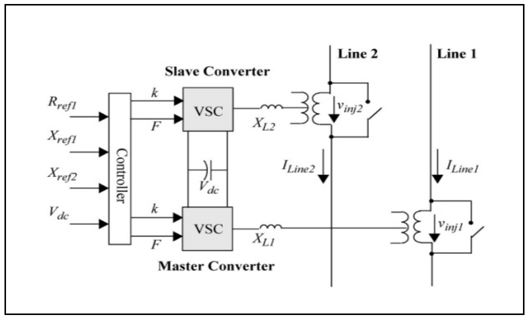


Fig. 1. Schematic of an IPFC

4.1.2. Converter Model

For the converter model, a 3-phase 3-level NPC VSC with a switching frequency of 900 Hz is used. Each converter consists of 12 valves and 2 dc capacitors C1 and C2. Each valve consists of a switch with turn-off capability and an anti-parallel diode. The diodes ensure bi-directional current flow and, therefore, the converter can operate in either rectifier or inverter modes. If the VSC losses are neglected, the injected voltage from the converter can be set to either lead or lag the transmission line current by exactly 90o, depending upon the requirement of the reactive power. The neutral point of the coupling transformer and dclink of the slave system VSC are connected with a large inductor *Lo*. This path is employed to equalize the dc capacitor voltages of the VSC.

4.2. Control Scheme of IPFC

The IPFC is designed to maintain the impedance characteristic of the two transmission lines. The IPFC consists of two converter systems: (a) a master converter system that is capable of regulating both resistive and inductive Impedances of Line 1; and, (b) a slave converter system that regulates Line 2 reactance and keeps the common dc-link voltage of the VSC at a desired level. So, each VSC is independently controllable. Balancing the dc voltages *Vdc1* and *Vdc2* on the capacitors C1 and C2 respectively, is an important concern in multi-level converter. Uneven voltage charging on the capacitors can cause over-voltages on the switching devices and that could be destructive for them. The problem may be solved by either (a) a modified PWM switching pattern, (b) by a voltage regulator for each level using an additional charge balancing leg, or (c) separate dc sources. In order to maintain an equal voltage in the dc-side, the voltage of the neutral point must be regulated. Here, based on, the zero sequence current *i0* is used to equalize voltages on the dc-link capacitors of the VSC.Fig. 2 shows the control diagram of the slave IPFC system. It consists of three control loops: (a) for regulating the injected reactance, (b) for regulating the dc-link voltage, and (c) for balancing the voltages on the dc side capacitors.

To regulate the injected voltage amplitude, the Reactance Controller is employed. The injected reactance *Xinj* is compared to a reference reactance value *Xref* and a PI controller is used to amplify the error. The resultant is added to the *d*-component of the desired reference waveform *Vd'*, and that modulates the reference signals *va**, *vb** and *vc** of the PWM controller. The active power exchange is regulated by the phase angle of the injected voltage in response to an error in the dc-link voltage via a PI controller. The dc-link voltage *Vdc* is maintained constant and is equal to *Vdc-ref*, and by changing the converter dc/ac gain, the injected voltage amplitude is controlled. The slave control system must not only absorb enough active power to compensate for the VSC losses, but it must also supply the required active power for the master system. Consequently, the slave system provides a constant dc voltage for the master system and acts as an Energy Storage System(ESS).

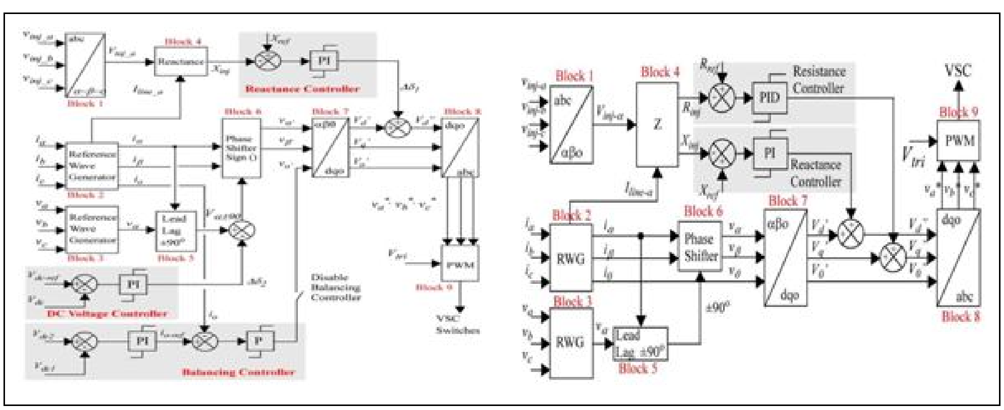


Fig. 2.: IPFC slave converter system controller & Fig. 3 IPFC master converter system controller

Fig. 3 shows the overall control structure of the master IPFC system. This block diagram is similar to the block diagram of the slave IPFC system, and has many of the same blocks except for two major differences: (a) the dc voltage controller and (b) the balancing controller. Since the dc-link voltage is controlled by the slave system, the dc voltage controller and balancing controller are no longer needed. However, here two control loops are required to regulate the *d*- and *q*-components in the synchronous reference frame in order to regulate both the reactance and resistance of the Line 1.

To regulate the injected reactance, a Reactance Controller is used. The injected reactance *Xinj-1* is compared to a reference value *Xref* and the error is fed to a PI controller. The resultant is added to the d-component of the desired reference waveform *vd'* to generate *vd"*. Similarly, the injected resistance – defined as the real part of (*Vinj*/*Iline*) - is regulated by a Resistance Controller. For this purpose, the injected resistance *Rinj-1* is compared to reference value *Rref* and the error is amplified by a PID controller. The result is added to the q-component of the desired waveform *Vq'* and generates *Vq"*. In this particular case, a PID controller is applied to reduce the oscillations of the time response. Block 8 receives the modified *d*- and *q*-components *Vd"* and *Vq"* and transforms them to 3-phase coordinates; these signals are used as the reference signals *va**, *vb**, and *vc** of the PWM controller. And the PWM Block provides firing pulses for the3-level NPC VSC switches. Since the master converter system regulates the dc-link voltage to a fixed level, theoretically it is capable of injecting a voltage with a phase angle in the range of 0-360o.

4.2.1. Balancing Controller

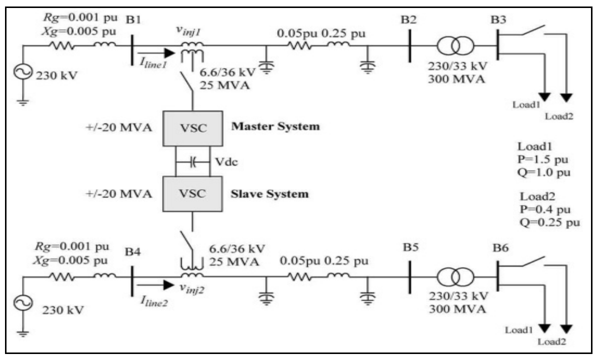
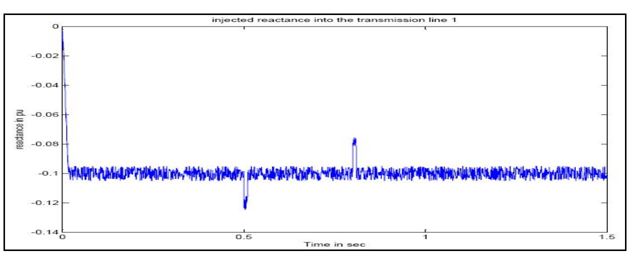


Figure 4

The zero sequence current is used to balance the voltages of the dc-link capacitors in a 3-level Neutral-Point-Clamped (NPC) VSC. This is achieved by connecting the neutral points of the slave system's coupling transformer and the dc-link of the IPFC through a large inductor *Lo*. If the dc-link capacitor voltages are unbalanced, a zero sequence current is generated. The generated zero sequence current i0-ref is compared to the actual zero sequence current of the converter's output i0 (neutral points of the coupling transformer), and amplified by a proportional controller. The zero sequence component v0' joins v α ' and v β ' components of the controller and are then converted to the 3-phase reference components va*, vb* and vc* (Fig. 2) that are used as the reference signals for the PWM controller. Consequently, the Balancing controller generates a zero sequence current that passes through the connection of the neutral point of the coupling transformer and the dc-link to equalize the voltage on the two capacitors.

5. Results and Conclusion

The simulated power system (Fig. 4), modelled with MATLAB/SIULINK, consists of two identical transmission systems. The study of an IPFC system with two parallel lines has demonstrated the flexible control of active/reactive power to assist in the transmission system. The behavior of the system under various load changes at the receiving-end of the transmission system are presented and analyzed. The results of an IPFC system with two 3-level NPC VSCs in MATLAB/SIMULINK have validated. The simulation results demonstrate the capability of the IPFC in compensating both resistance and reactance of the transmission line of the IPFC.



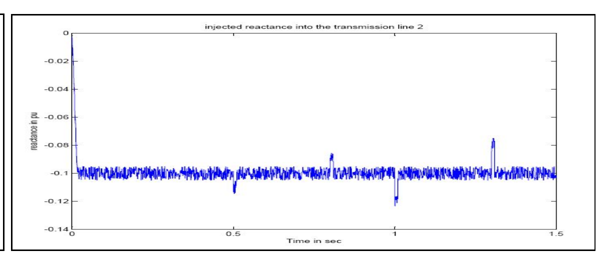
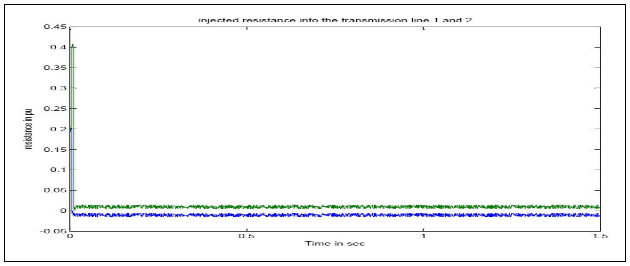


Fig.5: Injected Reactance into the transmission line 1
Fig.6: Injected Reactance into the transmission line 2



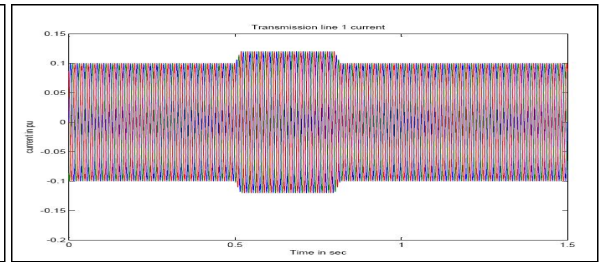
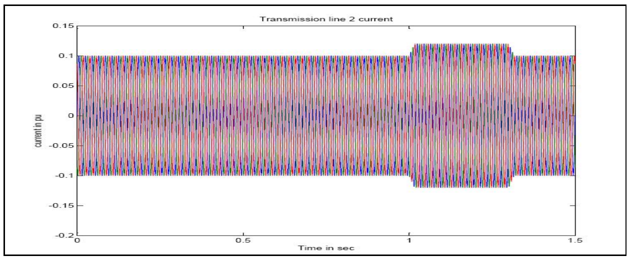


Fig.7: Injected Resistance into the transmission line1 and 2
Fig. 8: Transmission line 1 current



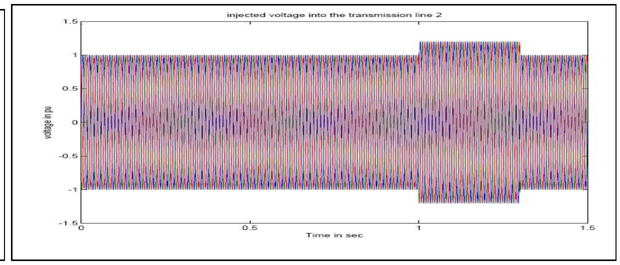


Fig. 9: Transmission line 2 current
Fig. 10: Injected voltage into the transmission line 2

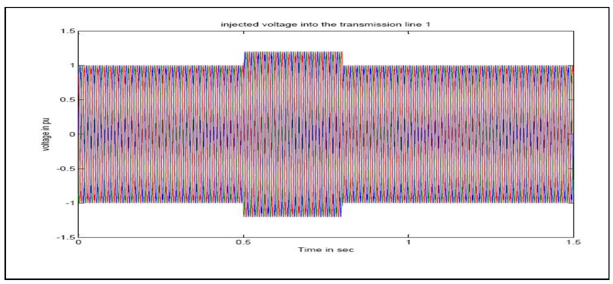
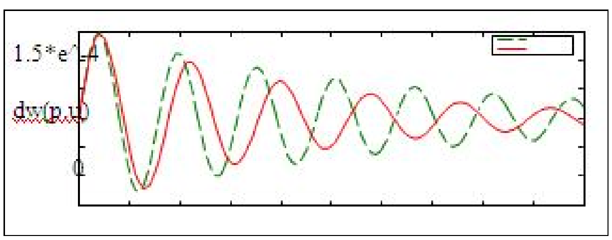


Fig. 11: Injected voltage into the transmission line 1



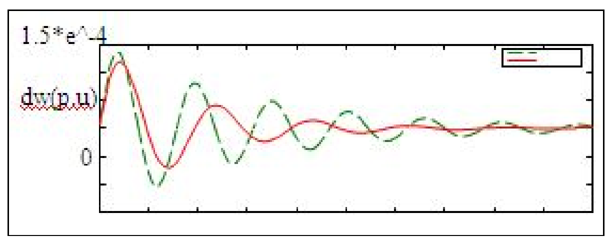
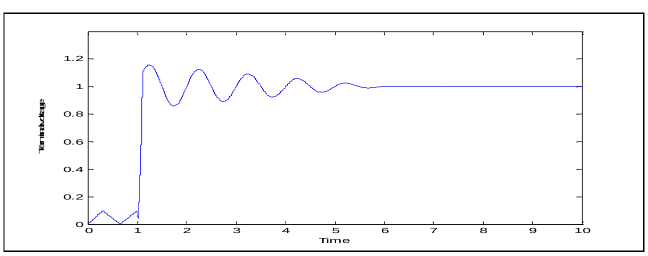
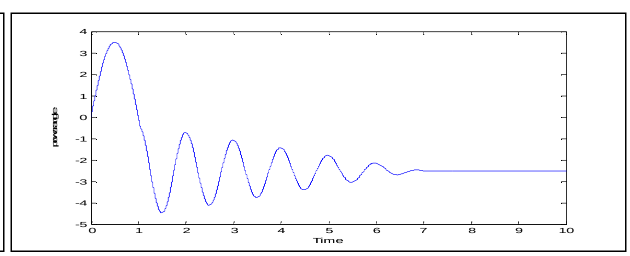
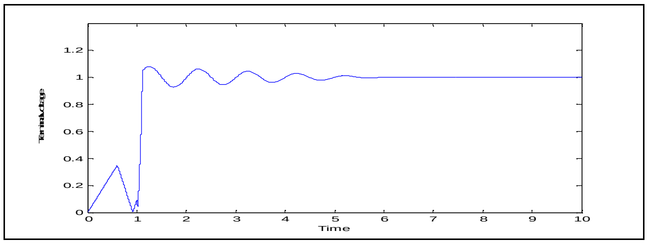


Fig.12.1: Rotorspeed deviation of machine with out pss Time(t)sec
Fig.12.2: Rotorspeed deviation of machine with pss Time(t)sec

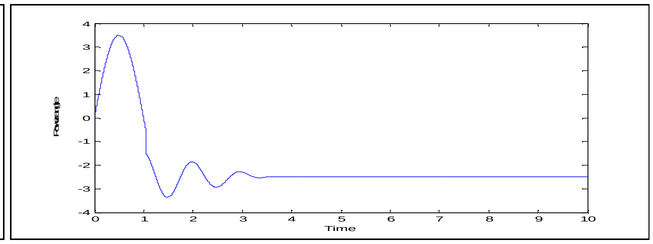




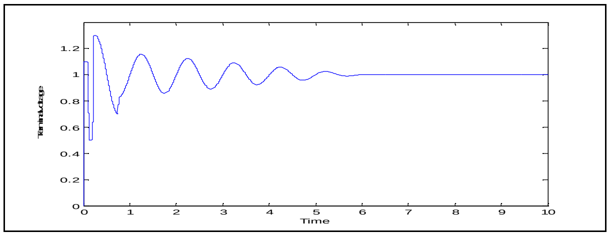
(i) Terminal voltage with conventional AVR (Test system 1) *(ii) Power Angle with conventional AVR (Test system 1)*



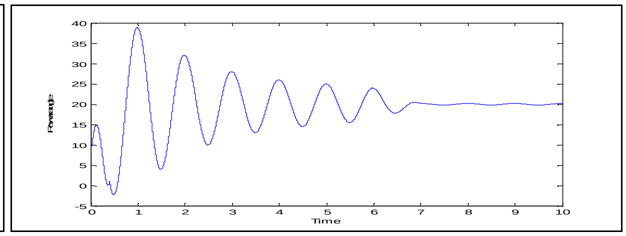
(iii) Terminal voltage with Fuzzy AVR (Test system 1)



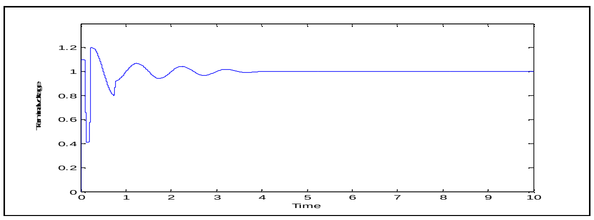
(iv) Power Angle with fuzzy AVR (Test system 1)



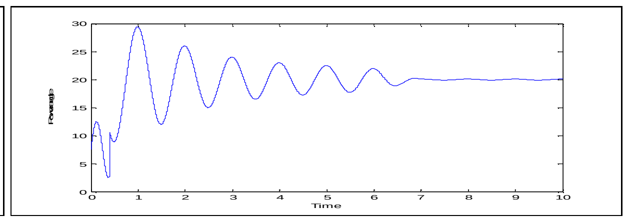
(v) Terminal Voltage with Conventional AVR (Test system 2)



(vi) Power Angle with Conventional AVR (Test system 2)



(vii) Terminal Voltage with Fuzzy AVR (Test system 2)



(viii) Power Angle with Fuzzy AVR (Test system 2)

6. References

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