# A ROBUST PSS AUTOMATED DESIGN BASED ON ADVANCED $H_2$ AND H∞ FREQUENCY CONTROL TECHNIQUES TO IMPROVE POWER SYSTEM STABILITY

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***Abstract -*** *This paper proposes the automated design of power system stabilizer (PSS) based on robust loop-shaping H∞ controller (HinfPSS). The control objective is to enhance the stability and to improve the dynamic response of a single-machine power system operating in different conditions. Simulation results show that this control strategy is very robust, flexible and alternative performance. The nonlinear model of the power system is constructed with the differential equations. In other part, the Linear Quadratic - Gaussian (LQG) control scheme (has the same structure as the traditional Russian AVR-PSS [4]), consists of an optimal state-feedback gain and a KALMAN state estimator, and equivalently in this paper on a robust $H_2$ controller 'H2PSS', who was applied as a test control system in this paper. A detailed sensitivity analysis for a one-machine-infinite-bus system reveals that the fuzzy sliding-mode power system stabilizer is quite robust to wide variations in operating load and system parameters. Stabilizers suggested in this work have the same structure as the traditional Russian PSS. The simulation results show that a highs performances and robustness using the first regulation technique method (HinfPSS) in comparison with using robust H2PSS, due to the initial physical (real) non-linear proprieties of power system.*
***Key words:*** *Synchronous machines and Excitations, AVR and PSS, advanced frequency control techniques, LQG control, Kalman filter, robust loop-shaping H∞ approach, stability and robustness.*

## 1. INTRODUCTION

Power system stability continues to be the subject of great interest for utility engineers and consumers alike and remains one of the most challenging problems facing the power community. Power system oscillations are damped by the introduction of a supplementary signal to the excitation system of a power system. This is done through a regulator called power system stabilizer. Classical PSS rely on mathematical models that evolve quasi-continuously as load conditions vary. This inadequacy is somewhat countered by the use of fuzzy logic in modelling of the power system. Fuzzy logic power system stabilizer is a technique of incorporating expert knowledge in designing a controller.

Power system oscillations are damped by the introduction of a supplementary signal to the Automatic Voltage regulator (AVR) in power system. This is done through a regulator called Power System Stabilizer. Classical PSS rely on mathematical models that evolve quasi-continuously as load conditions vary. This inadequacy is somewhat countered by the use of news intellectual adaptive and robust generation of the PSS, and using numerical methods (fuzzy logic for examples) in modelling of the power system. Fuzzy logic power system stabilizer is a technique of incorporating expert knowledge in designing a controller. Past research of universal approximation theorem shown that any Nonlinear function over a compact set with arbitrary accuracy can be approximated by a fuzzy system. There have been significant research efforts on adaptive fuzzy control for nonlinear system [16, 19]. First generation of fuzzy regulators possessing the rather small knowledge base and including the simplest operations with fuzzy sets has been created and recognized as being perspective [1, 6]. The choice of membership functions of linguistic variables and formation of rule base for such a regulator was made by a trial and error, which took a lot of time and was considered as non-effective. At the same time, the fuzzy regulator is shown to expand the areas of small signal stability in comparison with classical AVR-PSS (using a conventional PSS), particularly in under - excitation modes (Importing reactive power).

The first stabilizer of this new generation for the system AVR – PSS, aimed to improving power system stability, was developed using the robust loop-shaping H∞ approach [14-15]. This has been advantage of maintaining constant terminal voltage and frequency irrespective of conditions variations in the system study. The closed loop is available for H∞ control. This loop is dedicated for regulating the terminal voltage of the Synchronous Generator to a set point by controlling the field voltage of the machine. The H∞ control design problem is described and formulated in standard form with emphasis on the selection of the weighting function that reflects robustness and performances goals [9]. The proposed system has the advantages of advantages of robustness against model uncertainty and external disturbances, fast response and the ability to reject noise.

The second regulator was suggested in this paper was developed by using the Linear Quadratic - Gaussian (LQG) control scheme (has the same structure as the traditional Russian type PID AVR-PSS [4]), consists of an optimal state-feedback gain and a KALMAN state estimator, and equivalently in this paper on a robust $H_2$ controller 'H2PSS', was applied as a test control system

Simulation results shown the evaluation of the proposed linear control methods based on advanced frequency techniques applied in the automatic excitation regulator of synchronous generators: the robust loop-shaping H∞ linear stabilizer and robust H2 control schemes against system variation in the SMIB power system, with a test of robustness against parametric uncertainties of the synchronous machines, and make a comparative study between these two new generations of control techniques for AVR – PSS systems.

## 2. THE ROBUST LOOP – SHAPING H∞ SYNTHESIS OF POWER SYSTEM STABILIZER

Advanced control techniques have been proposed for stabilizing the voltage and frequency of power generation systems. These include output and state feedback control [20], variable structure and neural network control [21], fuzzy logic control [1,6, 19], Robust H2 (linear quadratic Gaussian with KALMAN filter) and robust H∞ control [8,15].

H∞ approach is particularly appropriate for the stabilization of plants with unstructured uncertainty [15]. In which case the only information required in the initial design stage is an upper band on the magnitude of the modelling error. Whenever the disturbance lies in a particular frequency range but is otherwise unknown, then the well known LQG (Linear Quadratic Gaussian) method would require knowledge of the disturbance model [8]. However, H∞ controller could be constructed through, the maximum gain of the frequency response characteristic without a need to approximate the disturbance model. The design of robust loop – shaping H∞ controllers based on a polynomial system philosophy has been introduced by Kwakernaakand Grimbel [10, 11].

H∞ synthesis is carried out in two phases. The first phase is the H∞ formulation procedure. The robustness to modelling errors and weighting the appropriate input – output transfer functions reflects usually the performance requirements. The weights and the dynamic model of the power system are then augmented into an H∞ standard plant. The second phase is the H∞ solution. In this phase the standard plant is programmed by computer design software such as MATLAB [12-13], and then the weights are iteratively modified until an optimal controller that satisfies the H∞ optimization problem is found [9].

Time response simulations are used to validate the results obtained and illustrate the dynamic system response to state disturbances. The effectiveness of such controllers is examined and compared with using the Non-linear adaptive Neuro – Fuzzy PSS at different operating conditions. The advantages of the proposed linear robust controller are addresses stability and sensitivity, exact loop shaping, direct one-step procedure and close-loop always stable [8].

The H∞ theory provides a direct, reliable procedure for synthesizing a controller which optimally satisfies singular value loop shaping specifications [7-9]. The standard setup of the control problem consist of finding a static or dynamic feedback controller such that the H∞ norm (a uncertainty) of the closed loop transfer function is les than a given positive number under constraint that the closed loop system is internally stable.

The robust H∞ synthesis is carried in two stages:

i. *Formulation*: Weighting the appropriate input – output transfer functions with proper weighting functions. This would provide robustness to modelling errors and achieve the performance requirements. The weights and the dynamic model of the system are hen augmented into H∞ standard plant.
ii. *Solution:* The weights are iteratively modified until an optimal controller that satisfies the H∞ optimization problem is found.

Figure 5 shows the general setup of the problem design where: P(s): is the transfer function of the augmented plant (nominal Plant G(s) plus the weighting functions that reflect the design specifications and goals),
u2: is the exogenous input vector; typically consists of command signals, disturbance, and measurement noises,
u1: is the control signal, y2: is the output to be controlled, its components typically being tracking errors, filtered actuator signals, y1: is the measured output.

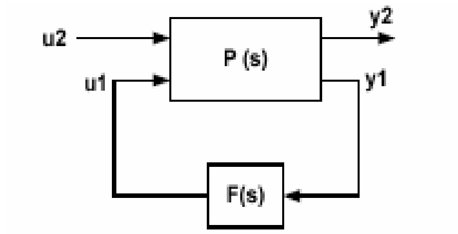


***Figure 5 -*** *General setup of the loop-shaping H∞ design*

The objective is to design a controller F(s) for the augmented plant P(s) such that the input / output transfer characteristics from the external input vector u2 to the external output vector y2 is desirable. The H∞ design problem can be formulated as finding a stabilizing feedback control law u1(s)-F(s).y1(s) such that the norm of the closed loop transfer function is minimized.

In the power generation system including H∞ controller, two feedback loops are designed; one for adjusting the terminal voltage and the other for regulating the system angular speed as shown on fig. 6. The nominal system G(s) is augmented with weighting transfer function $W_1(s)$, $W_2(s)$, and $W_3(s)$ penalizing the error signals, control signals, and output signals respectively. The choice proper weighting functions is the essence of H∞ control. A bad choice of weights will certainly lead to a system with poor performance and stability characteristics, and can even prevent the existence of solution to the H∞ problem.

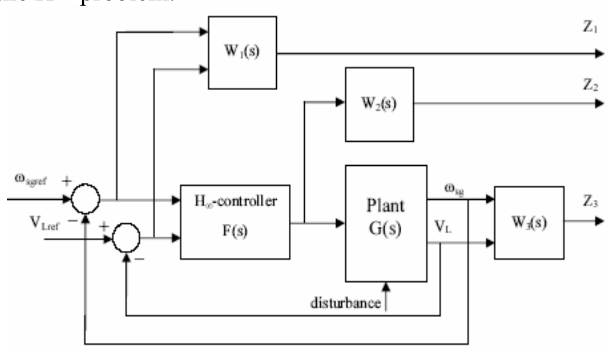


***Figure 6 –*** *Simplified block diagram of the augmented plant including H∞ controller*

The control system design method by means of modern neuro - fuzzy identification algorithms is supposed to have some linear H∞ test regulator. It is possible to collect various optimal adjustment of such a regulator in different operating conditions into some database. Robust H∞ technique was used in this work as a test system, which enables to trade off regulation performance, robustness of control effort and to take into account process and measurement noise [8].

## 3. THE ROBUST H2-PSS DESING BASED ON LQG CONTROL AND KALMAN FILTER

The control system design method by means of modern FSM algorithms is supposed to have some linear test regulator. It is possible to collect various optimal adjustment of such a regulator in different operating conditions into some database. Linear – Quadratic – Gaussian (LQG) control technique is equivalent to the robust $H_2$ regulator by minimizing the quadratic norm of the integral of quality [3]. In this work, the robust quadratic $H_2$ controller (corrector LQG) was used as a test system, which enables to trade off regulation performance and control effort and to take into account process and measurement noise [1,2]. LQG design requires a state-space model of the plant:

$$\begin{cases} dx/dt = Ax + Bu, \\ y = Cx + Du, \end{cases} \quad (1)$$

Where *x, u, y* is the vectors of state variables, control inputs and measurements, respectively.

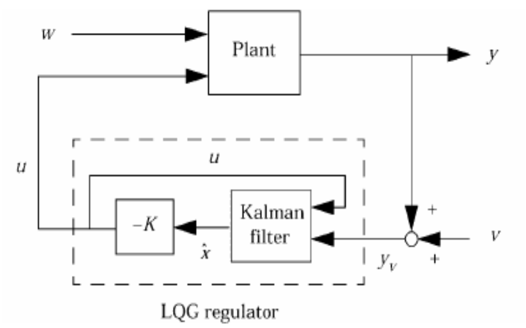


Figure 2 – Optimal LQG regulated system with Kalman filter.

The goal is to regulate the output *y* around zero. The plant is driven by the process noise *w* and the controls *u*, and the regulator relies on the noisy measurements $y_v = y+v$ to generate these controls. The plant state and measurement equations are of the form:

$$\begin{cases} dx/dt = Ax + Bu + Gw, \\ y_v = Cx + Du + Hw + v, \end{cases} \quad (2)$$

Both *w* and *v* are modelled as white noise.
In LQG control, the regulation performance is measured by a quadratic performance criterion of the form:

$$J(u) = \int_0^\infty \left(x^T Qx + 2x^T Nu + u^T Ru\right)dt \quad (3)$$

The weighting matrices *Q*, *N* and *R* are user specified and define the trade-off between regulation performance and control effort.

The LQ-optimal state feedback $u=-Kx$ is not implemental without full state measurement. However, a state estimate $\hat{x}$ can be derived such that $u = -k\hat{x}$ remains optimal for the output-feedback problem.
This state estimate is generated by the Kalman filter:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L\left(y_v - C\hat{x} - Du\right) \quad (4)$$

Thus, the LQG regulator consists of an optimal state-feedback gain and a *Kalman* state estimator (filter), shown in Figure 2.

On the basis of investigation carried out, the main points of fuzzy PSS automated design method were formulated [6,7]. The nonlinear model of power system can be represented by the set of different linearized models (22). For such models, the linear compensator in the form of $u = -Kx$ can be calculated by means of LQG - method. The family of test regulators is transformed into united fuzzy knowledge base with the help of hybrid learning procedure (based variable structure sliding mode). In order to solve the main problem of the rule base design, which called "the curse of dimensionality", and decrease the rule base size the scatter partition method [13] was used. In this case, every rule from the knowledge base is associated with some optimal gain set. The advantage of this method is the practically unlimited expansion of rule base. It can be probably needed for some new operating conditions, which are not provided during learning process. Finally, the robust $H_2$ stabilizer was obtained by minimizing the quadratic norm $\|M\|_2^2$ of the integral of quality *J(u)* in (3), where $Z(s)=M(s)x_0$ and $z=[x^TQ^{1/2}\ u^TR^{1/2}], s=j\omega$ [3].

## 4. Dynamic Power System Model

In this paper a simplified dynamic model of power system, namely, a single machine connected to an infinite bus (SMIB) is considered [17-18]. It consists of a single synchronous generator connected through a parallel transmission line to a very large network approximated by an infinite bus as shown in figure 7.

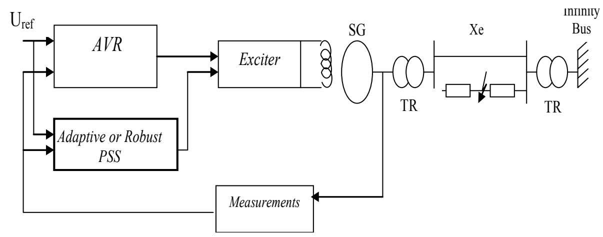


***Figure 7** – Block schematic diagram of the proposed SMIB Power system*

Let the state variable of interest be the machine's rotor speed variation and the power system acceleration.

$$x_1 = \Delta\omega \quad (5)$$

$$x_2 = \Delta P = P_m - P_e \quad (6)$$

Where $x_1$ is the speed deviation and $x_2$ is accelerating power, *Pm* and *Pe* represents respectively the mechanical and electrical power. It is possible to represent the power system in the following form [16]:

$$\begin{aligned} \dot{x}_1 &= \alpha x_2 \\ \alpha\dot{x}_2 &= f(x_1, x_2) + g(x_1, x_2)u \\ y &= x_1 \end{aligned} \quad (7)$$

Where $\alpha=1/2H$ and *H* is the per unit inertia constant of the machine. $x=[x_1\ x_2]$ is the state vector of the system and $f(x_1,x_2)$ and $g(x_1,x_2)$ are nonlinear functions and *u* is the *PSS* (Power System Stabilizer) control signal to be designed. We need to express *f* and *g* as function of active power *P* and reactive power *Q*. The governor time constant is large compared to the time constants of synchronous machine and its exciter, the power system can be easily be put in the form (7) for a transient period after a major disturbance has occurred in the system [19].

On the basis of investigation carried out, the main points of robust H∞ and H2 PSS automated design methods were formulated [1, 6]. The nonlinear model of power system can be represented by the set of different linearized models [7-9]. For such models, the robust H2 and H∞ compensators (based on advanced frequency control techniques) can be synthesis and calculated by means of MATLAB Software [12, 13].

## 5. Simulation Results and Discussion

In the system study type 'SMIB' (Single Machine Infinite bus system), based on SMIB system "Synchronous generator–transmission line–infinite bus", the main attention was devoted to receive Robust loop-shaping H∞ Control Power System Stabilizer 'HinfPSS' and robust H2 PSS 'HinfPSS', working in the wide spectrum of operating conditions. The change of operating conditions corresponds to the variation of transmission line parameters ($X_e$) and the powers of the generator ($P_G$, $Q_G$). Certain attention was devoted to the problem of the reactive power consumption (under - excitation modes), which is very important for all electric power systems. The illustration with using the proposed robust linear H2 controller and robust loop-shaping H∞ PSS method opportunities is given in Table 1 on the basis of the damping coefficient α comparison. Robust loop-shaping H∞ regulator allows receiving the same performance quality as the application of robust linear compensator, but without resetting optimal gain of the regulator.

The electromechanical damping oscillations of parameters of the SG under different operating mode in controllable power system, equipped by HinfPSS (Red) and H2PSS (Blue) are given in Figures 7 (a, b, c, d). Results of time domain simulations, with a test of robustness (parametric uncertainty by maximisation 100% of R applied at t= 4s), confirm both a high effectiveness of test robust H2 Regulator, which has various adjustments of regulation channels in different operating conditions, but more large degree of performances and much more robustness of the dynamic of power system are improving and obtained by using the Robust loop-shaping H∞ PSS (figures 7 (b) and (d), due to the initial non-linear characteristics of the system study. After appearance of the real (non-linear) properties of the power system, especially in the under - excitation mode (1), the H2PSS quickly loses his effectiveness under condition of uncertainties; in the same time where HinfPSS improve its efficiency by improving dynamics performances and its robustness.

***Table 1:*** *Damping coefficients 'α' and static error ε% in the Close Loop system with HinfPSS and H2PSS in different operating Conditions of the power system (xe=0.5p.u., Pg=0.85 p.u.)*

| $Q_g$ *(reactive power) p.u.* | $\alpha_{H2PSS}$ | $\varepsilon\%_{H2PSS}$ | $\alpha_{H\infty PSS}$ | $\varepsilon\%_{H\infty PSS}$ |
|---|---|---|---|---|
| -0.1801 | -1.689 | 10.93 | -2.673 | Very small |
| -0.2016 | -1.669 | 10.93 | -2.593 | Very small |
| -0.2230 | -1.646 | 10.93 | -2.483 | Very small |
| -0.2444 | -1.622 | 10.92 | -2.337 | Very small |
| 0.1896 | -1.792 | 10.84 | -2.766 | Very small |
| 0.2847 | -1.704 | 09.29 | -2.695 | Very small |
| 0.6355 | -1.377 | 05.83 | -2.150 | Very small |
| 0.6623 | -1.355 | 05.66 | -2.133 | Very small |
| 0.6896 | -1.334 | 05.49 | -2.116 | Very small |
| 0.7173 | -1.313 | 05.32 | -2.099 | Very small |

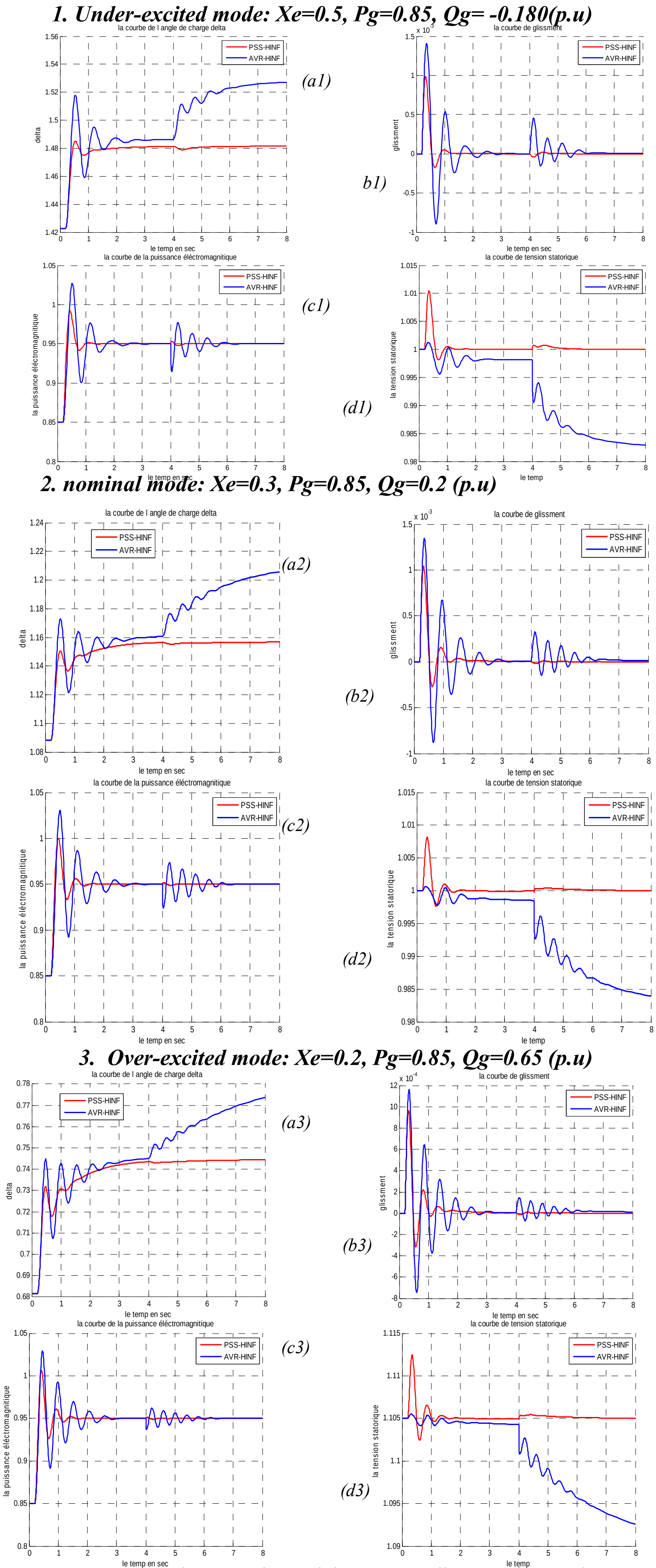


***Figure 7*** *– Electromechanical damping oscillations of SG under different operating mode With HinfPSS (Red) and H2PSS (Blue): (a) Active Power, (b) Interior angle, (c) Speed deviation, (d) Stator terminal voltage of SG Responses*

## 6. Conclusion

This paper proposes two advanced control methods based on advanced frequency techniques: Robust loop-shaping H∞ and robust H2 approach's (an optimal LQG controller with Kalman Filter), applied on the system AVR - PSS of synchronous generators, to improve transient stability and its robustness of a single machine-infinite bus system (SMIB). This concept allows accurately and reliably carrying out transient stability study of power system and its controllers for voltage and speeding stability analyses. It considerably increases the power transfer level via the improvement of the transient stability limit.

The computer simulation results have proved the efficiency and robustness of the Robust H∞ approach, in comparison with using robust H2 Controller, showing stable system responses almost insensitive to large parameter variations. This robust control possesses the capability to improve its performance over time by interaction with its environment. The results proved also that good performance and more robustness in face of uncertainties (test of robustness) with the linear robust Hinf stabilizer (HinfPSS), in comparison with using the linear robust H2 controller (optimal LQG controller with Kalman Filter). After appearance of the real (non-linear) properties of the power system, especially in the under - excitation mode (2), the H2PSS quickly loses his effectiveness under condition of uncertainties; in the time where HinfPSS improve its efficiency, enhance dynamics performances of power system and provides more robustness of its stability.

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## Appendix

***Power System model:***

$$\dot{\delta} = \omega_0 \Delta\omega$$

$$\dot{\omega} = (P_m - P_e)/M$$

$$\dot{E}'_q = (E_{fd} - (x_d - x'_d)i_d - E'_q)/T'_{do}$$

$$\dot{E}_{fd} = \frac{1}{T_A}(K_A(V_{ref} - V_t + U_{PSS}) - E_{fd})$$

$$V_d = V_s \sin\delta + R_e i_d - x_e i_q$$

$$V_q = V_s \cos\delta + R_e i_q + x_e i_d$$

$$V_t = \sqrt{V_d^2 + V_q^2}$$

$$T_e = E'_q i_q - (x'_d - x_q) i_d i_q$$

***Parameters of power system study:***

*$X_d$=2.56 pu, $X_0$= 2.56, $R_f$= 8.44 $10^{-4}$ pu, $X_f$=2.458 pu, $X'_d$=0.3361, $X''_d$=0.3423, $X''_q$=0.3316, $T_{d0}'$=4.14 sec, H=6s, $X_T$=0.12 pu, $V_{bus}$=1 pu, Uf0= 9.6523 $10^{-4}$ pu.*

***AVR and PSS parameters:***

*$T_A$= 0.05, $K_A$= 50, f= 50Hz,* $-1.5.Ef0 \le E_{fd} \le 3.Ef0$

$-0.2pu \le U_{PSS} \le 0.2pu$ ,