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Modelisation and Simulation of a Standard IEEE- SMIB Using Robust H2 and H∞ Power System Stabilizers

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Abstract— The idea of Power System Stabilizer (PSS) or supplementary excitation control is to apply a signal through the excitation system to produce additional damping torque of the generator in a power system at all operating and system condition.This paper presents a comparative study between both of robust Power System Stabilisers PSS-H2 (LQG controller associated with KALMAN filter), and PSS-H∞ (based on loop-shaping H_∞ optimization technique), and the conventional one PSS-PID. Our attention is focused on the robustness and stability of each PSS against disturbances, parametric variations and especially the operating mode change (nominal ,under-excited and over-excited).First the IEEE-SMIB power system (Single Machine-Infinite Bus) is mathematically modelled (Park- Gariov model) ,then we have successfully developed a Graphical User Interface (GUI MATLAB) in order to simulate the SMIB system in several conditions (opened loop and closed loop with PSSs mentioned above). The computer simulation results (static and dynamic stability) with test of robustness against machine parameters uncertainty (electric and mechanic) show that PSS-H2 and PSS-H∞ are more efficient and more robust than the classical one in term of dynamic performances stability. and robustness. However, the PSS-H∞ is the best one.

Key words— PSS, PID, Advanced Frequency Techniques H2 and H∞, stability and robustness, User Graphical Interface .

I. 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[1].

An important application area for the synchronous machine is used almost exclusively in power systems as a source of electrical energy. Keeping voltage within certain limits help to reduce energy losses, and improves voltage regulation. This is a difficult task because it's strongly influenced by dynamic load fluctuations [1] which must be effectively damped to maintain the power system stability. Several methods for increasing this damping are available in the literature, such as Static Voltage Condenser (SVC) ,High Voltage Direct Current (HVDC), and Power System Stabilizer (PSS) [2].

In this paper, we focused on the use of PSS in order to damping electro mechanical oscillations of electrical generators (also called power swings) which are the major cause of instability.

Power system oscillations are damped by the introduction of a supplementary signal to the excitation system of a power system through a classical PID-PSS. This later, rely on mathematical models that evolve quasi-continuously as load conditions vary. also, it ensure optimal performance only at a nominal operating point and do not guarantee good performance over the entire range of the system operating conditions due to exogenous disturbances such as changes of load and fluctuations of the mechanical power.In practical power system networks, a priori information on these external disturbances is always in the form of a certain frequency band in which their energy is concentrated. Remarkable efforts have been devoted to design appropriate PSS with improved performance and robustness. These have led to a variety of design methods using optimal control [2] and adaptive control [3]. The shortcoming of these model-based control strategies is that uncertainties cannot be considered explicitly in the design stage. More recently, robust control theory has been introduced into PSS design which allows control system designers to deal more effectively with model uncertainties [4, 5, 6 and 7].

In this paper, we proposed tow robust design PSS through tow robust frequential advanced technical's wish are "H2" (the linear quadratic Gaussian control with a Kalman filter) (PSS-H2), and the loop shaping control "H∞"(PSS-H∞) ,in order to regulating the terminal voltage of the Synchronous Generator (in the SMIB system) to a set point by controlling the field voltage of the machine. power system robustness stability voltage and best dynamic performances .so ,first ,the IEEE SMIB power system is chosen for this study ,then each of its elements is modelled mathematically with the permeances networks approach (analogic-digital) ,after that ,we present the H2 and H∞ theory ,thereafter, a Graphical User Interface (GUI) is developed with Matlab and the Simulink bloc of the SMIB system is implemented in this GUI. Finally, the computer simulation results are analysed, discussed and compared.

II. DYNAMIC POWER SYSTEM MODEL

2.1. Power System description

The Simple Standard IEEE SMIB model“ Single Machine (Turbo-Alternator) connected to an Infinite Bus” has stimulate a high researchers attention[1,2] ,in this paper ,it was considered.its basic configuration is shown in the following figure .

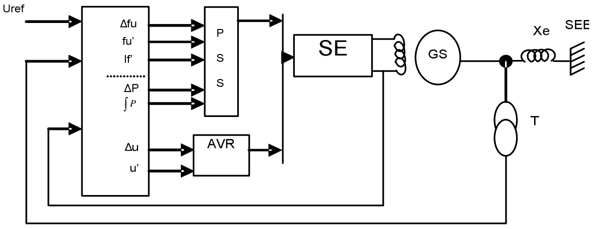

Figure 1.Standard system IEEE type SMIB with excitation control of powerful synchronous generators

2.2. The permeances networks modeling (Park-Gariov) of powerful synchronous generators

In the literature, we discern three main electrical machine modeling approaches :analogical (Park…),Analogical-Digital (Permeances Networks…),and numerical(finite elements…) [7,8,9,] ,in this paper ,the second one is chosen with the “Park-Gariov” model ,why ?

In order to eliminating simplifying hypotheses and testing the control algorithm of Power Synchronous Generator (noted from now PSG) .

The PSG model is defined by the following equations :

A. *Currants equations:*

$$I_q = (U_q - E_q^{''}) / X_d^{''} \qquad I_{1q} = (\Phi_{1q} - \Phi_{aq}) / X_{sr1q}$$
$$I_d = -(U_d - E_d^{''}) / X_q^{''} \qquad I_{2q} = (\Phi_{2q} - \Phi_{aq}) / X_{sr2q} \tag{1}$$
$$I_{1d} = (\Phi_{1d} - \Phi_{ad}) / X_{srd} \qquad I_f = (\Phi_f - \Phi_{ad}) / X_{sr}$$

$$E_q^{''} = \frac{{}^{1}\!/\!{}_{X_{sf}} \cdot \frac{X_f}{X_{ad}} E_q^{'} + {}^{1}\!/\!{}_{X_{sfd}} \cdot \frac{X_{fd}}{X_{ad}} E_{fq}^{'}}{\frac{1}{X_{ad}} + \frac{1}{X_{sf}} + \frac{1}{X_{sfd}}} \quad E_d^{''} = \frac{{}^{1}\!/\!{}_{X_{sfq}} \cdot \frac{X_{fq}}{X_{aq}} E_{fd}^{'}}{\frac{1}{X_{ad}} + \frac{1}{X_{sfq}}} \tag{2}$$

B. *Flow equations:*

$$\Phi_{ad} = E_q^{''} + (X_d^{''} - X_s) I_d \ ; \Phi_{aq} = E_d^{''} + (X_q^{''} - X_s) I_q$$
$$\Phi_{1q} = \omega_s \int_0^{\Phi_{1q}} (-R_{1q} I_{1q}).dt \ \Phi_{2q} = \omega_s \int_0^{\Phi_{2q}} (-R_{2q} I_{2q}).dt \tag{3}$$
$$\Phi_f = \omega_s \int_0^{\Phi_f} (-R_f I_f + U_{f0}) dt \ \Phi_{1d} = \omega_s \int_0^{\Phi_{1d}} (-R_{1d} I_{1d}).dt$$

C. *Mechanical equations*

$$d\delta = (\omega - \omega_s) dt \ , \quad s = \frac{\omega - \omega_s}{\omega_s} \tag{4}$$

$$M_T + M_j + M_e = 0 \quad avec\ M_j : \text{moment d'inertie} \quad \left(M_j = -j \frac{d\omega}{dt} \right)$$
$$T_j \frac{d}{dt} s + (\Phi_{ad}.I_q - \Phi_{aq}.I_d) = M_T \quad \text{ou} \quad T_j \frac{d}{dt} s = M_T \text{ - } M_e \tag{5}$$
$$j \frac{d\omega}{dt} + \frac{P_e}{\omega_s} = M_T$$

2.3. Models of regulators AVR and PSS:

The AVR (Automatic Voltage Regulator), is a PSG voltage controller that acts thought the exciter .Furthermore, the PSS was developed to absorb the generator output voltage oscillations [11].

In our study the synchronous machine is equipped by a voltage regulator model "IEEE" type – 5 [12, 13], as is shown in figure 4.

$$V_R = \frac{K_A V_E - V_R}{T_A} \quad , \quad V_E = V_{ref} - V_F \tag{6}$$

About the PSS, considerable’s efforts were expended for the developpement of the system. The main function of a PSS is to modulate the Synchronous Generator’s excitation to [10,11, 14].

In this paper the PSS signal used, is given by: [15]

$$\dot{V}_1 = \frac{V_2 - V_1}{T_1} + \frac{T_2}{T_1} \dot{V}_2 \ ; \qquad \Delta input = \begin{cases} \Delta P \ , \int p \\ or \\ \Delta \omega = \omega_{mach} - \omega_0 \\ and \\ \Delta I_f = I_f - I_{f0} \\ and \\ \Delta U_f = U_f - U_{f0} \end{cases} \tag{7}$$
$$\dot{V}_2 = \frac{V_3 - V_2}{T_2} + \frac{T_3}{T_2} \dot{V}_2 \ ;$$
$$\dot{V}_3 = \frac{V_3}{T_W} \dot{V}_1 ; \dot{V}_1 = K_{PSS} \cdot \Delta input$$

2.4. Simplified model of system studied SMIB

We consider the system of figure 2, where, the synchronous machine is connected to infinite bus by a transmission line .with Re: its resistance and Le: its inductance [7]

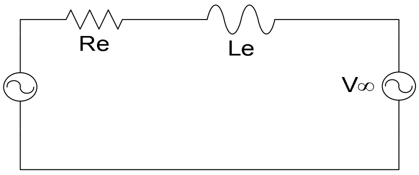

Figure 2. Synchronous machine connected to an infinite bus network

We define the following equation of SMIB system

$$V_{\infty odq} = Pv_{\infty abc} = \sqrt{2}\, V_{\infty} \begin{bmatrix} 0 \\ -Sin\,(\delta - \alpha) \\ \cos\,(\delta - \alpha) \end{bmatrix} + L_e I'_{odq} + X_e \begin{bmatrix} 0 \\ -i_q \\ i_d \end{bmatrix} \qquad (8)$$

2.5 Structure of power system with robust H_∞ and H_2 controllers

The basic structure of the powerful Synchronous Generator (SG) with robust controllers is shown in the following Figure.

As command object we consider (SG) with regulator AVR-FA (which is a conventional AVR+PSS type “PID”), an excitation system (exciter) and Measures and informations block (BIM) of output parameters to regulate.

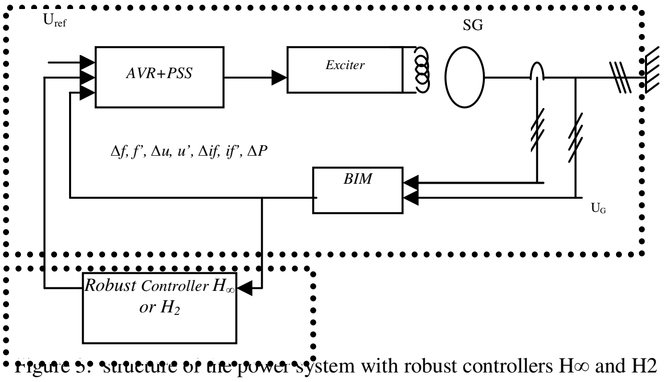

Figure 3: structure of the power system with robust controllers H∞ and H2

III. THE ROBUST PSS H2 AND H∞ THEORY

Advanced control techniques have been proposed for stabilizing the voltage and frequency of power generation systems. These include output and state feedback control variable structure and neural network control, fuzzy logic control robust H_2 (linear quadratic Gaussian with KALMAN filter) and robust H_∞ control [] .

H_∞ approach is particularly appropriate for the stabilization of plants with unstructured uncertainty [2. In which case the only information required in the initial design stage is an upper band on the magnitude of the modeling 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. 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 Kwakernaak [12] .

In this paper , 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 linear Robust H_∞ PSS at different operating conditions of power system study

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 .

3.1. Concept of H_∞ loop-shaping optimization

The H_∞ theory provides a direct, reliable procedure for synthesizing a controller which optimally satisfies singular value loop shaping specifications [24-8]. The standard setup of the control problem consist of finding a static or dynamic feedback controller such that the H-INFINITY norm (a uncertainty) of the closed loop transfer function is less than a given positive number under constraint that the closed loop system is internally stable.

H_∞ synthesis is carried out in two phases. The first phase is the H_∞ formulation procedure. The robustness to modeling 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 [21-22], and then the weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found.

So, In order to obtain a robust H∞ controller, these tow steps must be crossed:

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

Figure 4 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);u_2: is the exogenous input vector; typically consists of command signals, disturbance, and measurement noises;u_1: is the control signal; y_2: is the output to be controlled, its components typically being tracking errors, filtered actuator signals, y_1: is the measured output.

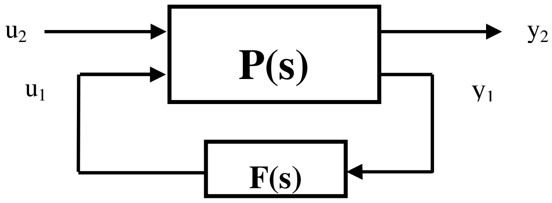

Figure 4. General Setup of the loop-shaping H_∞ design

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 u_2 to the external output vector y_2 is desirable. The H_∞ design problem can be formulated as finding a stabilizing feedback control law $u_1(s)$-F(s).$y_1(s)$ 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 figure 5. 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 are 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.

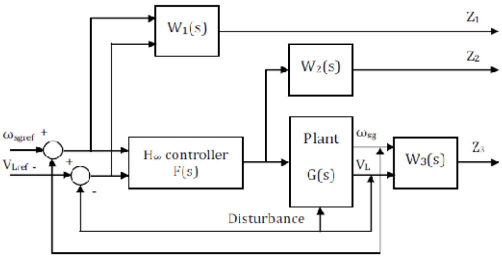

Fig.5. Simplified block diagram of the augmented plant including H_∞ controller

The control system design method by means of modern robust H-infinity algorithm is supposed to have some linear conventional PID test regulator.

It is possible to collect various optimal adjustment of such a regulator in different operating conditions into some database. Traditional Russian Power system stabilizer (realized on PID schema) was used in this study as a test system, which enables to trade off regulation performance, robustness of control effort and to take into account process and measurement noise

3. 2. GLOVER - DOYLE algorithm to synthesize a robust H_∞-PSS

The standard control problem solving is proposed as follow:

1. Calculate the Standing regime established (RP) ;
2. Linearization of the control object (GS+PSS+AVR) ;
3. The main problem in H∞ control is the definition of the control object increased P(s) in the state space:
    3-1. Choice of weighting functions: W_1, W_2, W_3 ;
    3-2. The obtaining of the command object increased from weighting functions $W_{1,2,3}$.
4. Verify if all conditions to the ranks of matrices are satisfied, if not we change the structure of the weighting functions;
5. Choosing a value of γ (optimization level) ;

$$J(u)=\int_0^\infty (x^TQx+u^TRu+2x^TNu)dt$$

6. Solving two Riccati equations which defined by the two matrices "H" and "J" of HAMILTHON;
7. Reduction of the regulator order if necessary ;
8. By obtaining optimum values and two solutions of Riccati equations we get the structure of controller H∞ and the roots of the closed loop with the robust controller;
9. We get the parameters of robust controller H_∞ in linear form "LTI" (SS state space, TF transfer function or ZPK zeros - pole - gains) ;
10. realization and computer simulation of the power system stability and dynamic performances robustness study under different operating conditions.

3.2. The robust H2-PSS design based on LQG control and Kalman filter

The control system design with modern 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 .In this study, the robust quadratic H_2 controller was used as a test system, which enables to trade off regulation performance , control effort and to take into account process and measurement noise . LQG design requires a state-space model of the plant:

$$\begin{cases} \dfrac{dx}{dt} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{9}$$

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

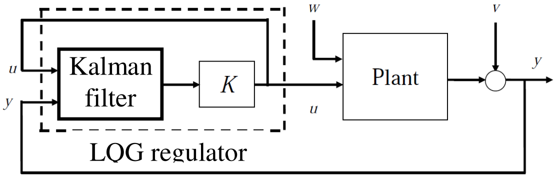

Fig.5. Optimal LQG regulated system with Kalman filter

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:

$$\begin{cases} \dot{x}(t) = A(t)x(t) + B(t)u(t) + v(t) \\ y_v(t) = C(t)x(t) + w(t) \end{cases} \qquad (10)$$

Both *w* and *v* are modeled as white noise.

In LQG control, the regulation performance is measured by a quadratic performance criterion of the form:

$$J(u) = \int_0^\infty (x^T Qx + u^T Ru + 2x^T Nu)dt \qquad (11)$$

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:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L(y_v - C\hat{x} - Du) \qquad (12)$$

Thus, the LQG regulator consists of an optimal state-feedback gain and a Kalman state estimator (filter) shown in figure 6.

The nonlinear model of power system can be represented by the set of different linearized models (10). For such models, the linear compensator in the form of $u = -Kx$ can be calculated by means of LQG - method. 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 $H_{2\ \text{stabilizer}}$ was Obtained by minimizing the quadratic norm $\|M\|_2^2$ of the integral of quality *J(u)* in where :

$$Z(s) = M(s)x_0 \quad and \quad Z = \left[x^T Q^{1/2} u^T R^{1/2}\right], s = j\omega.\ [17]. \qquad (13)$$

VI . COMPUTER SIMULATION RESULTS UNDER THE DEVELOPED "GUI"

A) A Created GUI/MATLAB

To analyzed and visualized the different dynamic behaviors we have creating and developing a "GUI" (Graphical User Interface) under MATLAB. , why?

Because, it allows us to:

- Perform control system from PSS, H_∞-PSS and H_2-PSS controller;
- View the system regulation results and simulation;
- Calculate the system dynamic parameters ;
- Test the system stability and robustness;
- Study the different operating regime (under-excited, rated and over excited regime).

- ***Stability study***

The following results were obtained by studying the "SMIB" static and dynamic performances in the following cases:

1. SMIB in Open Loop (OL)
2. SMIB in Closed Loop with the conventional stabilizer PSS-"PID" and robust controller H_∞-PSS, H_2-PSS.

Simultaneously, we simulated three operating regimes : the nominal, the under-excited, and the over-excited regime.

Our study is interested in the PSG type:TBB-1000 (1000 MW).

- ***Robustness test***

As a robustness test ,at t=4s. We performed simultaneously,an electrical parameter variation (increase 100% of stator resistance).and a mechanical parametric variations (lower bound 50% of inertia J) .The simulation time is evaluated at 10 seconds.

Figure 6.The SMIB system implemented under the developed "GUI-Matlab"

B) Simulation result and discussion

These following Figures show an example of simulation results of stator terminal voltage 'Ug' for PSG type TBB-1000 (1000 MW) .

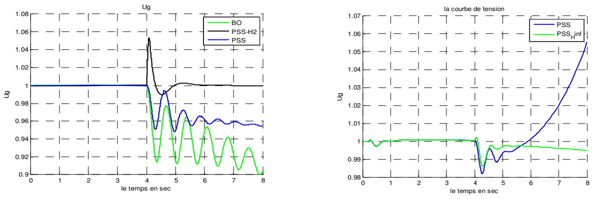

Figure 7. « Ug » in Open loop ,closed loop with PID-PSS , with robust PSS-H2 and PSS-H∞ at nominal regime and long line

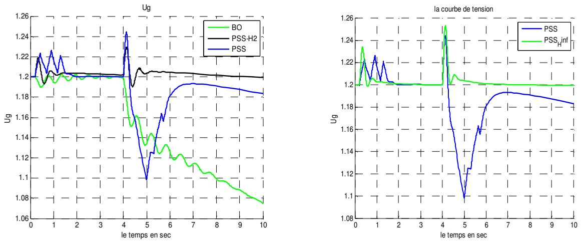

Figure 8. « Ug » in Open loop ,closed loop with PID-PSS ,with robust PSS-H2 and PSS-H∞ at over-excited regime and middle line

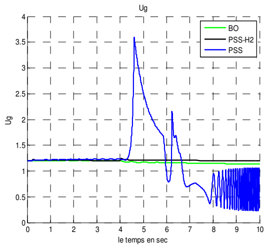

Figure 9. « Ug » in Open loop ,closed loop with PID-PSS ,with the robust PSS-H2 at under -excited regime and short line

From the simulation results, firstly, we find that after few oscillations, the SMIB system with robust PSS H2 and H∞ returns to its equilibrium state, in comparison with the conventional PSS-PID.

- In nominal mode :We highlight that contrary to the classical PSS-PID, with using robust controllers:PSS-H2 and PSS-H∞ the stator voltage vanishes even after having injected tow parametric disturbances at t=4s.

- In over excited mode (rush hours) :we notice that after few oscillations ,stator voltage in closed loop with PSS-PID,PSS-H2,and PSS-H∞ is damped ,however ,in opened loop ,it diverges.Starting from t=4s (when we injected tow disturbances simultaneously), "Ug" with robust controllers PSS-H∞, and PSS-H2 resists ,while with the classical PSS-PID, it cannot .

- In under excited mode (the night hours) :We found that stator voltage with both PSS-H2 and PSS-H∞ could resist to mechanical and electrical disturbances starting from t=4s, however, with the PSS-PID,"Ug" oscillates.

IV . CONCLUSION

This paper proposes tow advanced control methods based on frequency techniques: Robust loop shaping H∞ and robust H_2 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 H_2 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 H∞ stabilizer (H∞ PSS), in comparison with using the linear robust H_2 controller (optimal LQG controller with Kalman Filter). After appearance of the real (non-linear) properties of the power system, especially in the under - excitation , the H2PSS quickly loses his effectiveness under condition of uncertainties; in the time where H∞ PSS improve its efficiency, enhance dynamics performances of power system and provides more robustness of its stability.

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