Robust off-line PSS automated control design based H∞ - loop shaping optimization

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Abstract:–This article presents a contribution study of the advanced frequency control techniques based on off-line H∞ - loop shaping optimization method applied on power system stabilizer (PSS), to improve transient stability and robustness of a single machine- infinite bus system (SMIB). In this paper, the robust controller is designed and simulated under Matlab - Simulink. The robust H∞ based power system stabilizer (PSS-H∞) is designed using the concept of loop shaping optimization using the concepts of sensitivity and complementary sensitivity, which is one of the robust control methods used for designing the controllers for dynamical systems in electrical engineering. The computer simulation results (static and dynamic stability), completed by test of robustness against machine parameters uncertainty (electric and / or mechanic variation parameters of synchronous machine), have proved that good dynamic performances, showing a stable system responses almost insensitive to large parameters variations, and more robustness using the robust off-line H∞- loop shaping automated control design based Power System Stabilizer.

Keywords—H∞-loop shaping optimization, Power system Stabilizer, power system stability and robustness, PID control, synchronous generators, robust control.

I. INTRODUCTION

One of the most important problems arising from large scale power Systems is the low frequency oscillation. Excitation control or Automatic Voltage Regulator (AVR) is well known as an effective means to improve the overall stability of the power system. Power System Stabilizers (PSS) are introduced in order to provide additional damping to enhance the stability and the performance of the electric generating system. The output of the PSS as supplementary control signal is applied to the machine voltage regulator terminal. Conventional PSS have been widely used in power systems. Such PSS ensures optimal performance only at a nominal operating point and does not guarantee good performance over an entire range of the system operating conditions. Several robust control techniques [2]-[3]-[4] have been proposed for the design of more robust PSS structures. *H∞* optimal control [5] and the structured singular value (SSV or μ) technique [6] have received considerable attention. But, the application of μ technique for controller design is complicated due to the computational requirements of μ design. Besides the high order of the resulting controller, also introduces difficulties with regard to implementation [7]. The *H∞* optimal controller design is relatively simpler than the μ synthesis in terms of the computational burden. This paper uses the H∞ - loop shaping design procedure [8] to design the Robust Power System Stabilizer (RPSS). It combines the H∞ robust stabilization with the classical loop shaping technique. The loop shaping is done without explicit regard to the nominal plant phase information. Simulation results show the evaluation of the proposed linear control methods based on advanced frequency techniques applied in the automatic excitation regulator of Turbo alternator: the robust loop-shaping H∞ linear stabilizer against system variation in the Single Machine Infinity Bus (SMIB) power system, with a test of robustness against parametric uncertainties of the Turbo alternator, and make a comparative study between these new generations of (RPSS) and the traditional type conventional PID - PSS (CPSS) [9].

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II. DYNAMIC POWER SYSTEM MODELLING

A. Power System description

The Simple Standard IEEE - SMIB model based “Single Machine (Turbo-Alternator) connected to an Infinite Bus” has stimulate a high researchers attention [4]-[11], and it was considered in this paper (figure 1).

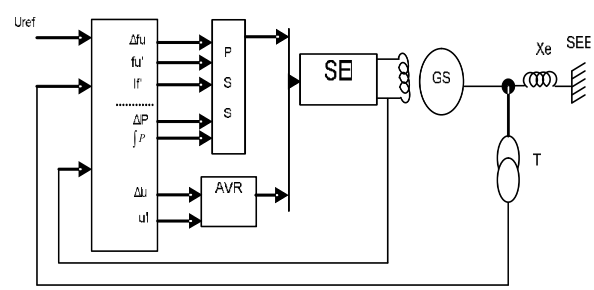


Fig.1 Standard system IEEE type SMIB with excitation control of synchronous generators

B. The Permeances networks modeling of synchronous generators

In the literature, we discern three main electrical machine modeling approaches: analogical (Park), Analogical-Digital (Permeances Network), and numerical (finite elements). In this paper, the second one is chosen using the "Park-Gariov" model.In order to eliminating simplifying hypotheses and testing the control algorithm of Power Synchronous Generator (SG).The SG model is defined by the following equations [3]:

- Electrical équations

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

$$E_q^{"} = \frac{\frac{1}{X_{sf}} \cdot \frac{X_f}{X_{ad}} E_q^{'} + \frac{1}{X_{sfd}} \cdot \frac{X_{fd}}{X_{ad}} E_{fq}^{'}}{\frac{1}{X_{ad}} + \frac{1}{X_{sf}} + \frac{1}{X_{sfd}}} \tag{2}$$

$$E_d^{"} = \frac{\frac{1}{X_{sfq}} \cdot \frac{X_{fq}}{X_{aq}} E_{fd}^{'}}{\frac{1}{X_{ad}} + \frac{1}{X_{sfq}}}$$

- Magnetical équations

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

- Mechanical equations

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

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

C. Mathematical Model of the used PSS-PID

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 an automatic voltage regulator model "IEEE" type–5[12].About the PSS, considerable's efforts were expended for the development of the system. The main function of a PSS is to modulate the Synchronous Generator's excitation. In this paper the PSS-PID used signal, is given by [13]:

$$\dot{V}_1 = \frac{V_2 - V_1}{T_1} + \frac{T_2}{T_1}\dot{V}_2 \;\; ;$$
$$\dot{V}_2 = \frac{V_3 - V_2}{T_2} + \frac{T_3}{T_2}\dot{V}_2 \;\; ; \tag{6}$$
$$\dot{V}_3 = \frac{V_3}{T_W}\dot{V}_1 ; \; \dot{V}_1 = K_{PSS} \cdot \Delta input$$

with

$$\Delta input = \begin{cases} \Delta P \;,\; \int p \\ or \\ \Delta\omega = \omega_{mach} - \omega_0 \\ and \\ \Delta I_f = I_f - I_{f0} \\ and \\ \Delta U_f = U_f - U_{f0} \end{cases} \tag{7}$$

D. The simplified model of SMIB system

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 [14].

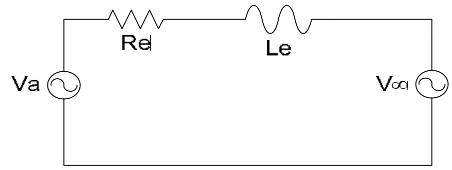


Fig.2. Synchronous machine connected to an infinite bus network

We define the following equation of SMIB system

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

E. Structure of power system with robust H_∞ controller

The basic structure of the Synchronous Generator with robust controller is shown in the Figure 3 [2]-[7].

As control object we consider the SG with controller AVR-FA (which is a conventional AVR-PSS type "PID-PSS"), an excitation system (exciter) and Measures and informations block (BIM) of output parameters to regulate.

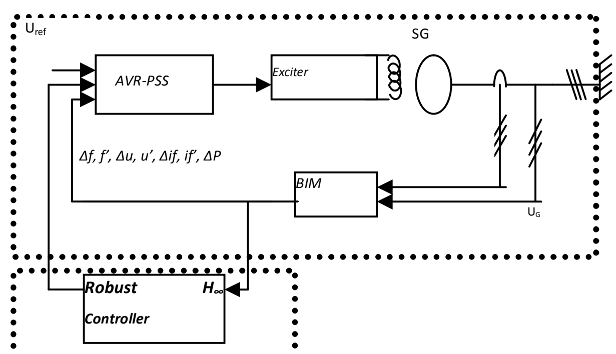


Fig.3.Structure of the power system withe the robust controllers H∞

On the basis of investigation carried out, the main points of robust H∞ PSS automated design methods were formulated. The nonlinear model of power system can be represented by the set of different linearized models. For such models, the robust H∞ compensator (based on advanced frequency loop-shaping control techniques) can be synthesis and calculated by means of MATLAB Software.

III. H∞-LOOP SHAPING PSS CONTROL DESIGN

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 [5]-[6], robust H_2 (linear quadratic Gaussian with KALMAN filter) and robust H_∞ control [15]-[16].

H_∞ approach is particularly appropriate for the stabilization of plants with unstructured uncertainty [8]. 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 [8]-[9].

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.

A. 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 [17]. The standard setup of the control problem consist of finding a static or dynamic feedback controller such that the H∞ norm (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 [18], and then the weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found.

H∞ loop-shaping control, proposed by McFarlane and Glover [8], is an efficient way to design the robust controller and has been applied to a variety of control problems.

A general H∞ control problem can be described using the framework of Fig.4.

$$j(k) = \left\| T_{zw} \right\| \prec 1 \tag{9}$$

So, In order to obtain a robust H∞ controller, these two 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.

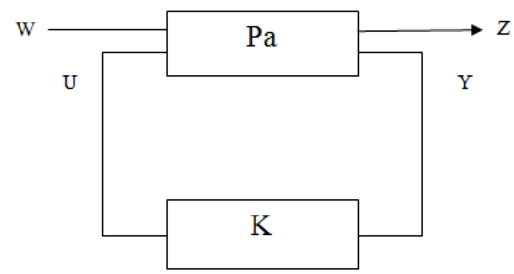


Fig.4. General Setup of the H_∞ - loop shaping designing

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* $W_3(s)$ *p*enalizing 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.

The design objective is to find an optimal controller K_{opt}, which minimizes the H∞ norm of the closed-loop transfer function $T_{wz}(s)$, between the exogenous inputs w=[r(control)d(uncertainties)] and the controlled outputs z.

The controller design consists of essentially two stages:

STAGE 1: open-loop shaping–the open-loop plant is augmented by pre- and post-compensators to give a desired shape of the open-loop frequency response (interns of the singular values for MIMO systems or gain for SISO systems).

STAGE 2: the resulting shaped plant is robustly stabilized with respect to comprise factor uncertainty using H∞ optimization.

Pa increased the system with the weighting function and given by the following equation:

$$P(s)=\left[\begin{array}{cccc:c:c} A_c & 0 & 0 & 0 & 0 & B_c \\ -BW_1C_G & AW_1 & 0 & 0 & BW_1 & -BW_1D_G \\ 0 & 0 & AW_1 & 0 & 0 & BW_2 \\ BW_3C_G & 0 & 0 & AW_1 & 0 & BW_3D_G \\ \hdashline -DW_3C_G & CW_1 & 0 & 0 & DW_1 & DW_1D_G \\ 0 & 0 & CW_2 & 0 & 0 & DW_2 \\ DW_1C_G & 0 & 0 & CW_3 & 0 & DW_1D_G \\ C & 0 & 0 & 0 & 1 & D_G \end{array}\right] \qquad (10)$$

With $W_1 W_2$, W_3: weightings functions

The nominal system $G(s)$ is augmented with weightings transfer functions $W_1(s)$, $W_2(s)$, and $W_3(s)$, penalizing the error signals, control signals, and output signals respectively. The choice proper weighting function is the essence of H∞-loop shaping control approach. 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.

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

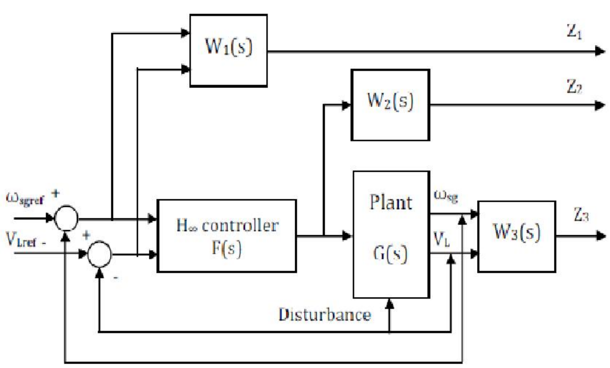


Fig.5. Simplified block diagram of the augmented plant including H_∞ controller

The Conventional Power system stabilizer in this paper (realized on PID) 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 [8].

B. GLOVER - DOYLE algorithm to synthesize the robust H_∞-PSS

The standard control problem solving is proposed as follows [5]:

1. Calculate the nominal established regime (PR);
2. Linearization of the control object (SG-AVR -PSS) ;
3. The main problem in H∞-loop shaping control is definition of the increased control object *P(s)* in state space:

3-1. Choice of weightings functions: W_1, W_2, *and* W_3;

3-2. Obtaining the increased control object 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);
6. Solving two Riccati equations which defined by the two Hamiltonian matrices “*H*” and “*J*”;
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. obtention of robust H_∞ controller in linear form type “LTI” ;
10. Computer simulation of power system stability and robustness studies under different operating conditions.

Figure 6 present the flowchart of the proposed algorithm in this paper for designing the robust PSS-H∞ based on loop shaping approach

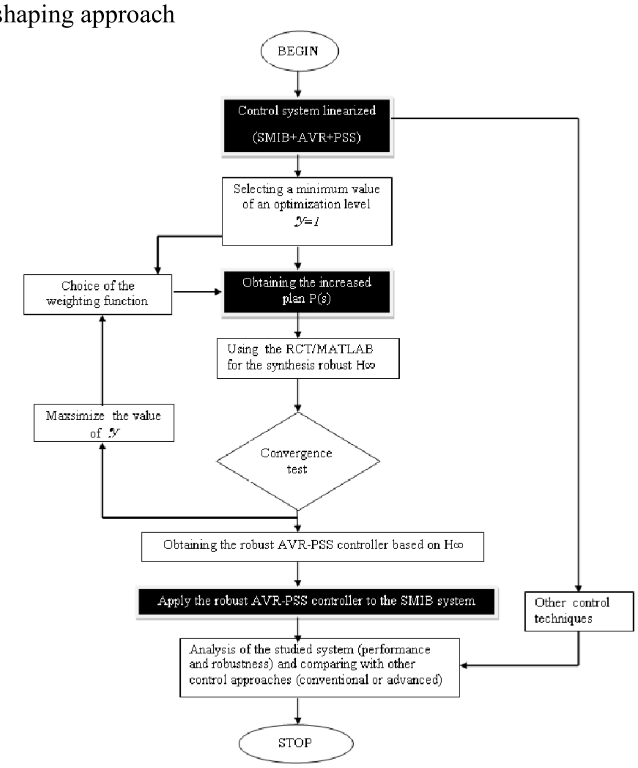


Fig. 6. Synthesis algorithm for robust H∞ controller using loop shaping approach

The standard problem of H∞ command is done by checking the following inequality infinity norm

$$T_{z1u1} = \sup(\,\sigma_{\max}\,(jw) < y \qquad (11)$$

$\sigma_{\max}$: the maximum singular value

γ: Optimization level

With

$$\begin{vmatrix} w_1^{-1} & S \\ w_2^{-1} & R \\ w_3^{-1} & T \end{vmatrix} \leq 1 \qquad (12)$$

Solving two Riccati equations for the synthesis of the regulator:

$$H\infty = \begin{bmatrix} A^T & -y^2 B_1 B_1^T - B_2 B_2^T \\ c_1 c_1^T & -A \end{bmatrix} \quad (13)$$

$$J\infty = \begin{bmatrix} A^T & -y^2 c_1 c_1^T - c_2 c_2^T \\ B_1 B_1^T & -A \end{bmatrix} \quad (14)$$

The existence of robust controller for if condition will be checked

1- *H and J* do not allow root on the imaginary axes

2- *X and Y* (two Riccati equation solutions), not negative defined,

3-$\varphi(X, Y) < \gamma^2$, with φ : spectral radius of solution

If all conditions are verified and check the robust controller has the form:

$$K(S) = -F\infty\left[(SI - A\infty)\right]^{-1} Z\infty I\infty \quad (15)$$

With

$A_\infty = A + \gamma^{-2} B_1 B_1^T X_\infty + B_2 F_\infty + Z_\infty L_\infty C_2 F_\infty = -B_2^T X_\infty$;
$L_\infty = -Y_\infty C_2^T$, $Z_\infty = (I_n - \gamma^2 Y_\infty X_c)^{-1}$

(b)

IV. Simulation Results and Discussion

A. Static and dynamic performances

Simulation results have been obtained using MATLAB/SIMULINK for the SMIB system model. Our study was interested in the powerful synchronous Generator type TBB-500 (Turbo Alternator 500 MW, see parameter in appendix 1).

We have simulated three operating modes: the nominal, the under-excited and the over-excited functioning regimes of electrical station.

The simulation results of static and dynamic performances: damping coefficients 'α', static error 'ε%' and settling time 'Ts', the maximum overshoot 'd%', with PSS-PID and PSS H∞, of the various parameters are shown respectively in Tables I and II. Comparing the obtained results of the studied system we can directly noted a very large improvements of static and dynamic performances of the SMIB system with the robust PSS-H∞ in comparison with the application of PSS-PID.

B. Stability and Robustness

Initially is carried out electrical parametric variations. Then it performs mechanical parameter variations assuming this time that the electrical parameters are known (constant). The simulation time is estimated at 10 seconds.

Results of time domain simulations, with a test of robustness: The figures (7a, 8a, and 9a) present the first test of robustness with electrical parametric uncertainty by maximization of stator Resistor R at t=4s and mechanical variation by lower bound at 50% of inertia J applied at t= 6s. The figures (7b, 8b, and 9b) present the second test of robustness: with electric and / or mechanic parametric uncertainty by maximization of R or by lower bound 50% of inertia J applied at t=4s and simultaneously at t= 6s.

From the simulation results, it can be noticed and observed that the PSS-H∞ produces better response characteristics as compared to the PSS-PID.

The PSS-H∞ improves considerably the dynamic performances (static errors negligible so better precision, and very short setting time so very fast system, and we found that after few oscillations, the system returns to its equilibrium state even in critical situations (specially the under-excited regime) and granted the stability and the robustness of the studied SMIB-IEEE system.

It should be mentioned here that for the critical regime stations power generation system which is under-excited, the PSS-H∞ has proved its effectiveness, it has greatly improved the stability and dynamics performances of our system during periods of very hard work of the power station while PSS-PID couldn't keep the stability of the system and specially in the critical under excited regime.

A. *Nominal mode TBB 500, XL=0.5, Q1 = 0.1896, Pg=0.85 (pu)*

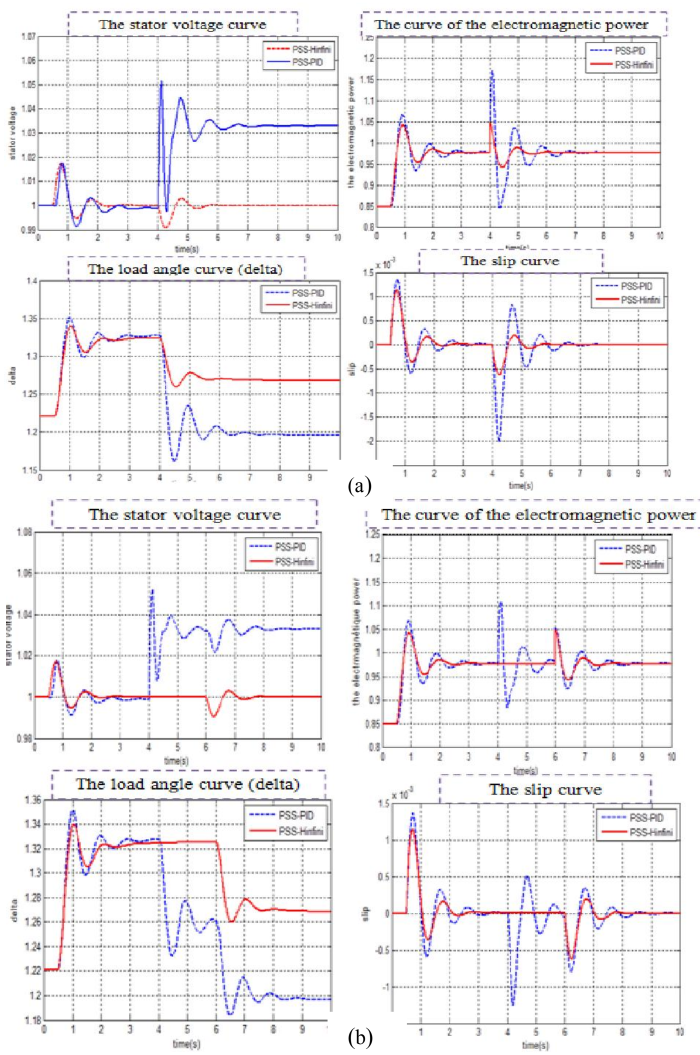
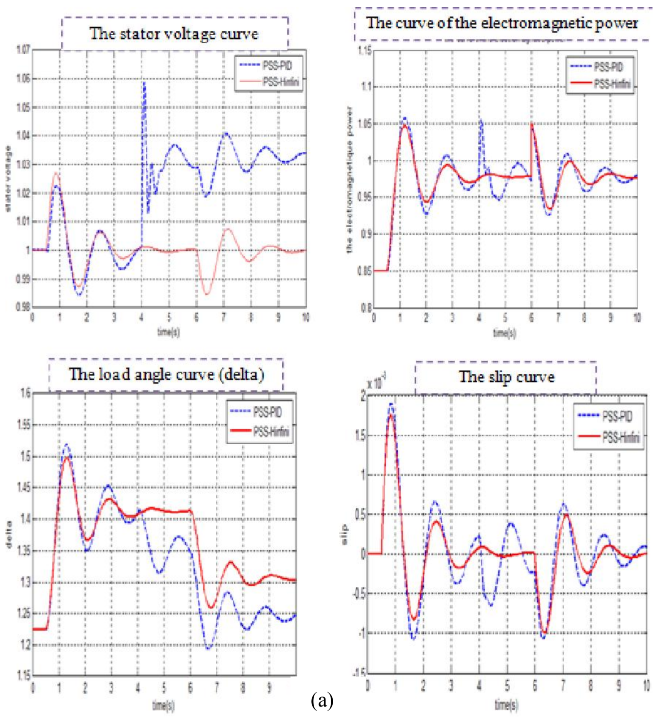
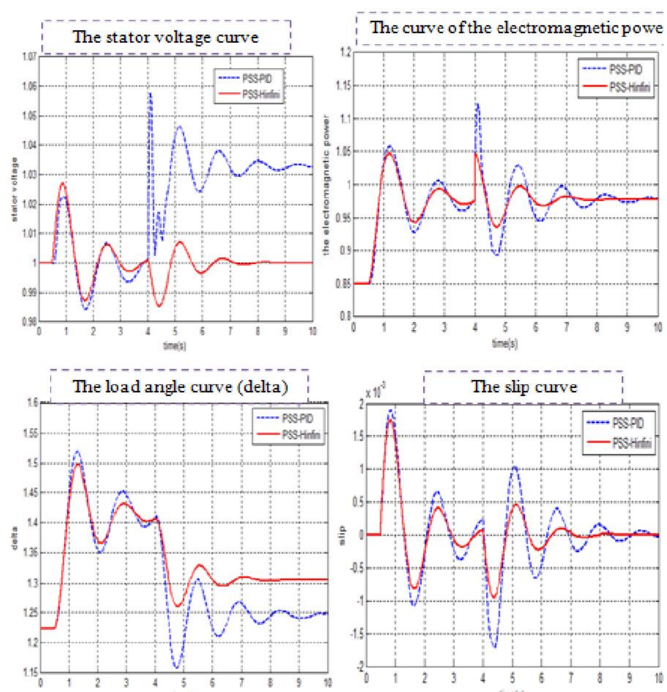


Fig.7. System Responses in the nominal mode with SG type TBB-500 connected to a long line: PSS-H∞ (red); PSS-PID (blue)

B. Over-excited mode TBB-500,Q=0.629,XL=0.5, Pg=0.85(pu)



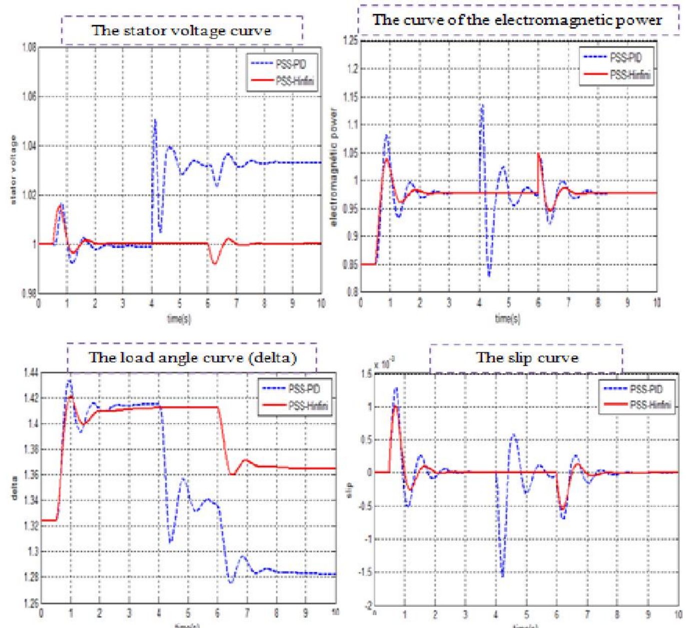
(a)



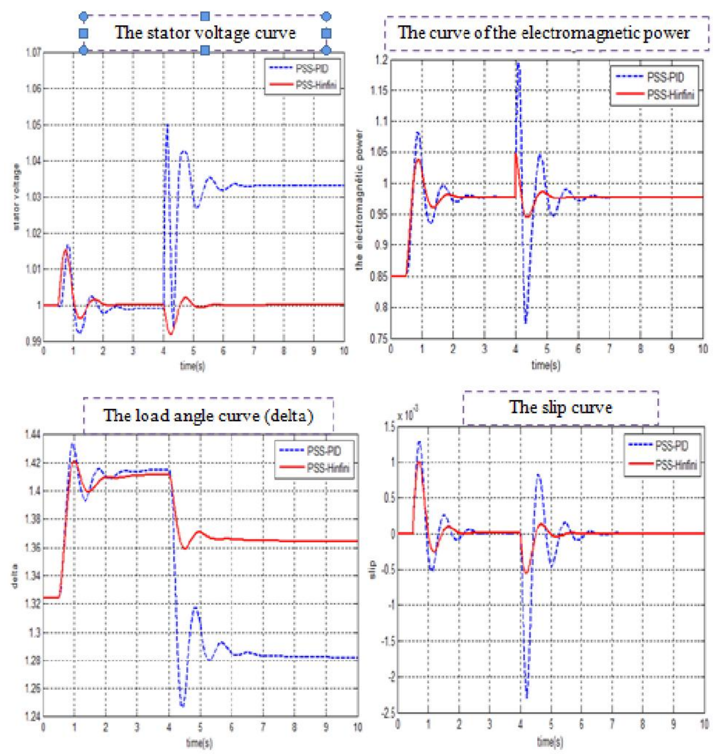
(b)

Fig.8. System Responses in the over-excited mode with SG type TBB-500 connected to a long line: PSS-H∞ (red); PSS-PID (blue)

C. Under-excited mode TBB-500, Q= -0.0292, XL=0.5, Pg=0.85(pu)



(a)



(b)

Fig.9. System Responses in the under-excited mode with SG type TBB-500 connected to a long line: PSS-H∞ (red); PSS-PID (blue)

Table I: Damping coefficients ‘α’ and static error ‘ε%’ in the Close Loop system with PSS-H∞ and PSS-PID in different operating Conditions of the power system

Q (pu) (reactive power)	***a(pu) pss-pid***	***ε%(pu) pss-pid***	***a(pu) pss-H∞***	***ε % (pu) pss-H∞***
-0.1807	*-1.604*	*1.073*	*-2.927*	*0*
-0.2313	*-1.571*	*1.071*	*-2.864*	*0*
0.2567	*-1.537*	*1.068*	*-2.294*	*0*
0.6254	*-1.500*	*1.064*	*-2.220*	*0*

Table II: Settling time ‘T_S’ and overshot ‘d%’ in the Close Loop system with PSS-H∞ and PSS-PID in different operating Conditions of the power system.

Q (pu) (reactive power)	***T_S (pu) pss-pid***	***d%(pu) pss-pid***	***T_S(pu) pss-H∞***	***d %(pu) pss-H∞***
-0.1807	*1.870*	*4.822*	*0.631*	*2.795*
-0.2313	*1.909*	*4.640*	*1.269*	*2.619*
0.2567	*1.951*	*4.453*	*1.307*	*2.423*
0.6254	*2.000*	*4.250*	*1.351*	*2.216*

V. Conclusion

This paper highlights a systematic approach for automated designing power system stabilizer using loop shaping optimization procedure (H∞ robust control) , applied on the AVR and PSS systems of turbo alternators, to improve transient stability and robustness of a SMIB-IEEE test power system. 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.

Study results show that the PSS-H∞ controller has best dynamic performance; the system is more stable and quite robust comparatively with using a conventional type PID controller (PSS).

APPENDIX

A. Parameters of the used SG: TBB-500

parameters	*SG: TBB-500*	*measure Units*
power nominal	*500*	*MW*
nominal Power Factor	*0.85*	*p.u.*
Xd	*1.869*	*p.u.*
Xq	*1.5*	*p.u.*
Xs	*0.194*	*p.u.*
Xf	*1.79*	*p.u.*
Xsf	*0.115*	*p.u.*
Xsfd	*0.063*	*p.u.*
Xsf1q	*0.0487*	*p.u.*
Xsf2q	*0.0487*	*p.u.*
Ra	*0.0055*	*p.u.*
Rf	*0.000844*	*p.u.*
R1d	*0.0481*	*p.u.*
R1q	*0.061*	*p.u.*
R2q	*0.115*	*p.u.*

B. Parameters of the Regulator AVR

Parameter	*SG: TBB-500*
T1u	*0.039*
Te	*0.04*
K1ua	*-7*
K0ua	*-50*

C. Parameters of the used conventional PID-PSS

Parameter	*SG: TBB-500*
T1u	*0.039*
Te	*0.04*
K1ua	*-8*
K0ua	*-15*
Tfc	*0.07*
T1ω	*0.026*
T0ω	*1*
K1ω	*1*
K0ω	*2*
Tif	*0.03*
Kif	*-1*
Tuf	*0.05*
Kuf	*1*

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