

An Advanced Robust AVR-PSS Based H₂ and H_∞ Frequency Approachs Simulated Under a Realized GUI

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Abstract

This article present a comparative study between two advanced robust frequency control strategies and their implementation using our realised Graphical User Interface 'GUI' under MATLAB software: the first method based on loop-shaping H_∞ optimization technique and the second on robust H₂ control method (LQG controller associated with KALMAN filter), and applied on automatic excitation control of synchronous generators, to improve transient stability and robustness of a single machine-infinite bus (SMIB) system operating in different several conditions. The computer simulation results (static and dynamic stability), with test of robustness against machine parameters uncertainty (electric and mechanic), have proved that good dynamic performances, showing a stable system responses almost insensitive to large parameters variations, and more robustness using robust H_∞ controller in comparison with H₂ approach by exploiting our developed GUI interface in this work.

Keywords: turbo-Alternator and excitation, Automatic Voltage Regulator Power System Stabilizer, Conventional PID control, Robust H₂ and H_∞ approahs, GUI – Matlab, Stability and Robustness

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1. Introduction

An important application area for the synchronous machine is used almost exclusively in power systems as a source of electrical energy [1]. Keeping voltage within certain limits help to reduce energy losses, and improves voltage regulation. Voltage control is a difficult task because it's strongly influenced by dynamic load fluctuations [1] and these must be effectively damped to maintain the power system stability which is a very important aspect of power systems studies. In this paper, we focused on electro mechanical oscillations of electrical generators also called power swings which are the major causes of instability.

Several methods for increasing this damping are available such as Static Voltage Condenser (SVC), High Voltage Direct Current (HVDC), and Power System Stabilizer (PSS).

To enhance system damping, the synchronous generators are equipped with PSS that provide supplementary feedback stabilizing signal in the excitation systems [2], it is an electrical devise which is used to enhance rotor electromechanically oscillation, and then maintain power system stability. In the early fifties, Demello and Concordia [3] had the idea of adding an additional signal to the AVR regulation loop (Automatic Voltage Regulator), to provide a sufficient damping of rotor's oscillations.

The first PSS invented was classical as a PID controller, it been widely accepted but its main default was its inability to adapt to operating electrical network changes, and especially, the over excited and the under-excited modes which are dangerous for any electrical installation. Therefore, Power system is a complicate nonlinear system which structure, parameters and running mode usually change. So, for some purposes, such as control loop design the study of the linearized system is necessary.

In this paper, we proposed tow robust PSS designed through tow robust frequential advanced technical wish are "H₂" the linear quadratic Gaussian control with a Kalman filter) (PSS-H₂), and the loop shaping control "H_∞" (PSS-H_∞), our main aim is related to power system robustness stability voltage and best dynamic performances.

2. Description of the Used Standard IEEE-SMIB System

2.2. System Configuration

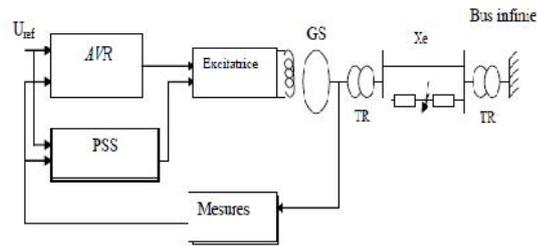


Figure 1. The SMIB system configuration

In this study, we opted for the simple IEEE standard SMIB (Single Machine input into Infinity Bus) power system, its configuration is shown in the figure above.

It includes:

- An Automatic Voltage Regulator (AVR) ;
- A Classical Exciter ;
- A Power System Stabilizer (PSS);
- A Synchronous Generator (GS) ;
- Two transformers ;
- A transmission line , "Xe" is its synchronous reactance .

Now, we have to modelize each SMIB's element mathematically, then turning them into Simulink bloc diagram, in order to launch the numerical simulation in Matlab-Simulink.

2.3. The 'Park-Gariv' Mathematical Model

The "Permeances Networks" approach and "Park-Gariv" model have chosen because it presents the best compromise between result's accuracy and computational cost.

1) Voltage equation:

$$v_d = R_s i_s + \frac{dW_d}{dt} - \check{S}_r W_q \quad (1)$$

$$v_q = R_s i_q + \frac{dW_q}{dt} - \check{S}_r W_d \quad (2)$$

$$v_f = R_f i_f + \frac{dW_f}{dt} \quad (3)$$

2) Flux equation

$$W_d = L_q i_q \quad (4)$$

$$W_q = L_f i_f + M_{id}$$

3) Mechanical equation

$$f\Omega_r + J \frac{d\Omega_r}{dt} = C_{em} - C_r - C_{fer} \quad (5)$$

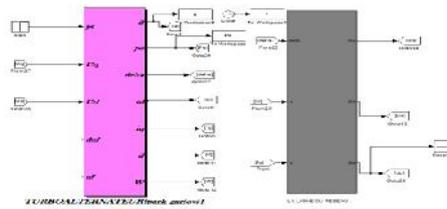


Figure 2. The Simulink Diagram of synchronous machine and the transmission line without controller

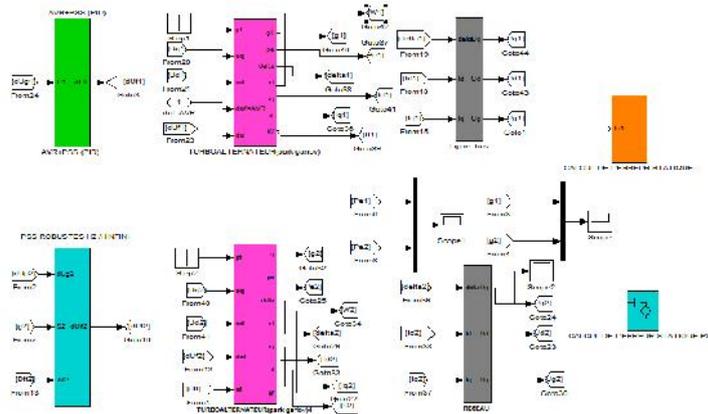


Figure 3. The Simulink Diagram of synchronous machine+AVR (green) and the AVR+PSS (blue) (closed loop)

3. AVR-PSS Based on Robust H2 AND H Approaches

Advanced control techniques have been proposed for stabilizing the voltage and frequency of power systems.

These techniques were born from the best formalization of specifications, they are based on a mathematical criteria, whose effective resolution allows to synthesize a controller with all the requirements of these specifications.

3.1. Robust H2 Technique Based LQG and Kalman Filter

Linear – Quadratic- Gaussian (LQG) control technique is equivalent to the robust H₂ regulator by minimizing the quadratic norm of integral of quality, [13], in this paper ,the robust quadratic H₂ 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 [11, 5]. LQG design requires a state- space model of the plant plus a Kalman filter:

$$\begin{cases} \frac{dx}{dt} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{6}$$

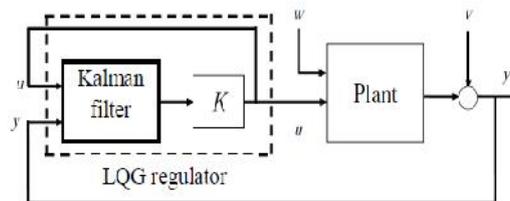


Figure 4. The Optimal LQG regulator with Kalman Filter

Where: x , u , y , is the vectors of states variables, control inputs and measurements, respectively.
We define the H_2 norm as follow:

$$\|G\|_2 = \sqrt{\frac{1}{2\pi} \int_{-\infty}^{\infty} \text{tr}[G^H(j\omega)G(j\omega)]d\omega} \quad (7)$$

With $D=0$ (a strictly proper system).

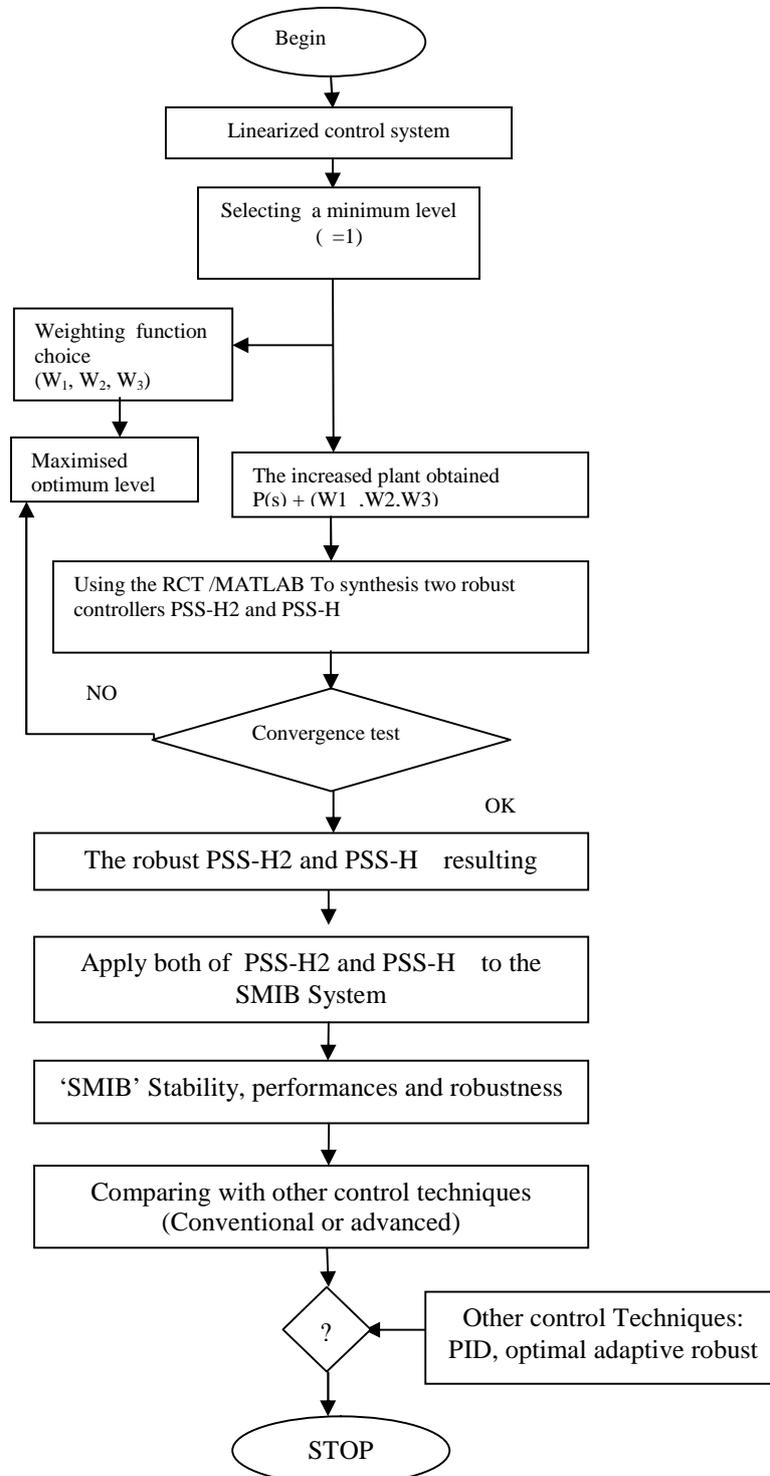


Figure 5. The used Glover-Doyle algorithm

At the other hand, the H_{∞} advanced robust control is used to design robust controllers achieving robust performances or stabilization, as well, it can be used to minimize the closed loop impact of a perturbation, this impact will either be measured in terms of stabilization or performance. the standard setup of the control problem consists of finding a static or dynamic feedback controller such that the H_{∞} norm of the closed loop transfer function is less than a given positive number constraint that the closed loop system is internally stable.

Considering $G(S)$, an LTI system (Linear Time Invariant), and a Multiple Input Multiple Output system (MIMO) defined by:

$$\begin{bmatrix} \dot{x}(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x(t) \\ u(t) \end{bmatrix} \tag{8}$$

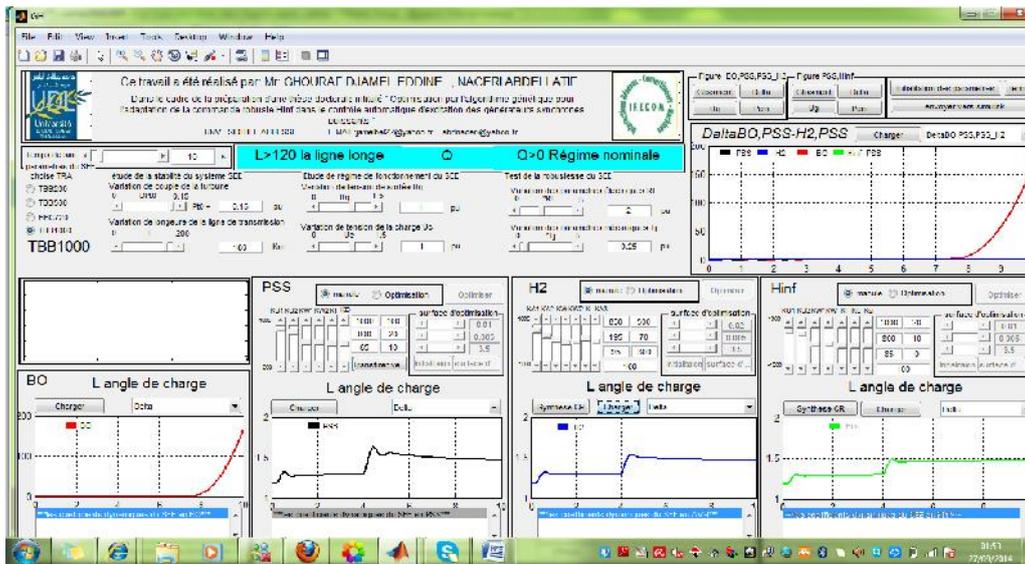


Figure 6. The SMIB system implemented in GUI-Matlab

3.2. The Robust PSS Based on H_{∞} Loop-Shaping Optimization

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 [16-18], robust H_2 (linear quadratic Gaussian with KALMAN filter) and robust H_{∞} control [19, 20].

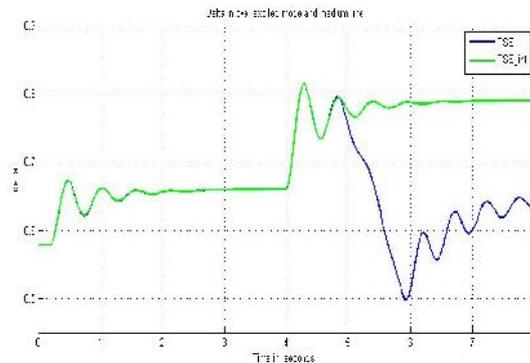


Figure 7. Delta in over-excited mode and medium line with PSS-PID(blue) and robust PSS-H (green)

H_∞ approach is particularly appropriate for the stabilization of plants with unstructured uncertainty [20]. 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 [19].

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 [21-22], and then the weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found.

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 [23].

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 [19].

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_∞ 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.

The robust H_∞ synthesis is carried in two stages:

- 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.
- Solution: The weights are iteratively modified until an optimal controller that satisfies the H_∞ optimization problem is found.

Figure 8 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.

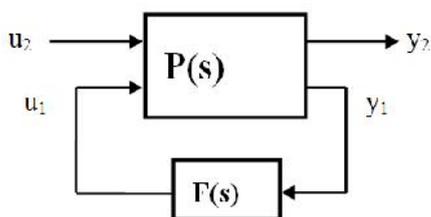


Figure 8. General Setup of the H_∞ loop-shaping design

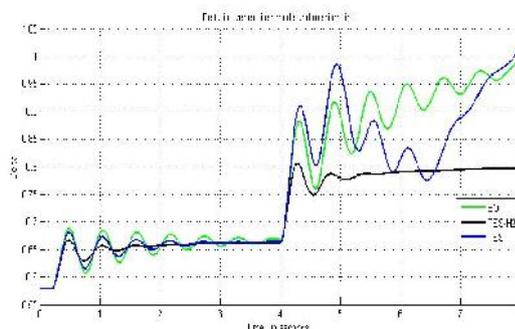


Figure 8. Delta in over-excited mode and medium line with open loop(green), PSS-PID(blue) and robust PSS-H2 (black)

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 $u_1(s) = F(s) \cdot y_1(s)$ 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 9. 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.

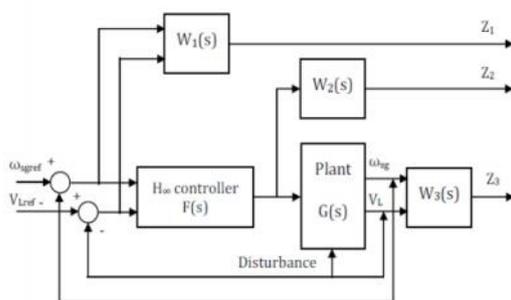


Figure 9. Simplified block diagram of the augmented plant including H_∞ controller

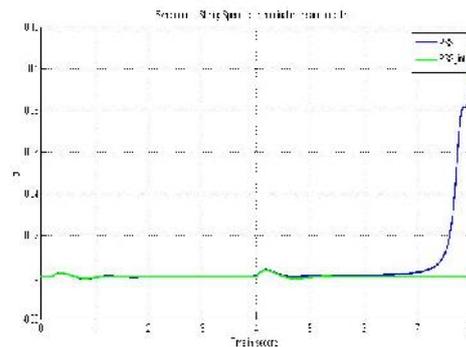


Figure 9. Synchronous sliding speed « g » in nominal mode and long line with PSS-PID (blue) and robust PSS-H (green)

The control system design method by means of modern robust H_∞ 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 schemes) 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 [25, 26].

3.3. GLOVER-DOYLE Algorithm to Synthesize a Robust Stabilizer H_∞ -PSS

Solving of the standard control Problem is proposed as follows:

- Calculates the Standing regime established (RP);
- Linearization of the control object (GS+PSS+AVR)
- The main problem in H_∞ control and the definition of the control object increased

$P(s)$ in the state space:

- Choice of weighting functions: W_1, W_2, W_3
- The obtaining of the command object increased from weighting functions $W_{1,2,3}$.
- Verify if all conditions to the ranks of matrices are satisfied, if not we change the structure of the weighting functions;
- Choosing a value of γ (optimization level);
- Solving two Riccati equations which defined by the two matrices H and J of HAMILTON;
- Reduction of the regulator order if necessary
- 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;
- We get the parameters of robust controller H_∞ in linear form 'LTI (SS state space, TF transfer function or ZPK zeros - pole - gains),

j) The simulation and realization of the stability study and robustness of electro-energy system under different functioning conditions.

In this paper, we use the “Glover-Doyle” algorithm to solve the optimal problem (iteration), in order to obtain tow robust voltage controllers: PSS-H2 and PSS-H , as is shown in the following diagram (Figure 10).

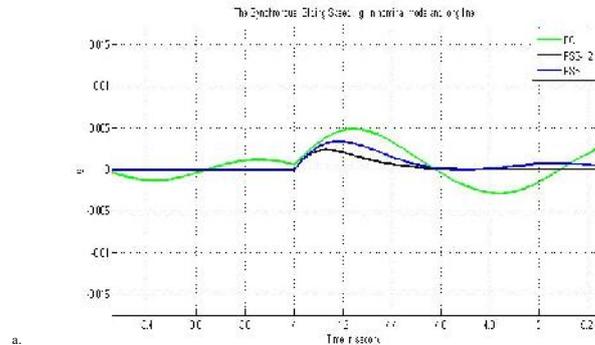


Figure 10. Synchronous sliding speed « g » in nominal mode and long line with open loop (green), PSS-PID(blue) and robust PSS-H2 (black)

3.4. Developpement of Graphical user interface (GUI) with Matlab

The SMIB system simulation is developed in the following four cases:

- Open loop without any voltage control;
- Closed loop with the classical PSS- PID;
- Closed loop with the robust PSS- H2;
- Closed loop with the robust PSS- H .

Under three operating mode (nominal, under-excited and over-excited modes), and with three different length of the network transmission line.

In addition, to bring out the robustness of both robust controllers H2 and H compared to the classical one PSS-PID, we have disturbed the SMIB with tow parametric variation simultaneously at $t=0.4$ s:

- Increasing stator resistance (100%);
- Decreasing electromechanical torque (50%) .

To facilitate and extend this simulation study, it seemed useful and judicious to develop a Graphical Interface User under Matlab-Simulink for the SMIB power system.

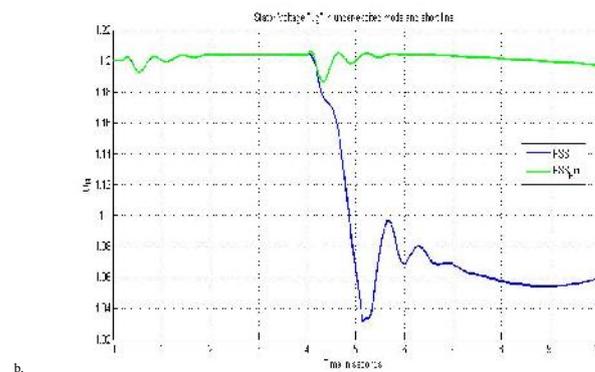


Figure 11. The Stator Voltage “Ug” in under-excited mode and short line with PSS-PID(blue) and robust PSS-H (green)

4. Simulation Results, Analysis and Discussion

The out-put shown in these following results are:

- DELTA :The load angle (difference between F.E.M and network voltage);

- b) U_g : The stator voltage;
 c) "G": The sliding synchronous speed
 The studied Turbo alternator is the TBB-1000 (1000 MW).

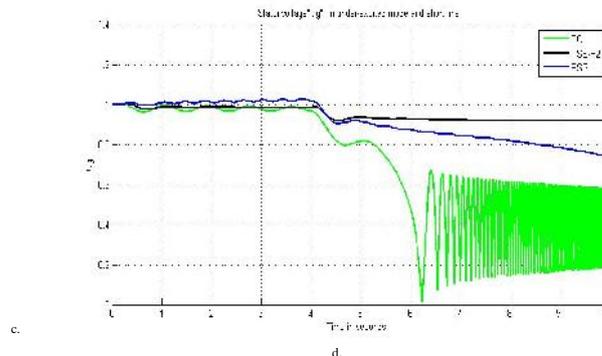


Figure 12. The stator voltage " U_g " in under-excited mode and short line with open loop (green), PSS-PID (blue) and robust PSS-H2 (black)

4.1. Results Analysis and Discussion

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.

- a) In nominal mode:

We highlight that contrary to the classical PSS-PID, with using robust controllers: PSS-H2 and PSS-H the sliding synchronous speed vanishes even after having injected tow parametric disturbances at $t=4s$, therefore, the synchronous speed is kept constant.

- b) In over excited mode (rush hours):

We notice that after few oscillations, Delta (voltage difference) 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), Delta with robust controllers PSS-H, and PSS-H2 resists, while with the classical PSS-PID, it cannot.

- c) 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, " U_g " oscillates.

5. Conclusion

In this article, our attention is focused on the synthesis of robust Power System Stabilizer to ensure stability and robustness of the SMIB power system in wich they are applied.

For this purpose, we have exploited both advanced frequency techniques H2 and H in order to obtain tow robust controllers: PSS-H2 and PSS-H.

Also, we have successfully attempted to developed a Graphical User Interface "GUI" in Matlab-Simulink, which allowed us to make reliable Simulation of the SMIB system under different conditions.

The simulation results shown that PSS-H2 and PSS-H are better than the classical PID one, in term of stability, dynamic performances, and robustness against mechanical and electrical parameters on one hand, and in front the operating change modes, at the other hand.

In the near future, we hope arriving to synthesize an hybrid H2/ H PSS, and then, testing it's robustness through mechanical, electrical and magnetic disturbances.

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