ROBUST H_∞ CONTROL DESIGN AND DYNAMIC PERFORMANCE ANALYSIS OF AN ISOLATED-GENERATION UNIT

Ahmed. M. KASSEM* and Ali M. YOUSEF**

* Control Technology Dep., Bini-Swief University, Egypt, Email: *Kassem_ahmed53@hotmail.com*
** Electrical Dept., Assiut University, Egypt, Email: Drali_Yousef@yahoo.com

***Abstract* -** *In this paper, the voltage and frequency control of an isolated synchronous generator, driven by diesel engine, is developed using the H_∞ approach. This has been advantage of maintaining constant terminal voltage and frequency irrespective of load variations. Two closed loops are available for the H_∞ control. The first loop is dedicated for regulating the terminal voltage of the synchronous generator to a set point by controlling the field voltage of the synchronous generator. The second loop is designed to control the rotor shaft speed via adjusting the mechanical input power to the generator from diesel engine. 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 performance goals. The proposed system has the advantages of robustness against model uncertainties and external disturbances, fast response and the ability to reject noise. The robustness of the diesel generation scheme has been certified through step changes in load impedance. Simulation results show the evaluated of the proposed H_∞ control scheme against system variation.*

Keywords: diesel engine, synchronous generator, robust control, H_∞ approach

Nomenclature

v_q^r, v_d^r	d-q stator voltages of synchronous generator,
v_{kd}^r, v_{kq}^r	d-q damper winding voltages of synchronous generator,
v_f^r	field winding voltage of synchronous generator
i_d^r, i_q^r	d-q stator currents of synchronous generator,
i_{kd}^r, i_{kq}^r	d-q damper winding currents of synchronous generator,
i_f^r	field winding current of synchronous generator,
R_s	stator resistance of synchronous generator,
R_{kd}, R_{kq}	d and q damper winding resistances,
L_{md}, L_{mq}	d and q mutual inductances,
L_d, L_q	d and q self inductances,
ω_{sg}	rotor speed (electrical rads/s) of the synchronous generator,
T_{md}	torque input from diesel engine,
φ_r, φ_f	applied and actual fuel flow rate of diesel engine,
τ_1	combustion delay time constant,
τ_2, K_2	time constant and gain of fuel rack position actuator,
J	moment of inertia,
β	friction coefficient,
p	differential operator d/dt ,
P_o	number of pole pairs.

1. Introduction

This paper presents the modeling, design and simulation of an isolated power generation system. This generation plant is conceived to supply electric power to an isolated load not connected to the electrical network. The electric power generator is a complex system with highly non-linear dynamics. The stability depends on the loading conditions of the power system and its topology. Low frequency oscillations are a common problem in large power systems. Excitation control or Automatic Voltage Regulator (*AVR*) is well known as an effective means to improve the overall stability of the power system.

Advanced control tehniques have been proposed for stabilizing the voltage and frequency of power generation systems. These include output and state feedback control [1], variable structure control [2-3], neural network control [4], fuzzy logic control [5,6], linear quadratic Gaussian control [7], and H_∞ control [8,9].

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 H_∞ controllers based on a polynomial system philosophy has been introduced by Kwakernaack [10] and Grimble[11].

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[12], 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 to illustrate the dynamic system response to state disturbances. The effectiveness of such controllers is examined at different extreme operating conditions. This article relies on H_∞ approach to design a robust power system stabilizer. The advantages of the proposed controller are addresses stability and sensitivity, exact loop shaping, direct one-step procedure stable and closed-loop always stable [9].

2. System Description

Fig. 1 shows a diesel energy system connected to an isolated load. It consists of a synchronous generator driven by a diesel engine. The synchronous generator is equipped with a voltage regulator and a static exciter. The diesel-generator unit is proposed to cater the local load power equipment.

3. System Dynamic Model

The dynamic models of the different parts of the system can be described as follows:

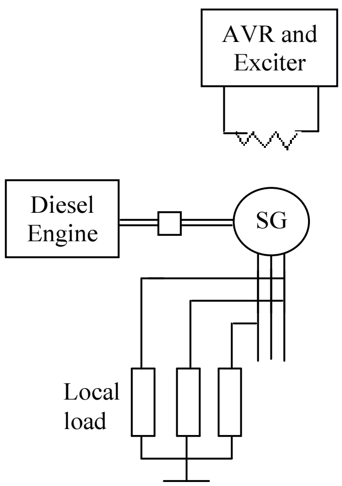

Fig. 1: Block Schematic diagram of the proposed diesel-generation system.

3.1 Synchronous Generator Dynamic Modeling

The dynamic behavior of the synchronous generator in the d^r-q^r axis synchronously rotating reference frame fixed in the rotor (i.e., d^r-q^r refrence frame rotating at the rotor speed ω_{sg}) is given by [13]:

$$pi_q^r = \frac{L'_{kq}}{\left(L'_{kq} - L_{mq}^2\right)}\left[\begin{array}{l} -R_s i_q^r - \frac{L'_{kq}L'_{mq}}{L'_{kq}} i_{kq}^{r'} \\ -\omega_{sg} i_d^r + \omega_{sg} L_{md} i_{kd}^{r'} + \omega_{sg} L_{md} i_f^{r'} - V_q^r \end{array}\right] \qquad (1)$$

$$pi_d^r = \frac{1}{K_{11}}\left[\begin{array}{l} \omega_{sg} L_q i_q^r - R_s i_d^r - \omega_{sg} L_{mq} i_{kq}^{r'} \\ +\left(K_{22} R'_{kd} L'_f + K_{33} R'_{kd} L_{md}\right) i_{kd}^{r'} \\ -\left(K_{22} L_{md} + K_{33} L'_{kd}\right) R'_f i_f^{r'} \\ +\left(K_{22} L_{md} + K_{33} L'_{kd}\right) v_f^{r'} - v_d^r \end{array}\right] \qquad (2)$$

$$pi_{kq}^{r'} = -\frac{R'_{kq}}{L'_{kq}} i_{kq}^{r'} + K_{44}\left[\begin{array}{l} -R_s i_q^r - \frac{R'_{kq} L_{mq}}{L'_{kq}} i_{kq}^{r'} \\ -\omega_{sg} L_d i_d^r + \omega_{sg} L_{md} i_{kd}^{r'} \\ +\omega_{sg} L_{md} i_f^{r'} - v_q^r \end{array}\right] \qquad (3)$$

$$pi_{kd}^{r'} = K_{22}\left[\begin{array}{l} v_f^{r'} + \frac{\left(L_{md} - L'_f\right)}{K_{11}}\left(\begin{array}{l} \omega_{sg} L_q i_q^r - R_s i_d^r - \omega_{sg} L_{mq} i_{kq}^{r'} \\ +(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd}) i_{kd}^{r'} \\ -(K_{22} L_{md} R'_{kd} + K_{33} L'_{kd}) R'_f i_f^{r'} \\ +(K_{22} L_{md} R'_{kd} + K_{33} L'_{kd}) v_f^{r'} - v_d^r \end{array}\right) \\ +\frac{R'_{kd} L'_f}{L_{md}} i_{kd}^{r'} - R'_f i_f^{r'} \end{array}\right]$$

……………………………………………………..(4)

$$pi_f^{r'} = \frac{L'_{kd}}{L_{md}} K_{33}\left[\begin{array}{l} v_f^{r'} + \frac{1}{K_{11}K_{55}}\left(\begin{array}{l} \omega_{sg} L_q i_q^r - R_s i_d^r - \omega_{sg} L_{mq} i_{kq}^{r'} \\ +(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd})\, i_{kd}^{r'} \\ -(K_{22} L_{md} + K_{33} L'_{kd}) R'_f i_f^{r'} \\ +(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd}) v_f^{r'} - v_d^r \end{array}\right) \\ +\frac{R'_{kd} L_{md}}{L'_{kd}} i_{kd}^{r'} - R'_f i_f^{r'} \end{array}\right]$$

……………………………………………………… (5)

Where

$$K_{11} = L_d - \frac{L_{md}^2\left(L_{md} - L'_f\right)}{\left(L_{md}^2 - L'_f L'_{kd}\right)} - \frac{L_{md}\left(L_{md} L'_{kd} - L_{md}^2\right)}{\left(L'_f L'_{kd} - L_{md}^2\right)}$$

$$K_{22} = \frac{L_{md}}{\left(L_{md}^2 - L'_f L'_{kd}\right)}, \quad K_{33} = \frac{L_{md}}{\left(L'_f L'_{kd} - L_{md}^2\right)},$$

$$K_{44} = \frac{L_{mq}}{\left(L_q L'_{kq} - L_{mq}^2\right)}, \quad K_{55} = \frac{L'_{kd}}{\left(L_{md} L'_{kd} - L_{md}^2\right)},$$

The q^r and d^r stator voltages in the reference frame fixed in the rotor are given by:

$$v_q^r = -i_q^r R_s - \omega_{sg} L_d i_d^r + \omega_{sg} L_{md} i_{kd}^{r'} + \omega_{sg} L_{md} i_f^{r'} \qquad (6)$$

$$v_d^r = -i_d^r R_s + \omega_{sg} L_q i_q^r - \omega_{sg} L_{mq} i_{kq}^{r'} \qquad (7)$$

The rotor speed w_{sg} is governed by the following differential equation:

$$\frac{2}{p_o}\left(Jp\omega_{sg} + \beta\omega_{sg}\right) = T_{md} - T_e \qquad (8)$$

Where, T_{md} is the input torque from the prime mover (diesel engine) and T_e is the electromagnetic torque representing the electrical load on the synchronous generator and is given by:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p_o}{2}\right)\left[\begin{array}{l} L_{md}\left(-i_d^r + i_f^{r'} + i_{kd}^{r'}\right) i_q^r \\ -L_{mq}\left(-i_q^r + i_{kq}^{r'}\right) i_d^r \end{array}\right] \qquad (9)$$

Lastly, the torque angle representing the electrical load on the synchronous generator is given by:

$$p\delta = \frac{2}{p_o}\left(\omega_{sg} - \omega_e\right) + \delta_o \qquad (10)$$

Where w_{sg} and w_e are the synchronous generator's rotor speed and electrical frequency respectively and δ_o is the initial torque angle. In steady state, w_{sg} and w_e are the same, but during transient w_{sg} changes and ultimately settles down to the value w_e. The v_q^e and v_d^e stator voltages in the reference frame fixed with the synchronously rotating frame MMF vector rotating at an angular velocity ω_e are given by:

$$v_q^e = v_q^r \cos(\delta) + v_d^r \sin(\delta) \qquad (11)$$

$$v_d^e = -v_q^r \sin(\delta) + v_d^r \cos(\delta) = 0 \qquad (12)$$

$$v_L = \sqrt{\left(v_q^e\right)^2 + \left(v_d^e\right)^2} = v_q^e \qquad (13)$$

The initial orientation of q and d reference frame is chosen such that v_d^e is initially zero and the load voltage

$$V_L = v_q^e = R_L\left(i_q^r \cos(\delta) + i_d^r \sin(\delta)\right) + \omega_e L_L\left(-i_q^r \sin(\delta) + i_d^r \cos(\delta)\right)$$

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3.2 Voltage Regulator and Static Exciter Model

The voltage and frequency at the local load bus are set by the synchronous generator. Under load excursion, the load voltage tends to vary. In order to regulate the bus voltage, the synchronous generator is equipped with an automatic voltage regulator (AVR) and a static exciter [13]. The static exciter is an "inverted" three phase generator, with the automatic windings on the rotor and the field windings on the stator. The AC armature voltage is rectified using diodes mounted on the rotating shaft, and the rectified voltage is applied to the synchronous generator field as shown in Fig. 2. The differential equations describing the excitation system for the synchronous generator are as follows:

$$pv_c = \left(V_{Lref} - V_L\right) = V_{Lref} - \begin{pmatrix} R_L\left(i_q^r \cos(\delta) + i_d^r \sin(\delta)\right) \\ + \omega_e L_L\left(-i_q^r \sin(\delta) + i_d^r \cos(\delta)\right) \end{pmatrix} \qquad (14)$$

$$pv'_f = \frac{K_e v_c - v'_f}{\tau_e} \qquad (15)$$

Where, K_e is the gain of the exciter and τ_e is the time constant of the exciter.

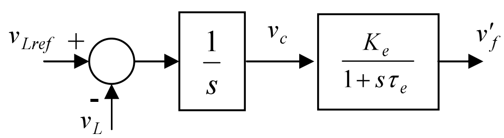

Fig. 2: Static voltage regulator loop

3.3 Speed Regulator and Diesel Engine Model

The synchronous generator is driven by a diesel engine which controls the mechanical power input to the generator to balance the electrical load on the machine. If the electrical load on the generator changes due to change in power drawn by the local load, the rotor speed and hence the electrical frequency tend to change. In such a situation the mechanical power (or torque) input to the synchronous generator is controlled to regulate the system electrical frequency. The block diagram of the diesel engine is shown in Fig. 3 [13]. The input signal is the speed (frequency) error and is used to determine the applied fuel flow rate φ_r depends on the position of the fuel rack which is controlled by the fuel actuator, characterized by a gain k_2 and a time constant τ_2. the torque output T_{md} of the diesel engine is proportional to the actual fuel flow rate φ_f, but is delayed by the fuel combustion process time delay τ_1. The torque output of the diesel engine is:

$$T_{md} = K_1 \phi_f e^{-\tau_1 s} \qquad (16)$$

Where K_1 is constant relating the torque output to the fuel flow rate. The combustion process delay can be approximated using first order Pad's approximation as follows:

$$e^{-\tau_1 s} = \frac{\left(\frac{2}{\tau_1} - s\right)}{\left(\frac{2}{\tau_1} + s\right)} \qquad (17)$$

The actual fuel flow rate φ_f is dependent on the applied fuel flow rate φ_r and is given by:

$$\varphi_f = \frac{K_2}{\left(1 + \tau_2 s\right)} \varphi_r \qquad (18)$$

Where K_2 and τ_2 are gain and time constant of the fuel actuator. The differential equations describing the diesel engine and its speed governor are given by [13]:

$$p\varphi_r = \omega_{sgref} - \omega_{sg} \qquad (19)$$

$$p\varphi_f = \frac{K_2\, \varphi_r - \varphi_f}{\tau_2} \qquad (20)$$

$$px_1 = \frac{4\varphi_f - 2x_1}{\tau_1} \qquad (21)$$

$$T_{md} = K_1\left(x_1 - \varphi_f\right) \qquad (22)$$

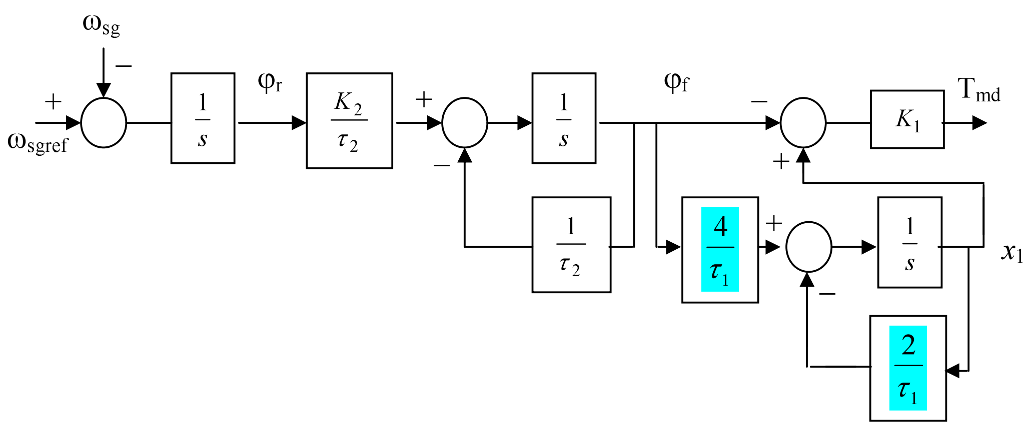

Fig. 3: state space representation of diesel engine and speed regulator loop.

3.4 Complete System and Small Signal Linearized Model

The subsystem models can be interfaced to form the unified nonlinear model. The complete system model can be described as:

$$pi_q^r = \frac{L'_{kq}}{\left(L'_{kq} - L_{mq}^2\right)} \begin{bmatrix} -R_s i_q^r - \frac{L'_{kq} L'_{mq}}{L'_{kq}} i_{kq}^{r'} - \omega_{sg} i_d^r \\ +\omega_{sg} L_{md} i_{kd}^{r'} + \omega_{sg} L_{md} i_f^{r'} - V_q^r \end{bmatrix} \tag{23}$$

$$pi_d^r = \frac{1}{K_{11}} \begin{bmatrix} \omega_{sg} L_q i_q^r - R_s i_d^r - \omega_{sg} L_{mq} i_{kq}^{r'} \\ +\left(K_{22} R'_{kd} L'_f + K_{33} R'_{kd} L_{md}\right) i_{kd}^{r'} \\ -\left(K_{22} L_{md} + K_{33} L'_{kd}\right) R'_f i_f^{r'} \\ +\left(K_{22} L_{md} + K_{33} L'_{kd}\right) v_f^{r'} - v_d^r \end{bmatrix} \tag{24}$$

$$pi_{kq}^{r'} = -\frac{R'_{kq}}{L'_{kq}} i_{kq}^{r'} + K_{44} \begin{bmatrix} -R_s i_q^r - \frac{R'_{kq} L_{mq}}{L'_{kq}} i_{kq}^{r'} - \omega_{sg} L_d i_d^r \\ +\omega_{sg} L_{md} i_{kd}^{r'} + \omega_{sg} L_{md} i_f^{r'} - v_q^r \end{bmatrix} \tag{25}$$

$$pi_{kd}^{r'} = K_{22} \begin{bmatrix} v_f^{r'} + \frac{\left(L_{md} - L'_f\right)}{K_{11}} \begin{pmatrix} \omega_{sg} L_q i_q^r - R_s i_d^r - \omega_{sg} L_{mq} i_{kq}^{r'} \\ +(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd}) i_{kd}^{r'} \\ -(K_{22} L_{md} R'_{kd} + K_{33} L'_{kd}) R'_f i_f^{r'} \\ +(K_{22} L_{md} R'_{kd} + K_{33} L'_{kd}) v_f^{r'} - v_d^r \end{pmatrix} \\ + \frac{R'_{kd} L'_f}{L_{md}} i_{kd}^{r'} - R'_f i_f^{r'} \end{bmatrix}$$
……………………………………………….. (26)

$$pi_f^{r'} = \frac{L'_{kd}}{L_{md}} K_{33} \begin{bmatrix} v_f^{r'} + \frac{1}{K_{11} K_{55}} \begin{pmatrix} \omega_{sg} L_q i_q^r - R_s i_d^r - \omega_{sg} L_{mq} i_{kq}^{r'} \\ +(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd})\, i_{kd}^{r'} \\ -(K_{22} L_{md} + K_{33} L'_{kd}) R'_f i_f^{r'} \\ +(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd}) v_f^{r'} - v_d^r \end{pmatrix} \\ + \frac{R'_{kd} L_{md}}{L'_{kd}} i_{kd}^{r'} - R'_f i_f^{r'} \end{bmatrix}$$
……………………………………………………… 27)

$$p\omega_{sg} = -\frac{\beta}{J}\omega_{sg} + \frac{P_o}{2J}\left(K_1\left(x_1 - \phi_f\right)\right) - \frac{3p_o^2}{8J} \begin{bmatrix} L_{md}\left(-i_d^r + i_f^{r'} + i_{kd}^{r'}\right) i_q^r \\ -L_{mq}\left(-i_q^r + i_{kq}^{r'}\right) i_d^r \end{bmatrix}$$
…………………………………………………… (28)

$$p\delta = \frac{2}{p_o}\left(\omega_{sg} - \omega_e\right) + \delta_o \tag{29}$$

$$pv_c = \left(V_{Lref} - V_L\right) = V_{Lref} - \begin{pmatrix} R_L\left(i_q^r \cos(\delta) + i_d^r \sin(\delta)\right) \\ +\omega_e L_L\left(-i_q^r \sin(\delta) + i_d^r \cos(\delta)\right) \end{pmatrix} \tag{30}$$

$$pv'_f = \frac{K_e v_c - v'_f}{\tau_e} \tag{31}$$

$$p\varphi_r = \omega_{sgref} - \omega_{sg} \tag{32}$$

$$p\varphi_f = \frac{K_2\ \varphi_r - \varphi_f}{\tau_2} \tag{33}$$

$$px_1 = \frac{4\varphi_f - 2x_1}{\tau_1} \tag{34}$$

The nonlinear model of the diesel-generation system, which expressed by equations (23) to (34) are linearized around an operating point as following:

$$px = A\,x + B\,\mu + v\,d \tag{35}$$

Where

$$x = \left[\Delta i_q^r \;\; \Delta i_d^r \;\; \Delta i_{kq}^r \;\; \Delta i_{kd}^r \;\; \Delta i_f^r \;\; \Delta\omega_{sg} \;\; \Delta\delta \;\; \Delta V_c \;\; \Delta V'_f \;\; \Delta\varphi_r \;\; \Delta\varphi_f \;\; \Delta x_1\right]^t$$

$$\mu = \left[V_{Lref} \quad \omega_{sgref}\right]^t, \quad d = \left[\Delta Z_L\right]$$

A = [a_{ij}] is a 12 x 12 matrix where the elements a_{ij} are written in appendix.

4. H∞ Controller Design

The H∞ theory provides a direct, reliable procedure for synthesizing a controller which optimally satisfies singular value loop shaping specifications. The standard setup of the H∞ control problem consists of finding a static or dynamic feedback controller such that the H∞ norm (a standard quantitative measure for the size of the system 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 H∞ synthesis is carried out in two stages:

i. 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 then augmented into H∞ standard plant.

ii. Solution: the weights are iteratively modified until an optimal controller that satisfies the H∞ optimization problem is found.

Fig. 4 shows the general setup of the H∞ design problem 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.

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.

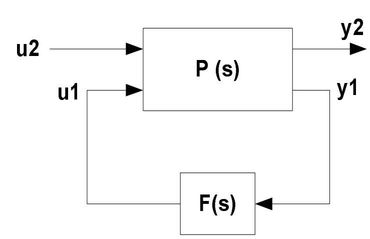

Fig. 4: General setup of the H∞ design problem

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 in Fig. 5. The nominal system G(s) is augmented with weighting transfer functions $W_1(s)$, $W_2(s)$ and $W_3(s)$ penalizing the error signals, control signals, and output signals respectively. The choice of 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 a solution to the H_∞ problem.

Consider the augmented system shown in Fig. 5. The following set of weighting transfer functions are chosen to reflect desired robust and performance goals as follows:

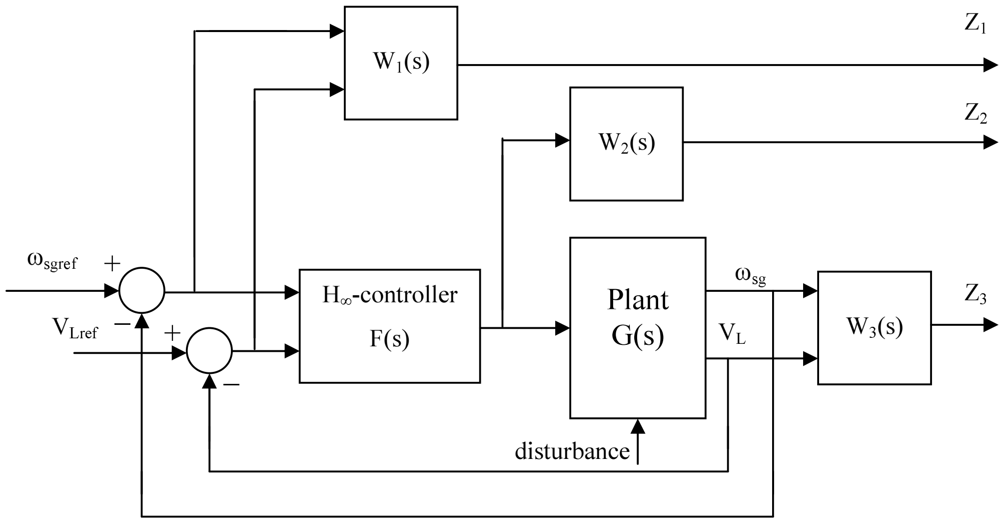

Fig. 5: Simplified block diagram of the augmented plant including H_∞ controller

A good choice of $W_1(s)$ is helpful for achieving good tracking of the input references, and good rejecting of the disturbances. The weighted error transfer function matrix Z_1 ; which is required to regulate, can be written as:

$$Z_1 = W_1(s)\begin{bmatrix} V_{Lref} - V_L \\ \omega_{sgref} - \omega_{sg} \end{bmatrix}$$

A good choice of the second weight $W_2(s)$ will aid for avoiding actuators saturation and provide robustness to plant additive perturbations. The weighted control function matrix Z_2 can be written as:

$$Z_2 = W_2(s).\, u(s)$$

where $u(s)$ is the transfer function matrix of the control signals output of the H_∞ controller.

Also a good choice of the third weight $W_3(s)$ will limit the closed loop bandwidth and achieve robustness to plant output multiplicative perturbations and sensor noise attenuation at high frequencies. The weighted output variable can be written as:

$$Z_3 = W_3(s) \begin{bmatrix} V_L \\ \omega_{sg} \end{bmatrix}$$

In summary, the transfer functions of interest which determine the behavior of the voltage and speed closed loop systems are:

a) Sensitivity function: $S = [\, I + G(s)\, .\, F(s)\,]^{-1}$

Where G(s) and F(s) are the transfer functions of the nominal plant and the H_∞ controller respectively, and I is the identity matrix. Minimizing S at low frequencies will insure good tracking and disturbance rejection.

b) Control function : $C = F(s)\, [\, I + G(s)\, .\, F(s)\,]^{-1}$

Minimizing C will avoid actuator saturation and achieve robustness to plant additive perturbations.

c) Complementary function: $T = I - S$

Minimizing T at high frequencies will insure robustness to plant output multiplicative perturbations and achieve noise attenuation.

5. System Configuration

The main objectives of the proposed controller are:

i) Regulating the terminal voltage of the synchronous generator by adjusting the field voltage using AVR and static exciter and according to the error between the reference and actual load voltages, and

ii) Controlling the rotor speed by controlling the mechanical input power to the synchronous generator to regulate the system electrical frequency.

For this purpose, the controlled system has been designed to contain two feedback loops. The first loop is designed for adjusting the synchronous generator terminal voltage according to a certain reference. The other loop has been dedicated for regulating the generator's rotational speed to a set point, thereby, the system electrical frequency can be kept constant.

The block diagram of the diesel energy conversion system with the proposed H_∞ controller is shown in Fig. 6. The entire system has been simulated on the digital computer using the Matlab / Simulink software package. The specifications of the system parameters used in the simulation procedure are as following [13]:

Rating: 2 KW, 208 V (line), 9 A, 4 poles, Unity power factor.

Constants: R_s=0.88Ω, R_f=67.0Ω, L_{md}=58 mH, L_{mq}=24.9 mH, L_{lsd}=L_{lsq}=2.92 mH, L_{lfd}=2.92 mH

$N_{se} : N_{fd} = 0.047 : 1$, $N_{se} : N_{kd} = 2.95 : 1$, $N_{se} : N_{kq} = 2.95 :1$

The following set of weighting functions is chosen after much iteration in order to achieve the desired robustness and performance goals:

$$W_1(s) = \begin{bmatrix} \gamma_{11}\dfrac{1}{s+0.17} & 0 \\ 0 & \gamma_{12}\dfrac{3.2}{s+12} \end{bmatrix},$$

$$W_2(s) = \begin{bmatrix} \gamma_{21}\dfrac{s+273}{s+3.87} & 0 \\ 0 & \gamma_{22}\dfrac{s+0.55}{s+3} \end{bmatrix} \quad \text{and}$$

$$W_3(s) = \begin{bmatrix} \gamma_{31}\dfrac{s+0.025}{s+750} & 0 \\ 0 & \gamma_{32}\dfrac{s+0.00523}{s+1500} \end{bmatrix}$$

Where: $\gamma_{11} = 0.728$, $\gamma_{12} = 0.1$, $\gamma_{21} = 0.0024$, $\gamma_{22} = 0.0028$, $\gamma_{31} = 0.014$, $\gamma_{32} = 0.64$

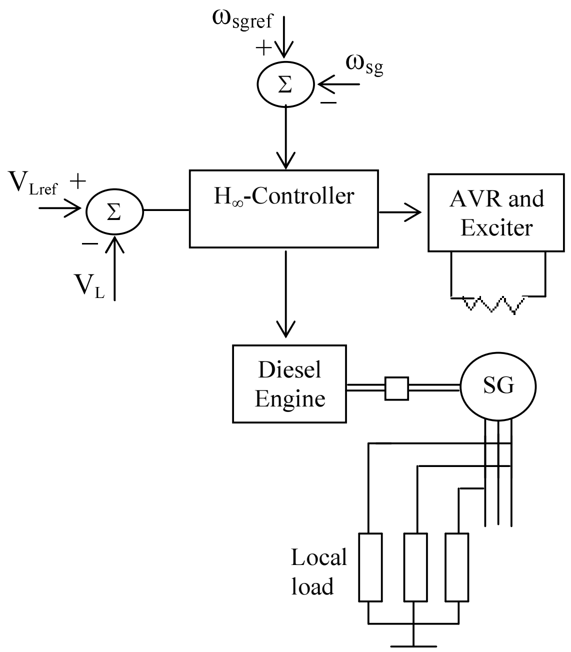

Fig. 6: Block diagram of the diesel-generation system with the proposed H_∞ controller

6. Simulation Results

Digital simulations have been carried out to validate the effectiveness of the proposed system under load variations. The performance of the proposed scheme has been tested with a step change in load impedance. Simulation results depicting the variation of different variables with step change in load impedance are shown in Fig. 7. The load impedance is assumed to vary between 46 Ω and 74 Ω. It has been noticed that as the load impedance decreases (the load current increases), the power output of the synchronous generator increases to meet the increased power demand. This is achieved by increasing the diesel fuel flow rate φ_r which in turn increases the torque (mechanical power) input to the synchronous generator. Also, the field current is increased to regulate the local load voltage. On the other hand, if the load impedance increases the controller decreases the diesel fuel flow rate φ_r which in turn decreases the torque input. Also, the field current is decreased to regulate the local load voltage. Also, Fig. 7 shows that the change in load does not affect the rotor speed significantly. This is because the H_∞ controller completes its job before the mechanical system responds to the variation.

Since our concerns are also in robust stability against various model uncertainties, some system parameters have been changed in the following ways:

i) The stator resistance and inductance are assumed to increase by 20% above nominal values.

ii) The field resistance and inductance are assumed to be 10% less than nominal.

For perturbed system the responses are shown in Fig. 8. It should be seen that the system is robustly stable in spite of parameters variations. Also, table 1 displays the eignvalues calculated of the system with and without H_∞ controller.

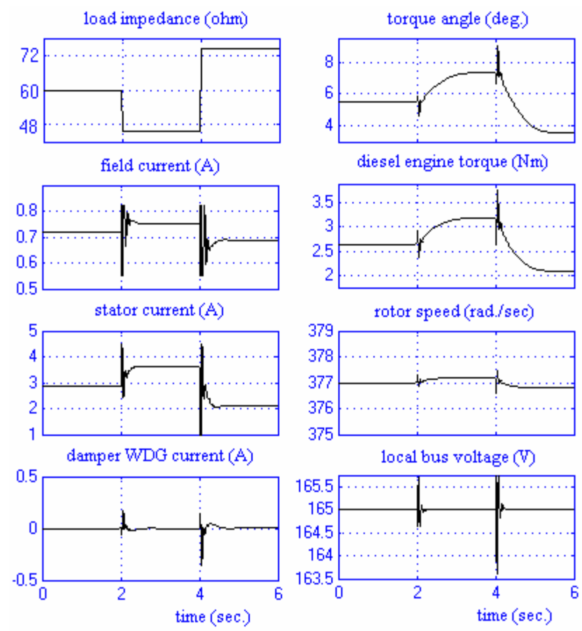

Fig. (7): Dynamic response of the proposed system due to step change in load impedance with H_∞ controller.

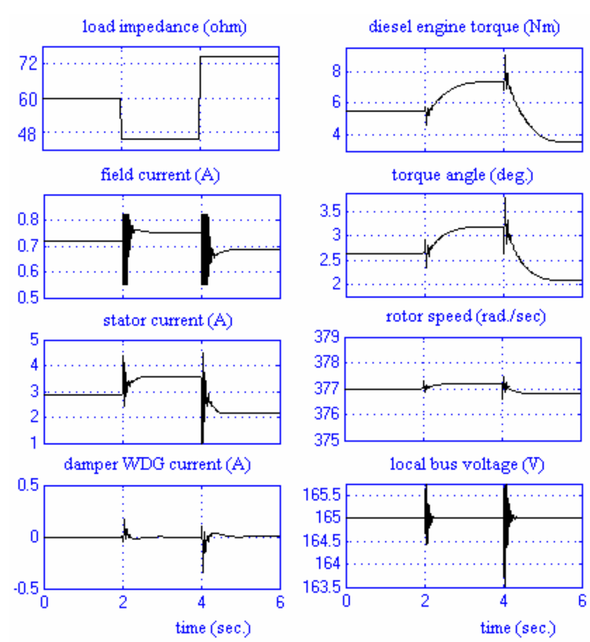

Fig. (8): Dynamic response of the proposed system due to step change in load impedance at parameters changes with H_∞ controller.

Table 1: Eignvalues calculation after and before H_∞ controller.

Operating conditions	Eignvalues without controller	Eignvalues with H_∞ controller
rmal load	-20303 70.442 + 123.85i 70.442 - 123.85i -144.06 -87.431 3.0971 + 25.775i 3.0971 - 25.775i 1.2658 5.1492e-013 -4.5537e-015 0 1.2911e+005	-0.01 , -5000 -5.4578 ,-2.6667 -900 , -1500 -5000 , -4139.5 -36.799 ± 984.01i -153.28 ± 1003i -68.036 ± 615.12i -68.014 ± 615.1i -900 , -630.63 -630.63 , -573.66 -300.02 , -112.87 ± 112.39i -112.74 ± 112.29i -85.524 ± 74.948i -35.066 , -23.669 -9.8668 -4.3708 ± 5.3745i -2.6327 -0.99516 ± 0.38064i -0.067154
parameters changes	-19206 63.909 + 112.53i 63.909 - 112.53i -130.98 -39.234 5.4977 + 21.104i 5.4977 - 21.104i 1.2658 3.5287e-013 -1.1779e-014 0 2.3462e+005	0.01 , -5000 -5.4578 , -2.6667 -900 , -1500 -5000 , -4139.5 -36.69 ± 780.38i -46.249 ± 752.26i -963.77 , -900.01 -622.26 , -622.26 -1.0826 ± 364.15i -1.9467 ± 364.17i -300.01 -67.332 ± 108.87i -103.85 ± 95.027i -103.75 ± 94.9i -42.683 , -23.709 -9.3329 -3.7097 ± 4.1993i -2.5505 -1.013 ± 0.31359i -0.10503

7. Conclusions

This paper proposes the application of H_∞ synthesis to design a robust controller for regulating the voltage and frequency of an isolated diesel-generation system. The controlled system consists of a diesel turbine that drives a synchronous generator connected to an isolated load and the synchronous generator is equipped with an automatic voltage regulator (AVR) and a static exciter. The terminal voltage is regulated via controlling the field current. Also, the rotor speed is adjusted by controlling the diesel fuel flow rate φ_r which in turn affects the torque (mechanical power) input to the synchronous generator and hence its rotation speed. The complete nonlinear dynamic model of the system has been described and linearized around an operating point. Also, the design problem of the H_∞ controller has been formulated in a standard form with emphasis on the selection of the weighting functions that reflect robustness and performance goals. The proposed control strategy has many advantages like robustness to plant uncertainties, simple implementation, and fast response.

Digital simulations have been carried out in order to evaluate the effectiveness of the proposed scheme. The diesel energy system with the proposed controller has been tested through step changes in load impedance. The results proved that good dynamic performance and high robustness in face of uncertainties can be achieved by means of the proposed controller.

8. References

[1] A. Abdin and X. Wilson, " *Control design and dynamic performance analysis of a wind turbine-induction generator unit*", IEEE Trans. On Energy Conversion, Vol. 15, No. 1, March, 2000, p 91-96.

[2] E. Suarez, and G. Bortolotto," *Voltage – Frequency control of a self excited induction generator*", IEEE Trans. on Energy Conversion, Vol. 14, No.3, Sept. 1999, p. 394-401.

[3] Felix, R.A.; Sanchez, E.N.; Loukianov, A.G., "*Synchronous generator control combining sliding modes and neural networks*". American Control Conference, Vo. 5, Issue 4-6, June 2003, p. 4065-4070.

[4] M. G. Simoes, B. K. Bose, and R. J. Spiegel, " *Design and performance evaluation of a fuzzy-logic based variable speed wind generation system*", IEEE Trans. on Industrial Applications, Vol. 33, No. 4, p..956-964, July/August 1997.

[5] A. A. Hassan, Y. S. Mohamed, Ali M. Yousef, and Ahmed. M. Kassem, "*Robust Control of a Wind Driven Induction Generator Connected to the Utility Grid*" , Journal of the Engineering Sciences, Assiut University, Vol. 34, No. 1, Jan 2006, p.107-121.

[6] Chedid, R.B., Karaki, S.H. and El-Chamali, C., "*Adaptive fuzzy control for wind-diesel weak power systems*". IEEE Trans. on Energy conversion, Mar 2000.

[7] A. A. Hassan, Y. S. Mohamed and Ahmed. M. Kassem," *A neural voltage regulator for a wind driven self excited induction generator*", MEPCON'2003, IEEE, Shebin EL-Kom, , 9th international Middel-East Power Systems Conference, Dec. 16-18, 2003, p. 691-699,.

[8] M. Bouhamida , A. Mokhtari and M. A. Denai, "*Power System Stabilizer Design Based on Robust Control Techniques*". ACSE Journal, Volume 5, Issue 3, Nov 2005, p. 33-41.

[9] Ali M. Yousef and Amer Abdel-Fatah " *A robust H_∞ Synthesis Controller For Power System Stabilization*" Automatic Control and System Engineering (ACSE) journal, ISSN 1687-4811, volume 05, Issue 2, 2005, p. 1-6.

[10] Kwakernaak H., "*A polynomial approach to H_∞ optimization of control systems in Modeling, Robustness and Sensitivity Reduction*". Ruth F.Curtain, Springer: Berlin, 1986, p.83-94.

[11] Grimble M.J., "*New direction in adaptive control theory and applications*". IFAC-IFIP-IMACS Conf., Control of industrial systems, Belfort, France, 1997, p. 95-110.

[12] "*MATLAB Math Library User's Guide*", by the Math Works. Inc., 2006.

[13] R. M. Hilloowala "*Control and interface of renewable energy systems*". Ph.D. Thesis, The University of New Brunswick, Canada, 1992.

9. Appendix

The elements a_{ij} of the 12 x 12 matrix A are :

$$a_{13} = \frac{R'_{kq} L_{mq}}{\left(L'_{kq} L_q - L^2_{mq}\right)},$$

$$a_{11} = a_{12} = a_{14} = a_{15} = a_{16} = a_{17} = a_{18} = a_{19} = a_{110} = a_{111} = a_{112} = 0$$

$$a_{21} = a_{22} = a_{23} = a_{26} = a_{27} = a_{29} = a_{210} = a_{211} = a_{212} = 0 \quad ,$$

$$a_{24} = \frac{K_{22} R'_{kd} L'_f + K_{33} R'_{kd} L_{md}}{K_{11}},$$

$$a_{25} = \frac{-R'_f (K_{22} L_{md} + K_{33} L'_{kd}\}}{K_{11}}, \quad a_{28} = \frac{K_{22} L_{md} L'_f + K_{33} L'_{kd}}{K_{11}}$$

$$a_{31} = a_{32} = a_{34} = a_{35} = a_{36} = a_{37} = a_{38} = a_{39} = a_{310} = a_{311} = a_{312} = 0 \quad ,$$

$$a_{33} = \frac{-R'_{kq}}{L'_{kq}} - \frac{K_{44} R'_{kq} L_{mq}}{L'_{kq}}$$

$$a_{41} = a_{42} = a_{43} = a_{46} = a_{47} = a_{49} = a_{410} = a_{411} = a_{412} = 0,$$

$$a_{44} = \frac{K_{22}\left(L_{md} - L'_f\right)\left(K_{22} L'_f R'_{kd} + K_{33} L_{md} R'_{kd}\right)}{K_{11}} + \frac{K_{22} L'_f R'_{kd}}{L_{md}} \quad ,$$

$$a_{45} = \frac{-K_{22} R'_f \left(L_{md} - L'_f\right)}{K_{11}}\left(K_{22} L_{md} R'_{kd} + K_{33} L'_{kd}\right) - K_{22} R'_f,$$

$$a_{48} = \frac{K_{22}\left(L_{md} - L'_f\right)}{K_{11}}\left(K_{22} L_{md} R'_{kd} + K_{33} L'_{kd}\right) + K_{22}$$

$$a_{51} = a_{52} = a_{53} = a_{56} = a_{57} = a_{59} = a_{510} = a_{511} = a_{512} = 0,$$

$$a_{54} = \frac{L'_{kd} k_{33}}{L_{md} k_{11} k_{55}}\left(k_{22} L'_f R'_{kd} + k_{33} L_{md} R'_{kd}\right) + k_{33} R'_{kd}$$

$$a_{1211} = \frac{4}{\tau_1}, \quad a_{1212} = \frac{2}{\tau_1}$$

$$a_{55} = \frac{L'_{kd} k_{33}}{L_{md}}\left(\frac{-R'_f \left(k_{22} L_{md} + k_{33} L'_{kd}\right) R'_{kd}}{k_{11} K_{55}} - R'_f\right),$$

$$a_{58} = \frac{L'_{kd} k_{33}}{L_{md}}\left(1 + \frac{1}{k_{11} k_{55}}\left(k_{22} L'_f R'_{kd} + k_{33} L_{md} R'_{kd}\right)\right),$$

$$a_{67} = a_{68} = a_{69} = a_{610} = 0$$

$$a_{61} = \frac{-3 p_o^2}{8J}\left(L_{md}\left(-i^r_d + i^r_f + i^r_{kd}\right) + L_{mq} i^r_d\right),$$

$$a_{62} = \frac{-3 p_o^2}{8J}\left(-L_{md} i^r_q - L_{mq}\left(-i^r_q + i^r_{kq}\right)\right), \quad a_{63} = \frac{3 p_o^2 L_{mq} i^r_d}{8J}$$

$$a_{64} = \frac{-3 p_o^2 L_{md} i^r_q}{8J}, \quad a_{65} = \frac{-3 p_o^2 L_{md} i^r_q}{8J}, \quad a_{66} = \frac{-\beta}{J}, \quad ,$$

$$a_{611} = \frac{-p_o k_1}{2J}, \quad a_{612} = \frac{p_o k_1}{2J},$$

$$a_{71} = a_{72} = a_{73} = a_{74} = a_{75} = a_{77} = a_{78} = a_{79} = a_{710} = a_{711} = a_{312} = 0, \quad a_{76} = \frac{2}{p_o},$$

$$a_{88} = \frac{-1}{\tau_e}, \quad a_{89} = \frac{k_e}{\tau_e},$$

$$a_{81} = a_{82} = a_{83} = a_{84} = a_{85} = a_{86} = a_{87} = a_{810} = a_{811} = a_{812} = 0$$

$$a_{91} = -R_L \cos(\delta) + \omega_e L_L \sin(\delta),$$

$$a_{92} = -R_L \sin(\delta) - \omega_e L_L \cos(\delta),$$

$$a_{97} = -R_L\left(-i^r_q \sin(\delta) + i^r_d \cos(\delta)\right) - \omega_e L_L\left(-i^r_q \cos(\delta) - i^r_d \sin(\delta)\right)$$

$$, \quad a_{93} = a_{94} = a_{95} = a_{96} = a_{98} = a_{99} = a_{910} = a_{911} = a_{912} = 0$$

$$a_{101} = a_{102} = a_{103} = a_{104} = a_{105} = a_{107} = a_{108} = a_{109} = a_{1010} = a_{1011} = a_{1012} = 0 \quad ,$$

$$a_{106=-1}$$

$$a_{1101} = a_{1102} = a_{1103} = a_{104} = a_{1105} = a_{1106} = a_{1107} = a_{1108} = a_{1109} = a_{1112} = 0 \quad ,$$

$$a_{1110} = \frac{k_2}{\tau_2}, \quad a_{1110} = \frac{-1}{\tau_2} \quad ,$$

$$a_{1201} = a_{1202} = a_{1203} = a_{124} = a_{1205} = a_{1206} = a_{1207} = a_{1208} = a_{1209} = a_{1210} = 0 \quad ,$$