Robust Compensating Function Scheme for Adequate Electrical Power System Stabilization

Michael Macmammah[1*], J. Atuchukwu[1], C. I. Obinwa[1]
and Chukwudi E. Agbaraji[2]

[1]*Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria.*
[2]*Federal Polytechnic Nekede, Owerri, Nigeria.*

Authors' contributions

This work was carried out in collaboration among all authors. Author MM designed the study, performed the simulation and wrote the first draft of the manuscript. Authors JA, CIO and CEA managed the analyses of the study. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

This work centers on robust compensating function scheme for adequate electrical power system stabilization. There has been high level of disturbances in the power line and lack of adequate compensation technique to cancel the effects of the resultant instability which has caused power failures. The problem was addressed by the consideration of disturbances in the power line during the design of the compensating function for the improvement of the power system performance and stability. H-Infinity synthesis robust compensating function design method was used to design an adequate compensator that can improve the performance and stability of the power system. From the results, the H-infinity Synthesis Controlled Generating Plant (HCGP) recorded an overshoot of 0%, settling time of 1.04 seconds, tracking error of 0dB, gain margin of 21.7dB and phase margin of 79.6 degrees. The simulation was repeated by varying the value to k to -0.3, and the generating plant produced same results. This shows that the system can maintain performance and stability equilibrium even when there is change in its parameters. Since the HCGP satisfied the performance and stability robustness, therefore it was concluded that power system robust compensating function scheme for improved performance and stability robustness was achieved using H-Infinity synthesis method.

_____

Corresponding author: E-mail: wattchux@gmail.com;

1. INTRODUCTION

Power instability occurs as a result of the imbalance in the power system between the power supplied and power consumed which is caused by line faults, power losses, loads etc. When the disturbance is small and last for few seconds, it could be taken care of by some devices such as the tap-changer, reactors, PSSs, governors etc. But when the disturbance is large and last for a longer time, it affects the generator and could cause the generator to trip. When one generator goes off it triggers more power imbalance into the network. These stability challenges are categorized in many studies as steady-state and transient stability issues. Steady-state stability, which is also known as small-signal stability is an electric power system challenge which involves small changes or disturbances such as load variations and adjustment of generation schedules. Transient stability concerns severe disturbances of the system such as short-circuit faults and substation outage. Oscillations of small magnitude and low frequency linked with the electromechanical modes in power systems often persist for long periods of time, and in some cases, present limitations on the power transfer capability. In addition, such oscillations may sustain and grow to cause system separation if adequate damping is not available [1].

Sustainable balance between electricity generation and load demand varies and greatly needed in the power systems control [2]. In the power systems, interconnection generator is supported by the main loop control with Automatic Voltage Regulator (AVR) that regulates the voltage by controlling the excitation. The high-performance controller excitation for providing rapid control of terminal voltage is necessarily to maintain the steady state, dynamic, and transient stability of synchronous generators in the modern power systems. Additional control loop signal to the AVR for excitation control is provided by power system stabilizer (PSS). AVR-PSS excitation control configuration has a primary objective to provide damping and voltage regulation [3]. Due to rapid increase in the complexity of power line as a result of increase in load connections, there is need for a robust damping technique that can address the increasing instability issues in the system. Robust control deals explicitly with uncertainty in its approach to controller design, aiming to achieve robust performance and stability in the presence of modeling errors and disturbances [4]. System controllers designed using robust control methods tend to be able to cope with the disturbances or imbalances in order to ensure the system stability. In this work the H-infinity synthesis is applied for the development of a robust compensator for the power system stability control. This approach makes use of weights to achieve desired robustness and performance characteristics through loop shape for the compensator design.

2. LITERATURE REVIEW

2.1 Power System Stability

Instability in a power system is initiated by a disturbance in the system. Such a disturbance could be as an example that line impedance was changed due to an external cause. The behavior of the system after the disturbance depends on the intensity or capacity of the disturbance. A small disturbance results usually in small transient effect in the system which is quickly damped out, while a larger disturbance will excite larger oscillations. Stability is associated with the ability of a power system to decay oscillation and continue its operation in equilibrium without any major impacts for any of the consumers. However as the power system is a nonlinear system, system stability depends on the kind and magnitude of the disturbance. This distinguishes nonlinear systems from linear systems that can be classified as stable or unstable independent of the disturbance. Stability of a power system is strongly coupled to both the magnitude and character of the disturbance as well as to the initial operating point. The stability of a power system is the ability of the system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [5]. In order to achieve a better understanding of stability analyses of power system, it is important to classify possible power system stability. The classification is based on the physical mechanism being the main driving force in the development of the associated instability. It could be either the active or the reactive power that is the important quantity. A common characteristic of the instabilities is that

they originate from large imbalance of active or reactive power in the system, locally or globally. This imbalance of power can then develop in different ways and cause unstable behavior depending on system characteristics.

2.1.1 Rotor angular or synchronous stability

The total active electrical power fed into the power system by the generating plants is meant to be equal to the active power consumed by the loads including the losses in the system. However, in practice, there is not always a similar balance between the loads and the power fed into the generators by the prime movers, e.g. the hydro and steam turbines. If such an imbalance develops the rotating parts of the generators, and other rotating machines, will act as energy buffer, and the kinetic energy stored in these will decrease or increase as a result of the imbalance. Rotor angle stability is referred to as the ability of synchronous machines of a power system to remain in synchronism after a disturbance. If the disturbance is local and significant, e.g. an earth fault close to the generator, the generator can fall out of step since it has been accelerated during the fault. A huge amount of currents will flow in the generator windings; in such a case the generator must be disconnected to prevent it from damaging. Typical time scale for such instability to develop can be in a second to a couple of seconds. This type of instability is called transient instability, and, such instability is usually in form of aperiodic angular separation due to lack of synchronizing torque. This form of instability is also referred to as large-disturbance [6] rotor angle instability. Small-disturbance (or small-signal) rotor angle stability is concerned with the ability of the power system to maintain synchronism under small disturbances. These disturbances are considered to be sufficiently small that linearization of the system equations is permissible for purposes of analysis. Usually small-disturbance rotor angle stability is associated with inadequate damping of low frequency oscillations in the power system.

2.1.2 Frequency stability

Another important type of active power imbalance is when the imbalance is not local but global which is the case of frequency stability. In such case if the sum of active power infeed is enough there may be an imbalance locally. But if the total power fed into the system by the prime movers is less than what is consumed by the

loads, including losses, this imbalance will influence the frequency of the whole system. As a result, the kinetic energy stored in rotating parts of the synchronous machines, and other rotating electrical machines, will compensate for the imbalance resulting in a frequency deviation. If the imbalance is not too large, the generators participating in the frequency control will regulate the active power input from their prime movers and bring back the frequency deviation to acceptable values. If the imbalance is very large, the frequency deviation will be significant with possible serious consequences. Particularly thermal power plants are sensitive to large frequency drops of long durations, since detrimental oscillations could be excited in the turbines. As a last resort the generators are disconnected, making the situation even more serious. This type of instability is called frequency instability and the time scale could be from a few seconds up to several minutes. Since the involved mechanisms could be quite different, it helps to distinguishes between short-term and long-term frequency instability in the system.

2.1.3 Voltage stability

In the case of reactive power balance the situation is not as clear and simple as it is in active power. There is always a balance between produced and consumed reactive power in every node of a network. This is a consequence of Kirchoff's first current law. Imbalance in this context means that the injected reactive power is normally too small, that the voltage in the node cannot be kept to acceptable values. At low load the injected reactive power could be high resulting in a too high voltage, possibly higher than the equipment might be designed for. This is not desirable but it is usually controlled in such a way that no instabilities develop. In this case the imbalance means that the injected reactive power differs from the desired injected reactive power, needed to keep the desired voltage. If this imbalance gets too high, the voltages become outside the acceptable range.

Reactive power is a more local quantity than active power since it cannot be transported as easily in power system. This explains why voltage problems often are local, and often only occur in part of the system. When the imbalances (voltage problems) develop into instabilities these are called voltage instabilities or voltage collapses [5]. The instability could later develop into very low voltages in the system. In

principle too high voltages can also occur at voltage instability. Low voltages arise at high load conditions, while high voltages are associated with low load conditions. Depending on the time scale the voltage instabilities are classified as short-term, a couple of seconds, or long-term, tens of seconds to minutes. The short-term voltage instability involves dynamics of fast acting components such as induction motors, electronically controlled loads and HVDC converters, while the long-term voltage instability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads and generator current limiters [5]. The classification of power system instabilities is summarized as follows in Fig. 1.

From the review, generators, i.e. the synchronous machines, are very important in angular instabilities, and it is sometimes said that these are the driving force in this instability. Also the analysis shows that the loads are very often the driving force when it comes to voltage instability, which consequently sometimes is called load instability. Since all instability problems (or disturbances) finally return to the generator and affect its function, therefore the control of the generator function becomes very important to enable it regain equilibrium in operation whenever the system goes off from balance due to these disturbances and also address the instability issue.

2.2 Power System Stabilization Methods

The transmission facilities in power systems provide equal medium for power evacuation to all participants at all times, ensure full capability and reliability at minimum technical loss and ensure equitable load allocation to consumers [7]. The power transferred through a transmission network is a function of transmission line impedance. Low transmission line impedance enables larger power flow while high impedance limits the flow of electricity [8]. Longitudinal transmission systems such as Nigerian transmission system have high impedance and are characterized by various steady-state operational problems such as congestion, high transmission line losses, voltage limit violations, loss of system stability and inability to utilize transmission line capacity up to their thermal limits [9]. In [7] it was opined that these problems have been reduced by reinforcement of generating station and transmission line; building new power plants and transmission lines as well as using traditional electromechanical devices. Also the use of reactors and tap-changers are

recorded in some of the Nigerian transmission stations. However, long construction time, high cost of implementation and regulatory pressure hinder the reinforcement of transmission lines and generation stations while low speeds, mechanical wear and tear, limit the use of electromechanical devices [7]. The reactors and tap-changers have been proved ineffective as the electrical power system becomes more complex and experiences higher level of disturbance.

In the generation sector of the national power supply, the generator output is usually decided by the turbine mechanical torque, which could be altered by excitation value transiently [10]. This alteration is associated with some disturbances in the form of power swing/oscillations that are usually unwanted. In interconnected large electric power systems, there have been always unwanted spontaneous system oscillations at very low frequencies in order of 0.2-2.0Hz [11]. There is need to damp the unwanted power swing by changing output power, controlling the excitation value and reducing the power oscillation in order to have a stable system. The stability of electrical power can most simply be defined as its ability to continue in a stable operation after some disturbances [10]. The emergence of Power System Stabilizer (PSS) brought some relief in power swing problems. Power utilities worldwide used PSS as effective excitation controllers to enhance the system stability [12]. However, there have been problems experienced with PSS over the years of operation worldwide. Some of these problems were due to the limited capability of PSS in damping only local modes of electromechanical oscillations. Furthermore, PSS can cause great variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing stability [13]. In [14] whale optimization algorithm was used to tune PID and PIDA controllers on AVR system and in [15] a robust PID-PSS was designed for an uncertain power system with simplified stability conditions. However, the stability margins (i.e., gain and phase margins) were not considered in their designs which make it difficult to ascertain the stability robustness of the systems.

3. METHODOLOGY

3.1 Generating Plant Model

The frequency of a power system is dependent on real power balance. A change in real power

demand at one point of a network is reflected throughout the system by a change in frequency. Therefore, system frequency provides a useful index to indicate system generation and load imbalance. Slight or short-term energy imbalance results to an instantaneous change in system frequency as the disturbance is initially offset by the kinetic energy of the rotating plant. Significant loss in the generation without an adequate system response can produce extreme frequency excursions outside the working range of the plant. The control of frequency and power generation is commonly referred to as load–frequency control (LFC) which is a major function of automatic generation control (AGC) systems [16]. Depending on the type of generation, the real power delivered by a generator is controlled by the mechanical power output of a prime mover such as a steam turbine, gas turbine, hydro-turbine or diesel engine. In the case of a steam or hydro-turbine, mechanical power is controlled by the opening or closing of valves regulating the input of steam or water flow into the turbine. Steam (or water) input to generators must be continuously regulated to match real power demand, failing which the machine speed will vary with consequent change in frequency [16]. For satisfactory operation of a power system, the frequency should remain nearly constant [17]. In addition to a primary frequency control, most large synchronous generators require a supplementary frequency control loop and some of them are equipped with it. A schematic block diagram of a synchronous generator equipped with frequency control loops is shown in Fig. 2.

Power systems are highly non-linear and time-varying in nature. However, for the purpose of frequency control synthesis and analysis in the presence of load disturbances, a simple low-order linearized model is used. A simplified frequency response model for the described schematic block diagram in Fig. 2 with one generator unit is described, and then the resulting model is generalized for an interconnected power system in Fig. 4. The overall generator–load dynamic relationship between the incremental mismatch power (ΔPm−ΔPL) and the frequency deviation (Δf) can be expressed as [16]:

$$\Delta P_m(t) - \Delta P_L(t) = 2H\frac{d\Delta f(t)}{dt} + D\Delta f(t) \quad (1)$$

Where $\Delta f(t)$ is the frequency deviation, ΔP_m is the mechanical power change, ΔP_L the load change, H is the inertia constant and D is the load damping coefficient.

Equation 1 helped to achieve the generating plant block diagram model for the generating plant and also helps to study the relationship between the mechanical power change and the load change with the damping coefficient. The damping coefficient is usually expressed as a percent change in load for a 1% change in frequency. Using the Laplace transform, equation 1 can be written as [16]:

$$\Delta P_m(s) - \Delta P_L(s) = 2Hs\Delta f(s) + D\Delta f(s) \quad (2)$$

Equation (2) can be represented in a block diagram as in Fig. 2. That is, a block diagram representation for a non-reheat steam generator unit with associated frequency control loops (LFC system) comprising turbine, generator, governor, supplementary control and load.

The rotating mass is the rotating shaft and generator. In order to simplify the model for control and analysis purposes, Fig. 3 can be reduced to the diagram shown in Fig. 4.

Where $M_0 = \frac{1}{R}$, $G_0 = \frac{1}{1+sT_g}$, $T_0 = \frac{1}{1+sT_t}$, $L_0 = \frac{1}{D+2Hs}$

The transfer function of the generating plant system model can be expressed as follows:

$$G(s) = \frac{kG_0T_0L_0}{1+G_0T_0L_0M_0} \quad (3)$$

The electrical power generating plant analysis and compensator development simulations were carried out using the plant parameter data values as stated in the Table 1.

Table 1. Simulation data [16]

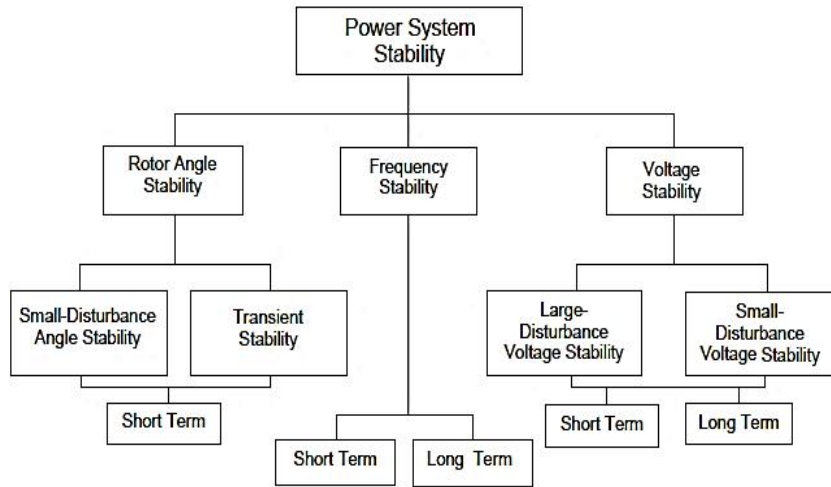| Proportional Controller Gain, k(s)	Load damping coefficient, D	Inertia constant, H	Primary control Loop gain, R	Governor time constant, $T_g(s)$	Turbine time constant, $T_t(s)$
-0.3	0.015	0.08335	3.00	0.08	0.4

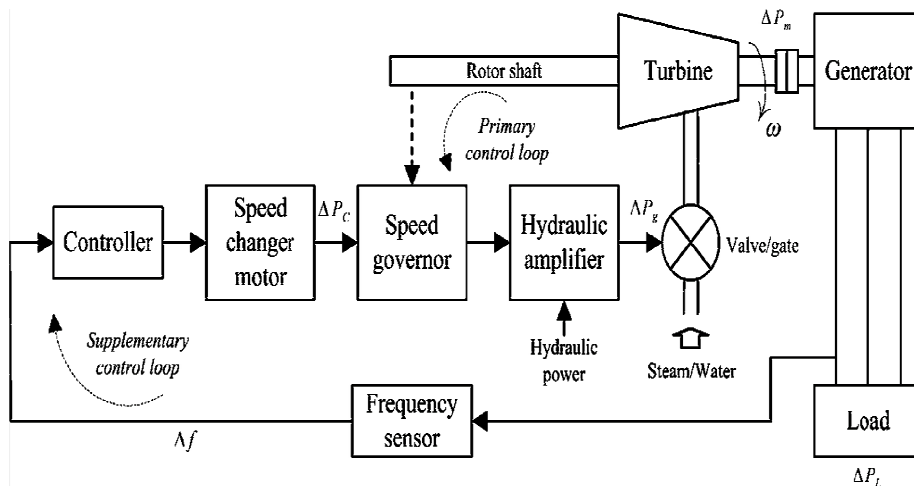**Fig. 1. Connection between Instabilities and system components [5]**

Fig. 2. Schematic block diagram of a synchronous generator [16]
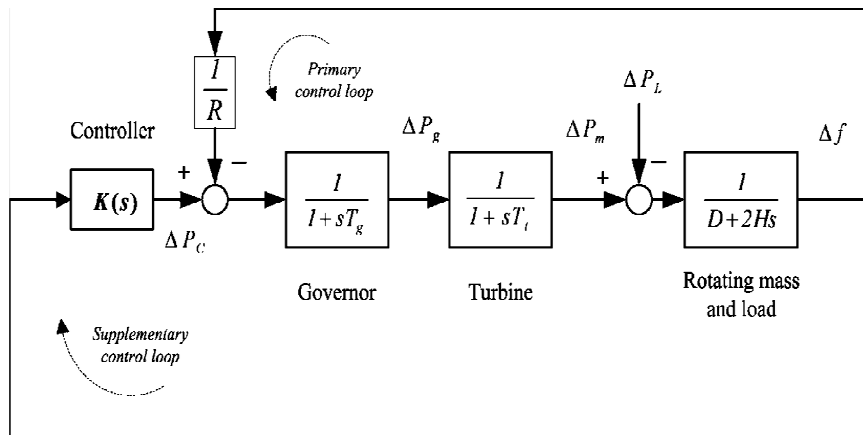

Fig. 3. Block diagram model a non-reheat steam generator unit [16]

3.2 Robust Compensating Function Scheme for the Generating Plant

Due to the presence of uncertainties in the generating plant as a physical system, the output is termed disturbed output or actual output. This means that the output must be affected by the disturbances and noise introduced into the system. This problem can be solved by the development of the robust controller with reduced sensitivity to disturbances, reduced reference tracking error and improved stability of the system. The compensator development objectives here are to select the controller gains in such a way that the generating plant output "tracks" the desired output or the reference input. The issue becomes the application of a method with which the controller gains that can make the plant robust in order to achieve the development objectives can be achieved. Considering the power generating plant in a real environment in Fig. 5, with uncertainties, the inputs to the system becomes the reference input r, and uncertainty inputs: the disturbance D, and feedback sensor noise N.

The general transfer function of the feedback controlled system in a real environment is represented as follows [4,18]:

$$Y(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)}(R(s) - N(s)) + \frac{1}{1+G_c(s)G_p(s)}D(s) \quad (4)$$

$$E(s) = \frac{1}{1+G_c(s)G_p(s)}(R(s) - D(s) + N(s)) \quad (5)$$

From equation 4, the following functions are derived

$$T(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)}, \ S(s) = \frac{1}{1+G_c(s)G_p(s)}, \ L(s) = G_c(s)G_p(s)$$

T(s) is the complementary sensitivity function. S(s) is the Sensitivity function. L(s) is the open loop function. The robust compensator development objective becomes, to find the compensating function Gc, that can optimize the system output responds to satisfy the robustness specifications. This was achieved using H-Infinity synthesis method.

4. RESULTS AND DISCUSSION

4.1 Existing Generating Plant Analysis Results

Applying the generating plant model parameters and carrying out the computation and simulation in MATLAB, the following results were obtained.
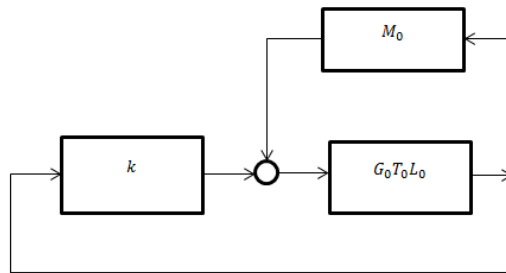

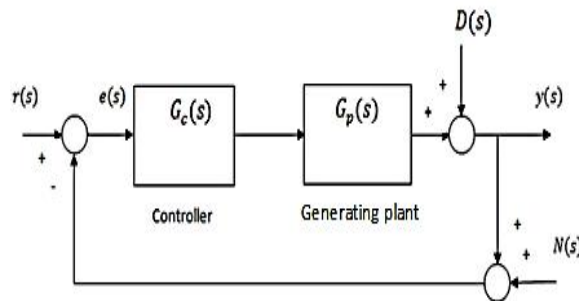**Fig. 4. Reduced generating system model with primary control loop**

Fig. 5. Control system with disturbance and noise inputs in real environment

The results in Figs 6 and 7 show that the overshoot was very high and the settling time was also high also, which means it will take the system a long time to settle if there occurs a small disturbance. Low gain margin and negative phase margin indicates that the power system is slightly stable.

4.2 Robust Compensating Function Scheme Analysis Results

Applying the H-Infinity synthesis method on the existing generator model, the compensator Gc was developed and presented in state space equations as follows:

$$A = \begin{bmatrix} -1960 & -6566 & -19580 & -43180 & -41640 & -7147 & -36590 \\ 16 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0 & 0 \\ 0 & 0 & -1.11e-16 & -4.441e-16 & 4.441e-16 & -1.11e-16 & -0.01 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 3.519 \end{bmatrix}$$

$$C = [-1097 \quad -3721 \quad -1.113e+04 \quad -2.454e+04 \quad -2.366e+04 \quad -4062 \quad -2.08e+04]$$

$$D = [0]$$

The results in Figs.. 8, 9 and 10 show that H-Infinity Controlled Generating Plant (HCGP) achieved better performance with overshoot of 0% and settling time of 1.04 seconds than that of the existing system that achieved overshoot of 18.1% and settling time of 3.75seconds. The HCGP achieved robust stability with gain margin of 21.7dB and phase margin of 79.6deg than the existing system that achieved marginal stability with gain margin of 1.3dB and phase margin of -79.5deg.
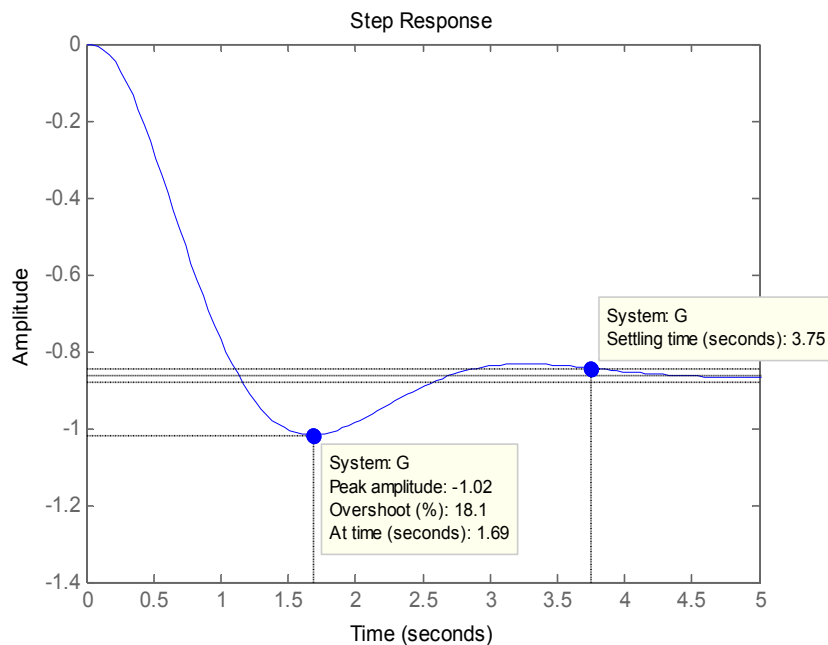

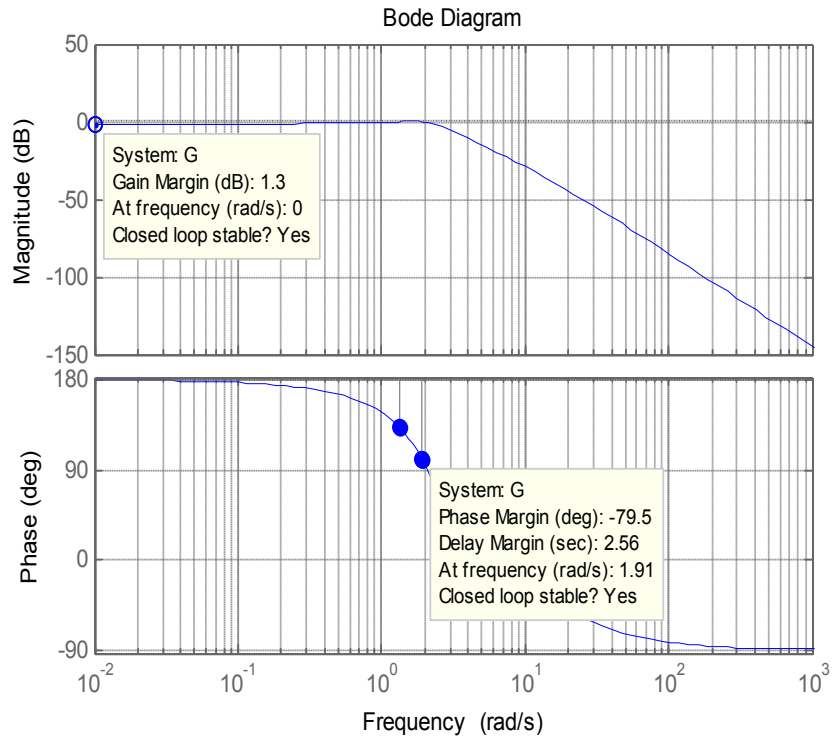**Fig. 6. Step function graph for generating plant**
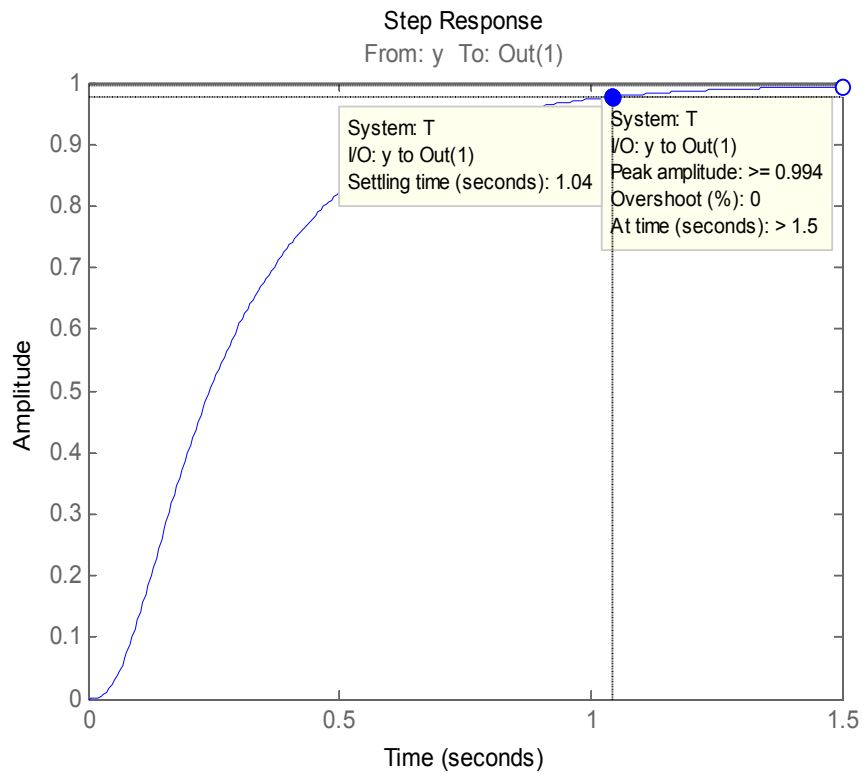
87

Fig. 7. Bode plot of the generating plant

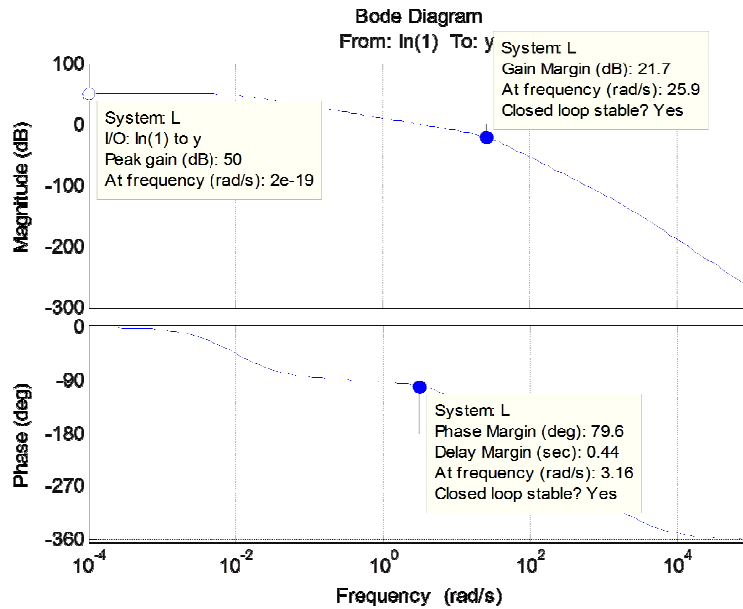

Fig. 8. Step function response of the HCGP

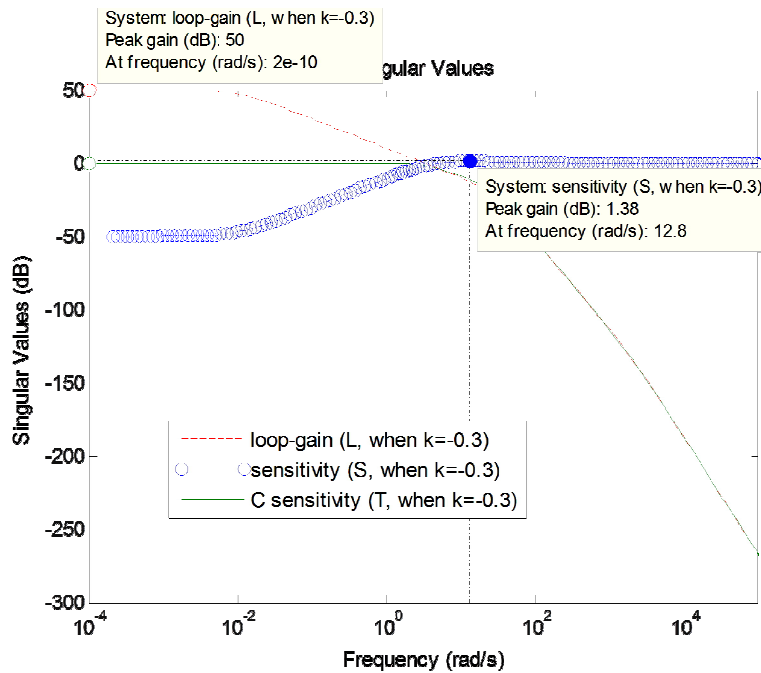**Fig. 9. Bode plot of the HCGP**

Fig. 10. Sigma plot of the HCGP

5. CONCLUSION

The existing generating plant was analyzed based on its model parameters for performance and stability and it recorded an overshoot of 18.1%, settling time of 3.75 seconds, gain margin of 1.3dB, and phase margin of -79.5degrees. These show that the generating plant performance was very poor and marginally stable. Hence it requires an adequate compensating function to operate well in a high disturbance prone grid like the national power system.

In order to achieve this, H-infinity synthesis controller development method was used to develop a robust compensator which can help the system to achieve performance and stability robustness characteristics. From the results, the H-infinity synthesis controlled generating plant recorded an overshoot of 0%, settling time of 1.04 seconds, tracking error of 0dB, gain margin of 21.7dB and phase margin of 79.6 degrees. The simulation was repeated by varying the value to k to -0.3, and the generating plant produced same results. This shows that the system can maintain performance and stability equilibrium even when its gain parameter was varied. Since the HCGP satisfied the performance and stability robustness, therefore it was concluded that power system robust compensation for improved performance and stability robustness was achieved using H-Infinity synthesis method. This means that the developed HCGP provides adequate damping than the existing power generating plant.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Awadallah MA, Soliman HM. A Neuro-fuzzy Adaptive Power System Stabilizer Using Genetic Algorithms, Electric Power Components and Systems. 2009;37:158–173.

2. Manuaba IBG, Abdillah M, Priyadi A, Purnomo M.H. Coordination Tuning PID-PSS and TCSC Based Model of Single Machine Infinite-Bus Using Combination Bacteria Foraging-Particle Swam Optimization Method, Control and Intelligent Systems; 2015.

3. Oonsivilai A, Marungsri B. Stability enhancement for multi-machine power system by optimal PID tuning of power system stabilizer using particle swarm optimization, WSEAS Transactions on Power Systems. 2008;3:465–474.

4. Agbaraji CE. Robustness Analysis of a Closed-loop Controller for a Robot Manipulator in Real Environments, Physical Science International Journal. 2015;8(3):1-11.

5. Smith M. Electric Power System Modeling & Simulation; 2010.

Available:https://www.cs.nmt.edu/~jholten/ ModelingAndSimulation/lectures/9b_EP_S ystem_Modeling.pdf

6. Anderson PM, Fouad AA. Power System Control and Stability, Iowa State University Press, Ames, Iowa; 1977.

7. Adepoju GA, Sanusi MA, Tijani MA. Application Of SSSC to the 330KV Nigerian Transmission Network for Voltage Control, Nigerian Journal of Technology (NIJOTECH). 2017;36(4):1258 – 1264.

8. Vakula P. Study the Power Flow Control of a Power System with Unified Power Flow Controller, Unpublish Master Thesis Submitted to California State University, Sacramento; 2010.

9. Bada ASA. Transmission Evacuation and Constraints, at National Power Sector Retreat Abuja, Nigeria; 2012.

10. Ambafi JG, Nwohu MN, Ohize HO, Tola OJ. Performance Evaluation of PSS and STATCOM on Oscillation Damping of a North-Central Power Network of Nigeria Grid System, International Journal of Engineering and Technology. 2012;2(2):209-219.

11. Kundur P. Power System Stability and Control, McGraw Hill, New York. 1994;817-822.

12. Abido MA. Power System Stability Enhancement Using Facts Controllers: A Review, the Arabian Journal for Science and Engineering. 2009;34(1B):153-171.

13. Eriksson R. Security-Centred coordinated Control in AC/DC Transmission Systems, Master thesis, TRITA-EE. 2008;034.

14. Mosaad AM, Attia MA, Abdelaziz AY. Whale Optimization Algorithm to Tune PID and PIDA Controllers on AVR System, Ain Shams Engineering Journal. 2019;10:755-767.

15. Lakshmi ASVV, Manyala RR, Mangipudi SK. Design of a robust PID-PSS for an Uncertain Power System with Simplified Stability Conditions, Protection and Control of Modern Power Systems. 2020;5(20):1-16.

16. Bevrani H. Robust Power System Frequency Control, Springer Science+Business Media, LLC; 2009.

17. Nagsarkar TK, Sukhija MS. Power System analysis, New Delhi: Oxford University Press; 2007.

18. Agbaraji CE, Udeani UH, Inyiama HC, Okezie CC. Robust Control for a 3DOF

Articulated Robotic Manipulator Joint Torque under Uncertainties, Journal of Engineering Research and Reports. 2020;9(4):1-13.