

A New Design of Robust H_∞ Load-Frequency Controller for Optimal Coordination of Energy Generation in Power System Stability Using LMI Approach

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Abstract

This paper presents the problem of robust H_∞ load frequency controller design and robust H_∞ based approach called advanced frequency control (AFC). The objective is to split the task of balancing frequency deviations introduced by renewable energy source (RES) and load variations according to the capabilities of storage and generators. The problem we address is to design an output feedback controller such that, all admissible parameter uncertainties, the closed-loop system satisfies not only the prespecified H_∞ norm constraint on the transfer function from the disturbance input to the system output. The conventional generators mainly balance the low-frequency components and load variations while the energy storage devices compensate the high-frequency components. In order to enable the controller design for storage devices located at buses with no generators, a model for the frequency at such a bus is developed. Then, AFC controllers are synthesized through decentralized static output feedback to reduce the complexity. The conditions for the existence of desired controllers are derived in terms of a linear matrix inequality (LMI) algorithm is improved. From the simulation results, the system responses with the proposed controller are the best transient responses.

Keywords

Optimal Coordination, Robust H_∞ Controller, Load Frequency Control, LMI Approach

1. Introduction

In power systems, frequency deviations from the nominal value indicate the imbalance between active power supply and consumption. Large unattended frequency deviations could impede the performance of generating units by influencing the performance of their auxiliary electric motor drives and even lead. The control relies on

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generating units equipped with local speed droop governors to fast stabilize the frequency while the centralized secondary control is an optimal coordination scheduling task involving economic dispatch and unit commitment programs. In this paper, we focus on the integration of storage into load frequency control (LFC). In this paper incorporates energy limits associated with energy storage and proposes a novel H^∞ and structure preserving approach called AFC to integrate energy storage into the framework of frequency control, the decentralized static output feedback and the iterative linear matrix inequality (ILMI) approach are adopted in AFC design.

However, there have recently been only a few reports that combine robust H^∞ load frequency controller for power systems with pole-clustering constraints not only to assure in robust stability, but also to improve better transient performance, are derived in terms of LMI in order to construct a desired controller [1].

2. Power System Model

The model of power flow control in **Figure 1**, considered here. The following simplifying assumptions are made: 1) the power network is represented by a DC power flow model; 2) since the variations in loads within the considered time frame are small compared with the RES disturbances, the loads are assumed to be constant during the small signal analysis, but the same control concept can be applied for load variations and 3) the conventional generators are assumed to be of non-reheat thermal type. In addition, following the general practice in power system analysis.

2.1. Conventional Generator

The considered model of the conventional generator is a fourth order governor-turbine-generator model including the dynamics of the speed governor and the turbine and is given by [2]

$$\begin{bmatrix} \Delta \dot{\omega} \\ \Delta \dot{\theta} \\ \Delta \dot{P}_m \\ \Delta \dot{Y} \end{bmatrix} = \begin{bmatrix} \frac{-k_D}{2H} & 0 & \frac{S_N}{2HS} & 0 \\ \omega_0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{T_{CH}} & \frac{1}{T_{CH}} \\ 0 & 0 & 0 & \frac{-1}{T_G} \end{bmatrix} \begin{bmatrix} \Delta \omega \\ \Delta \theta \\ \Delta P_m \\ \Delta Y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{T_G} \end{bmatrix} [\Delta P_G^{\text{ref}}] + \begin{bmatrix} \frac{-S_N}{2HS} \\ 0 \\ 0 \\ 0 \end{bmatrix} [\Delta P_e] \quad (1)$$

The parameters and variables in this model are: S_N is power network VA base, S is generator VA base, H is inertia constant based on S , ω is rotor speed, Δ is the deviation from operating point, θ is voltage angle in radians, P_m is mechanical power, P_e is electrical power, k_D is damping factor, T_{CH} is turbine time constant, Y is valve position point, T_G is governor time constant, ω_0 is nominal speed in rad/s. and P_G^{ref} is control input.

We denote the state space model (1) of the i th conventional generator in a compact form as

$$\dot{x}_{G,i} = A_{G,i}x_{G,i} + B_{G,i}u_{G,i} + E_{G,i}P_{e,i} \quad (2)$$

In conventional frequency control, the control input is set to $\Delta_G^{\text{ref}} = ((-S)/(S_N R))\Delta\omega + P_{AGC}$ where R is the speed droop coefficient Δ_G of primary control loop and P_{AGC} is the AGC signal of the secondary control loop.

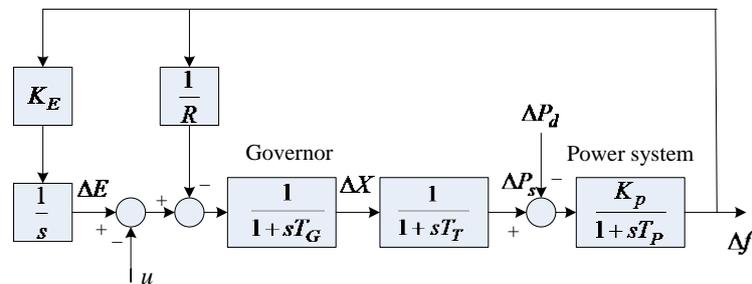


Figure 1. Block diagram of power system.

2.2. Energy Storage Device

The storage device consists of the actual storage and the power electronic inverter connecting the device to the grid. The model for the storage captures the relationship between charging/discharging power system, the energy level. The dynamics of the inverter can be modeled using a first order model with time constant T_s capturing the response of the inverter to the control signal. The model for the storage device results in the second order model given by

$$\begin{bmatrix} \Delta \text{SOC} \\ \Delta \dot{P}_s \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{E_{cap}} \\ 0 & \frac{-1}{T_s} \end{bmatrix} \begin{bmatrix} \Delta \text{SOC} \\ \Delta P_s \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{T_s} \end{bmatrix} \left[\Delta P_s^{\text{ref}} \right] \quad (3)$$

where the parameters and variables are; E_{cap} is energy capacity in p.u. [3], T_s is inverter time constant, Δ is the deviation from operating point, SOC is state of charge, P_s is storage power injection and P_s^{ref} is control input. The power injection ΔP_s can be changed instantaneously in the reduced order model resulting in

$$\left[\Delta \text{SOC} \right] = [0] \left[\Delta \text{SOC} \right] + \left[\frac{-1}{E_{cap}} \right] \left[\Delta P_s^{\text{ref}} \right] \quad (4)$$

2.3. Frequency at Load Buses

The challenge which arises in AFC design if the storage is placed at a non-generator bus is the local frequency is not part of the state variables in the traditional power system model.

$$\begin{bmatrix} \Delta P_G \\ \Delta P_L \end{bmatrix} = H \begin{bmatrix} \Delta \theta_G \\ \Delta \theta_L \end{bmatrix} \triangleq \begin{bmatrix} H_{GG} & H_{GL} \\ H_{LG} & H_{LL} \end{bmatrix} \begin{bmatrix} \Delta \theta_G \\ \Delta \theta_L \end{bmatrix} \quad (5)$$

where ΔP_G and ΔP_L are vectors for power injections at generator and non-generator buses; $\Delta \theta_G$ and $\Delta \theta_L$ are vectors for voltage angles at generator and non-generator buses; H is the bus admittance matrix.

3. Control Design

3.1. Design of H_∞ Controller via LMI Approach

The standard configuration of the H_∞ control problem is depicted in **Figure 2**, where $G(s)$ is the transfer function of the plant, $K(s)$ is the transfer function of the controller, ω is the exogenous input including disturbances, references and measurement noise, u is the control input, z is the performance vector, we want to minimize to satisfy the control objective and y is the measurement vector [3]-[5]

The corresponding state space model of the standard H_∞ control problem in **Figure 2** is given as

$$\dot{x} = Ax + B_1 w + B_2 u \quad (6)$$

$$z = C_1 x + D_{11} w + D_{12} u \quad (7)$$

$$y = C_2 x + D_{21} w + D_{22} u \quad (8)$$

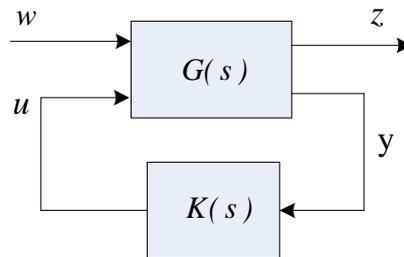


Figure 2. Close-loop system via H_∞ control.

where x is the vector of internal states of $G(s)$. The assumption $D_{22} = 0$ is typically made to simplify calculations without loss of generality. The objective of H_∞ control is to find the optimal stabilizing controller $K(s)$ that minimizes and the H_∞ norm of the transfer function from ω to z , which is defined as the peak of the maximum singular value control of the complex matrix $T_{zw}(j\omega)$ over all frequencies ω , that is

$$\|T_{zw}(s)\|_\infty \triangleq \sup_\omega \bar{\sigma}(T_{zw}(j\omega))$$

where $T_{zw}(s)$ is the closed-loop transfer function from ω to z . Consequently, H_∞ control gives a guaranteed bound on the performance vector z for any bounded exogenous input ω , for wind power with given maximal root-mean-square (RMS) variations the resulting control.

The specific design requirements and the focus of the exogenous input signals system, weighting functions are typically assigned to the performance vector and the exogenous input signals, the resulting weighted H_∞ control problem becomes [5]

$$\min_{K(s)} \|W_z(s)T_{zw}(s)W_w(s)\|_\infty \quad (9)$$

where $W_z(s)$, $W_w(s)$ are the matrix valued weighting functions for z and ω , respectively. The matrices allow defining the importance of the individual control.

3.2. H_∞ -Based AFC Controller Synthesis

The objectives of AFC design are to minimize the influence of RES variations on frequency deviations and the SOC deviations of the storage devices, and to achieve the frequency separation goal mentioned in Section 1 and the performance vector z in (7) is selected as

$$z = [\Delta\omega_1, \dots, \Delta\omega_{N_G}, \Delta SOC_1, \dots, \Delta SOC_{N_S}, \Delta P_{m,1}, \dots, \Delta P_{m,N_G}, \Delta P_{s,1}, \dots, \Delta P_{s,N_S}]^T \quad (10)$$

For each of the elements in the performance vector, a frequency dependent weighting function $W_{z(s)}$ as defined in (10). These weighting functions are design parameters and reflect the importance of each of the objectives along the frequency spectrum of the respective performance element. The weighting functions for the frequency deviations $\Delta\omega_i$ and the SOC deviations, ΔSOC_i are chosen to be constant values shown as follows:

$$W_{G,i}(s) = \frac{(10s + 20\pi f_c)^n}{m_{G,i}(s + 20\pi f_c)^n} \quad (11)$$

$$W_{S,i}(s) = \frac{(s + 2\pi f_c)^n}{m_{S,i}(s + 0.2\pi f_c)^n} \quad (12)$$

where f_c is the cut-off frequency in the frequency separation objective, n is the order of the weighting function [5], and $m_{G,i}$, $m_{S,i}$ are the participation factors of the i th generator, the i th storage device under AFC respectively. Hence, where $W_{G,i}(s)$ and storage device of $W_{S,i}(s)$ with design variables and the weighting function $W_z(s)$ in (9) is given by

$$W_z(s) = \text{diag}\{\eta_{G,1}, \dots, \eta_{G,N_G}, \eta_{S,1}, \dots, \eta_{S,N_S}, W_{G,1}(s), \dots, W_{G,N_G}(s), W_{S,1}(s), \dots, W_{S,N_S}(s)\} \quad (13)$$

where $\eta_{G,i}$ and $\eta_{S,i}$ are the constant weights values for $\Delta\omega_i$ and ΔSOC_i in the performance vector z .

4. Control System Results

4.1. Output Feedback Controller Design

Theorem 1 The design of system problem, we consider the following norm-bounded uncertain control systems in **Figure 1**. The uncertainties are described by

$$\begin{pmatrix} \Delta A & \Delta B_u & \Delta F_w \\ \Delta C & * & * \end{pmatrix} = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \Delta(t) (E \quad E_u \quad E_w) \quad (14)$$

where ΔC is assumed to be used in practice and $*$ are neglected, our approach for robust H_∞ controller with pole-clustering constraints is proposed [2].

We consider the system and desire to place all closed-loop poles of uncertain systems in $D(\alpha, r)$ region can be shown as follows:

$$\dot{x}_K(t) = A_K x_K(t) + B_{Ky}(t) \quad (15)$$

$$u(t) = C_K x_K(t) \quad (16)$$

where $x_K(t) \in \mathfrak{R}^{n_K \times n_K}$ is the state of the controller, and A_K , B_K and C_K are matrices with the appropriate dimensions. For a dynamic output feedback controller, we denote its transfer function as follows.

$$K(s) = C_K (sI - A_K)^{-1} B_K \quad (17)$$

Hence, the overall closed-loop system is given by:

$$\dot{x}_{cl}(t) = A_{cl}(\Delta) x_{cl}(t) + B_{cl}(\Delta) w(t) \quad (18)$$

$$y(t) = C_{cl}(\Delta) x_{cl}(t) \quad (19)$$

where

$$\begin{pmatrix} A_{cl}(\Delta) & B_{cl}(\Delta) \\ C_{cl}(\Delta) & * \end{pmatrix} = \begin{pmatrix} A_{cl} & B_{cl} \\ C_{cl} & * \end{pmatrix} + \bar{H}_1 \Delta (\bar{E} \quad E_x),$$

$$x_{cl}(t) = \begin{pmatrix} x(t) \\ x_K(t) \end{pmatrix}$$

$$A_{cl} = \begin{pmatrix} A & B_u C_K \\ B_K C & A_K \end{pmatrix}$$

$$\bar{H}_1 = \begin{pmatrix} H_1 \\ B_K H_2 \end{pmatrix}$$

$$\bar{E} = (E \quad E_u \quad C_K)$$

$$B_{cl} = \begin{pmatrix} F_w \\ 0 \end{pmatrix}$$

$$C_{cl} = (C \quad 0)$$

Theorem 2 As for the uncertain linear power system, the desired circular pole region of $D(\alpha, r)$ and the H_∞ norm bound constraint $\gamma > 0$ on the disturbance rejection are given. The closed-loop system can achieve the expected performance requirement 1 and 2, if and only if there exist $X, Y, \bar{A}, \bar{B}, \bar{C}$ and a scalar $\epsilon > 0$ such that [2]

$$\begin{pmatrix} \Omega_{11} & \Omega'_{21} & \Omega'_{31} & \Omega'_{41} & 0 & \Omega'_{51} & \Omega'_{61} & 0 \\ \Omega_{21} & \Omega_{22} & 0 & 0 & 0 & 0 & 0 & \Omega'_{61} \\ \Omega_{31} & 0 & -I & 0 & 0 & 0 & 0 & 0 \\ \Omega_{41} & 0 & 0 & -\gamma^2 I & \sqrt{\alpha} E'_w & 0 & 0 & 0 \\ 0 & 0 & 0 & \sqrt{\alpha} E_w & -\epsilon I & 0 & 0 & 0 \\ \Omega_{51} & 0 & 0 & 0 & 0 & -\epsilon I & 0 & 0 \\ \Omega_{61} & 0 & 0 & 0 & 0 & 0 & -\epsilon I & 0 \\ 0 & \Omega'_{61} & 0 & 0 & 0 & 0 & 0 & -\epsilon I \end{pmatrix} < 0 \quad (20)$$

where X and Y are variables of arbitrary nonsingular matrices satisfying $M'N = I - XY$.

where

$$\begin{aligned}\Omega_{11} &= -\begin{pmatrix} r^2 X & r^2 I \\ r^2 I & r^2 Y \end{pmatrix}, \\ \Omega_{21} &= \begin{pmatrix} AX + \bar{B}C + \alpha X & A + \alpha I \\ \bar{A} + \alpha I & YA + B_u \bar{C} + \alpha Y \end{pmatrix}, \\ \Omega_{22} &= -\begin{pmatrix} X & I \\ I & Y \end{pmatrix}, \quad \Omega_{31} = \sqrt{\alpha} (CX \quad C), \\ \Omega_{41} &= \sqrt{\alpha} (F_w' \quad F_w' Y), \quad \Omega_{51} = (EX + E_u \bar{C} \quad E).\end{aligned}$$

As a result, a dynamic output feedback controller can be constructed as:

4.2. Problem Analysis

Remark 1 It is obvious that (20) is not an LMI due to the product of a scalar ϵ with variables Y and \bar{B} , respectively. As a result, the LMI software fails to solve (20). However, we are able to achieve difficulty by setting ϵ as a prior value and then apply the LMI software. We need to tune ϵ is value until the solver returns a feasible solution.

Remark 2 In LFC problem, when the H_∞ constraint is not considered ($\gamma \rightarrow \infty$), the problem reduces to robust LFC controller design with pole-clustering constraints considered as in [2] is reduced to the following LMI:

$$\begin{pmatrix} -r^2 P & PA'_\alpha & PE' & 0 \\ A_\alpha P & -P & 0 & \epsilon H_1 \\ EP & 0 & -\epsilon I & 0 \\ 0 & \epsilon H'_1 & -\epsilon I & 0 \end{pmatrix} = \begin{pmatrix} -r^2 P & PA'_\alpha & PE' & 0 \\ A_\alpha P & -P & 0 & H_1 \\ EP & 0 & -I & 0 \\ 0 & H'_1 & 0 & -I \end{pmatrix} < 0 \quad (21)$$

Similarly, when the pole-clustering constraint is absent and the system problem is reduced to the standard of robust H_∞ controller design. As a result, (21) is reduced to the following LMI:

Remark 3 It is easy to design the state feedback controller, when all state variables can be available.

$$\begin{pmatrix} A'P + PA & PC' & F_w & PE' & \epsilon H_1 \\ CP & -I & 0 & 0 & 0 \\ F_w' & 0 & -r^2 I & E_w' & 0 \\ EP & 0 & E_w & -\epsilon I & 0 \\ \epsilon H'_1 & 0 & 0 & 0 & -\epsilon I \end{pmatrix} < 0 \quad (22)$$

5. Simulation Results

The proposed controllers are applied to the line diagram 8 bus test power system is shown in **Figure 3** to illustrate the performance of the AFC approach. The RES generator is installed at Bus 4 and the energy storage device is placed at Bus 8. The parameter of the test power system, the capacity of the storage device is 2 MWh with 50 MW maximum power input/output capability, the fact that the energy storage application in frequency regulation is a high power application. The RES variations are within about $\pm 5\%$ around the average value of 600 MW and the RES generator capacity is 800 MW [5].

The Bode magnitude diagram of the transfer functions from the RES disturbance w to the real power output of the three generators and the storage device is depicted in **Figure 4**. The frequency separation objective in the AFC design is successfully achieved, all the three generators are mainly responsible to balance of the low-frequency components of the RES variations below is 0.1 rad/s, the storage device takes of the high-frequency components above 0.1 rad/s, the frequency spectrum up to 3 rad/s.

Figure 5 shows the comparison of frequency deviations at Bus 4 between AFC and CFC in the presence of the aforementioned RES variations, and frequency deviation curves are observed at the other two generator buses.

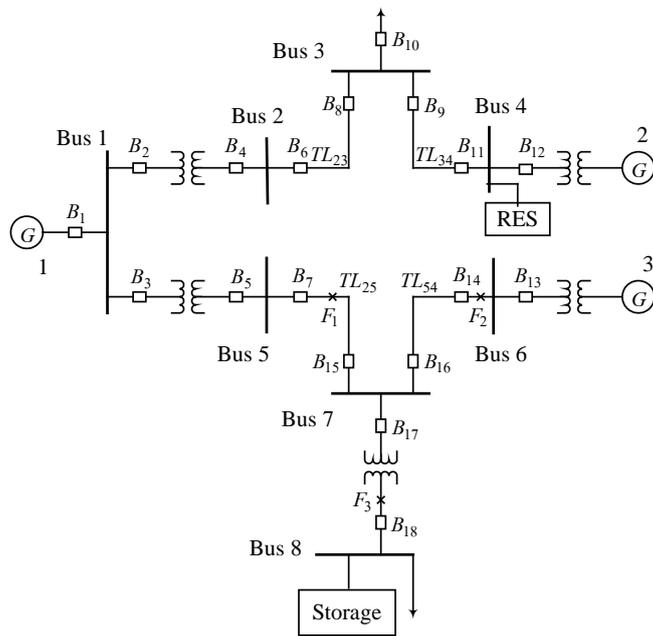


Figure 3. Test power system and RES variations.

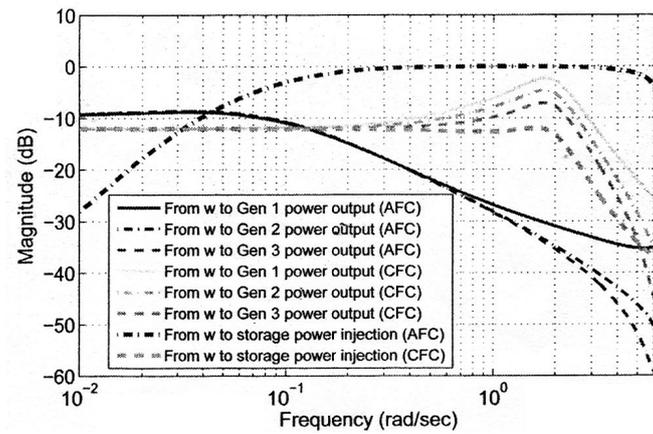


Figure 4. Real power output in frequency domain.

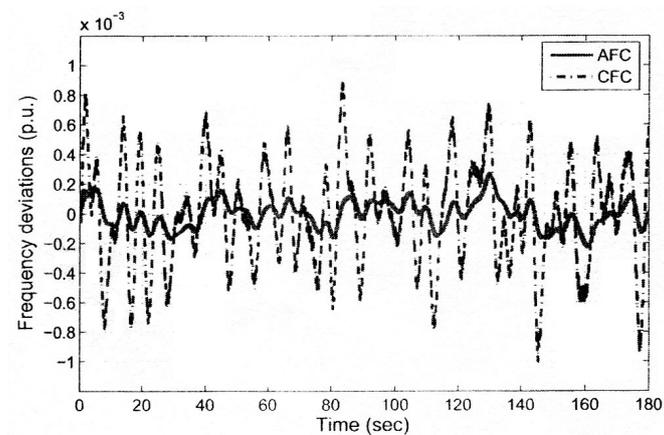


Figure 5. Frequency deviations at Bus 4.

The numerical results of the performance robustness of the proposed controller is superior compared to these methods are shown in **Table 1**.

The power output deviations of Generator 3 from its operating point are plotted in **Figure 6**. Similar power output deviation curves are observed for the other two generators. Compared with the base case, the power output of the three generators under AFC is smoothed out and high frequency fluctuations in the power output.

6. Conclusions

In this paper, a controller design problem involving both pole clustering constraint and the prespecified H_∞ norm constraint for load-frequency control via LMI approach is considered. A proof of concept is given for the AFC design using the 8 bus test system. Under the proposed AFC framework, conventional generators and energy storage devices are coordinated to take the responsibility of power balancing according to the spectrum of the RES variations, high frequency RES variations are balanced by the storage devices, low frequency RES deviations are balanced by the conventional generators reducing the required ramping of the conventional generators. The necessary and sufficient conditions for the existence of a desired controller have proved and the feasible solution to LMI can be used to find a desired controller. In paper comparison with Azzam and Mohamed and the standard robust H_∞ controller. As can be seen from **Figure 7**, the power injection deviations

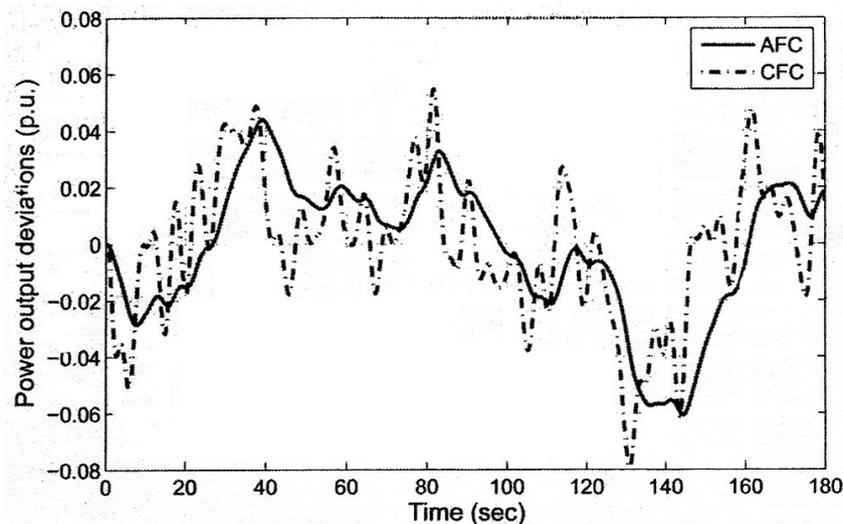


Figure 6. Power output deviations of Generator 2 from its operating point.

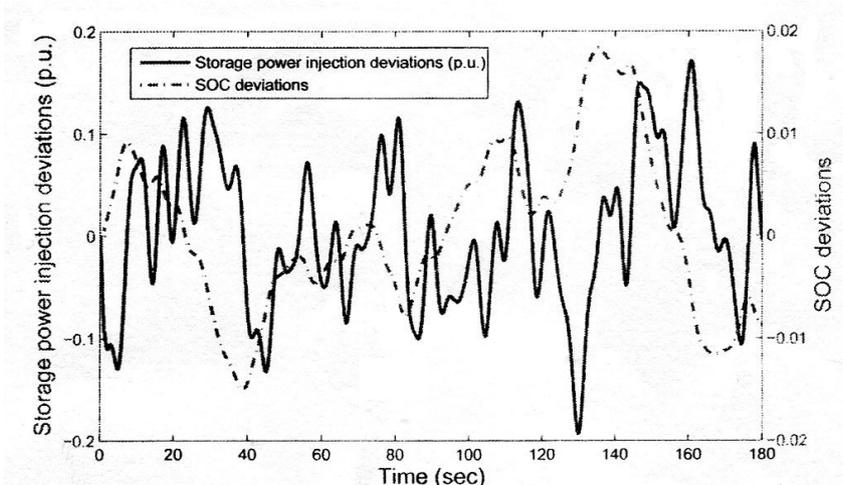


Figure 7. Storage controller response under AFC.

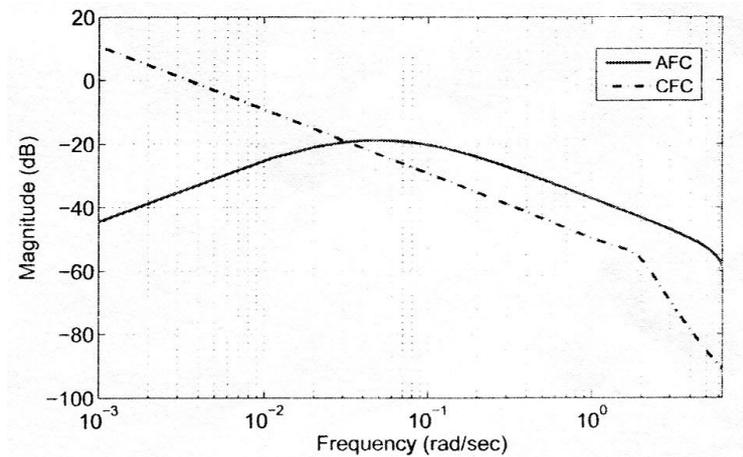


Figure 8. Bode magnitude diagram of the transfer function.

Table 1. Comparison of performance robustness: 3 method

Method	ΔP_{G1}^{ref}	ΔP_{G2}^{ref}	ΔP_{G3}^{ref}	ΔP_{S1}^{ref}
Azzam & Mohamed	-21.3	-7.69	-1.65	-805.4
Proposed method	-17.5	-6.34	-1.52	-731.6
The standard method	19.4	-7.21	-1.59	-758.2

and the SOC deviations of the storage device under AFC design. The storage device is sensitive to the high-frequency component of the RES.

The comparison of SOC between AFC and CFC in the frequency domain is plotted as in **Figure 8**, showing the magnitudes of transfer functions from the RES disturbance (to SOC deviations under AFC and CFC over the entire frequency spectrum. The peak magnitude of the closed loop transfer function from disturbance (to SOC deviations under AFC is approximately -20 dB.

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