Robust Controller Design for Frequency Regulation of Power Systems

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***Abstract*—This paper investigates the issue of robust frequency regulation of single-area alternating current (AC) power applications. The robust stability and disturbance rejection performance criteria are considered in the design procedure of an output feedback controller. Four cases of single-area AC power systems, which comprise the different types of governors and generators, are considered. These components are modeled by first- and second-order transfer functions and exhibit non(minimum) phase behavior. Based on the uncertain linear transfer functions of the governors and generators, the resilient controller against uncertainties and unknown *power* load demand is designed numerically. Several numerical simulations are carried out to show the merits of the developed controller. Also, the effects of different types of governors and generators on the AC MG frequency deviation are also investigated.**

Keywords—Microgrid, Load frequency control, Robust control, Stability.

I. Introduction

Alternating current (AC) power systems are inherently fragile against the inconsistency of load demand and generated power which causes undesired devotions in frequency and main bus voltage. Though, in the AC system, voltage and frequency deviations can be studied separately, because of their different origin source and frequency bandwidth responses.

This feature makes it possible to evaluate the AC system frequency arisen by small power inconsistency lonely. In this regard, the issue of regulating the output active power of generating components in response to frequency variations in AC power application is called load frequency control (LFC) [1]. The LFC is vital for the proper operation of AC power systems.

The pioneer works on LFC were established by an integral controller. Though, choosing the integral gain high degrades the system performance leading into large fluctuations and overshoots [2]. Transient overshoot response and the steady-state performances were simultaneously improved by suggesting a modified version of the integral controller in [3]. To further improve the results, fuzzy proportional-integral (PI) controllers were developed in [4] for the LFC problem.

It was shown that equipping the PI controller with the differential feedback enhances the performance, resulting in several proportional-integral-deferential (PID) control approaches [5], in which tuning of PID for LFC was presented. However, as the size and intricacy of modern AC power applications are enlarged, the tuning of conventional PID controllers turns into an obstacle factor to design a proper controller for the nonlinear systems.

Thereby, advanced control techniques were emerged dealing with the LFC, some of them are optimal [6], passivity-based [7], variable structure [8], adaptive and self-tuning [9], and intelligent [10,11] approaches. More recently, the LFC issue under new deregulated market [12], communication delay [2], [13], and new energy systems [14] received much attention. Although such advanced control methods were successful in satisfying the desired performances, the computational burden and complexity of such techniques have been reported as their common drawbacks [15].

Whereas a linear dynamical representation around a nominal operating point is utilized for designing an LFC, it is feasible to reduce the computational burden and keep the closed-loop performance high by advanced robust linear methods. These approaches including H∞ control [16], μ-synthesis approach [17], robust pole assignment approach [18] can assure robust stability and highly disturbance attenuation level of the AC power systems.

This feature is gaining more and more attention, as practical power system nonlinear components act differently from their associated linear models. In other words, robustness and resiliency of control input become a key objective to achieve zero steady-state response as well as admissible transient frequency deviations.

In [15,17], the μ-synthesis approach was performed on stand-alone AC MGs islanded and ships. However, in those approaches, the generators together with their governors were modeled by first-order models, which degrades the accuracy and therefore the applicability of that control system. In [19], more complicated representations were used in the μ-synthesis LFC design. However, limited representation of the governors and turbines studied in [19]. Many other components can be not modeled by those representations in [19].

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To sum up, this paper considers the advanced robust μ-synthesis approach to design a robust linear control to regulate the frequency in single-area AC power plants. In the typical case study, several representations of governor and generators are considered. More precisely, two hydraulic and mechanical-hydraulic governors are studied, and three non-reheated, re-heated, and hydro turbines are considered. These systems are modeled by first or second order and by minimum-phase or non-minimum phase transfer functions. Several simulations and comparisons are provided to show the applicability and merits of the suggested advanced controller and the transient and steady-state performances of the AC MG power system deviation frequency response.

This paper is continued as follows: In Section II, the LFC problem and the transfer function representations of the governors and turbines are provided. In Section III, the details of the robust μ-synthesis controller are presented. In Section IV, four case-study simulations are conducted and the results of each case-study are compared with other cases. Section V ends this paper by evoking some concluding remarks and future perspectives.

II. LFC Problem

Electric power systems comprise non-linear and complex dynamics and their complexity is increased if numerous generators and loads are connected to them. Though, for modeling purpose and secondary LFC issues, power plants are subjected to slight load power demand changes and the dynamics of the components can be characterized by linear models [20]. The open-loop schematic of a single-area AC power plant in which a generator delivers power to load in a single service area is illustrated in Fig. 1.

As can be seen in Fig. 1, the valve incremental position, ΔX_G, of a governor (with the transfer function P_G) actuates a turbine unite (with the transfer function P_T) whose output, ΔP_G, as well as the load incremental power change, ΔP_d, affects the AC MG frequency incremental change Δf (with the transfer function P_P). Moreover, two nonlinear blocks governor dead band (GBD) and generation rate constraint (GRC), and the droop control feedback $1/R$ are added. The transfer function $P_p(s)$ can be written as:

$$P_P(s) = \frac{K_P}{T_P S + 1} \quad (1)$$

where K_P and T_p are electric system gain and time constant, respectively.

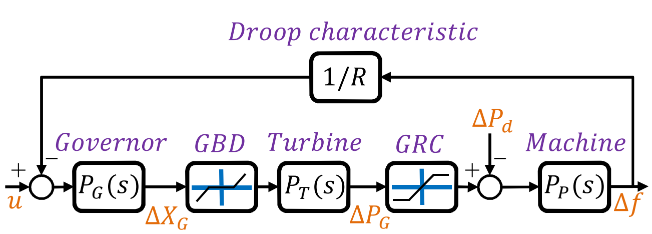

Fig. 1: Block diagram of a single-area power system.

Several representations for the selection of the governor and generator are suggested in the literature [21]. The most widely used transfer functions representations of the governor and generator are as follows:

Case 1: If a hydraulic governor and a non-reheated turbine are involved in the single-area power plant, their corresponding transfer functions are as follows [20]:

$$P_G = \frac{1}{T_G S + 1} \quad (2)$$

$$P_T = \frac{1}{T_T S + 1} \quad (3)$$

Case 2: Considering a hydraulic governor in (2) and a reheated turbine results in the following transfer function [20]:

the reheated turbine is:

$$P_T = \frac{c T_r S + 1}{(T_T S + 1)(T_r S + 1)} \quad (4)$$

Case 3: For a hydraulic governor in the transfer function (2) and a hydro turbine, one has [21]:

$$P_T = \frac{1 - T_W S}{1 + 0.5 T_W S} \quad (5)$$

Case 4: For the case that a mechanical hydraulic governor and a hydro turbine are utilized, the following transfer functions are available [21]:

$$P_G = \frac{1 + T_R S}{(1 + T_{RH} S)(1 + T_{GH} S)} \quad (6)$$

$$P_T = \frac{1 - T_W S}{1 + 0.5 T_W S} \quad (7)$$

By ignoring the nonlinearities of Fig. 1, including backlash and wind-up blocks (i.e. GDB and GRC) [20], [21], the overall transfer function of the LFC problem can be obtained as:

$$\Delta f(s) = \frac{R P_{p(s)} \left(\Delta P_d(s) - P_T(s) P_G(s) u(s) \right)}{R + P_{p(s)} P_T(s) P_G(s)} \quad (8)$$

The objective is designing a robust control law for the input signal $u(s)$ such that the output Δf reaches zero in the presence of the external disturbance input ΔP_d and parameters uncertainties of the transfer functions.

III. μ-SYNTHESIS METHOD

In this paper, the robust control law is designed by the means of μ-synthesis approach. In this design method, the control law is numerically calculated such that the robust stability and good tracking issue are met. The schematic of an uncertain system that is meant to be controlled by the μ-synthesis technique is given in Fig. 2. As can be seen in Fig. 2, the overall closed-loop uncertain perturbed system is decomposed into three main inter-connected blocks uncertainty $\Delta(s)$, nominal system $G(s)$, and controller $K(s)$, and two auxiliary blocks disturbance and tracking error weights $w_d(s)$ and $w_e(s)$.

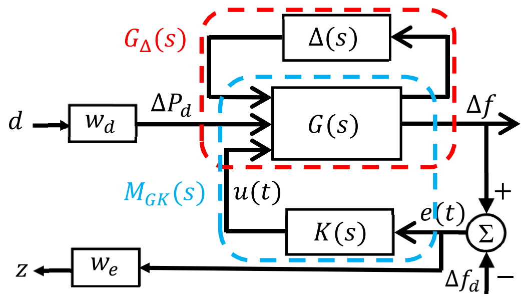

Fig. 2: The LFC scheme of the power system.

The first two blocks (i.e. $\Delta(s)$ and $G(s)$) are obtained on the basis of the case study transfer function. The conservativeness of the μ-synthesis is reduced by involving the frequency information of the system disturbance input and output by the weighting functions $w_d(s)$ and $w_e(s)$.

Moreover, $d(t)$ and $z(t)$ are the auxiliary information-free disturbance input and output vectors, respectively and Δf_d is the desired system output reference. For the ease of presenting the μ-synthesis formulation, two further notations uncertain open-loop $G_\Delta(s)$ and nominal closed-loop system $M_{GK}(s)$ are also given in Fig. 2.

Now, the controller block $K(s)$ must be obtained in a way that the nominal closed-loop system $M_{GK}(s)$ is robustly stable against the uncertainties $\Delta(s)$; and also, the axillary tracking error $z(t)$ is inflicted from the axillary disturbance vector $d(t)$ as low as possible. For the robust stability, it is necessary to have the constraint $|I - M_{GK}(s)\Delta(s)| \neq 0$. To check this constraint, the maximum admissible uncertainty $\Delta(s)$ should be found. This issue is feasible by introducing the μ-function $\mu_\Delta\big(M_{GK}(s)\big)$ as [15,17]:

$$\mu_\Delta = \frac{1}{\min\limits_{\Delta(s)}\{\sigma(\Delta): |I - M_{GK}(s)\Delta| = 0 \,\&\, \Delta \in \Delta(s)\}} \qquad (9)$$

If the μ-function $\mu_\Delta\big(M_{GK}(s)\big)$ is minimized, then the maximum admissible uncertainty is obtained. On the other hand, this minimization does not have an analytical solution and should be solved numerically by the so-called *D-K* approach [15]. The *D-K* approach offers an iterative method in which minimization of (9) is replaced by:

$$\min_{K(s)}\left(\min_{D(j\omega)}\left\|D(j\omega)M\big(G(j\omega),K(j\omega)\big)D^{-1}(j\omega)\right\|_\infty\right) \qquad (10)$$

The other desired performance should be considered is having good tracking and a disturbance rejection action. To achieve this objective, the following constraint must be involved in the design procedure [15], [17]:

$$min\left\|\begin{bmatrix}TF_{\Delta fe}\\ TF_{dz}\end{bmatrix}\right\| \leq 1 \qquad (11)$$

where the transfer functions TF_{dz} and $TF_{\Delta fe}$ relates the axillary disturbance input $d(t)$ to the axillary tracking error $z(t)$ and the desired system output reference Δf_d to the tracking error $e(t)$, respectively.

The optimization problem (11) minimizes the effects of auxiliary disturbance inputs and the desired reference on the tracking error are diminished. To have both robust stability and good tracking at the same time in the controller design procedure, (10) and (11) should be considered.

IV. Results and Discussions

In this part, the μ-synthesis method presented in Section III is applied to robustly stabilizes each of the cases presented in Section II.

The power variation of the load demand is given in Fig. 3, which is used as disturbance input in the closed-loop system simulations of all cases.

Case 1: For the transfer functions (2) and (3) and the parameters given in Table I, the closed-loop output and control input signals are illustrated in Fig. 4. The achieved results demonstrate that the suggested controller makes the frequency deviation zero about 5 seconds after a change in the power load.

Case 2: In this case, the μ-synthesis approach is applied to the power plant with transfer functions (2) and (4) with the uncertain parameters presented in Table II. The power System frequency deviation and the exerted control input signal as illustrated in Fig. 5. Simulation results of Fig. 5 illustrate that the hydro turbine has a slower response than the (non)reheated generator and it takes about 8 seconds to damp the frequency deviation. Comparing with the results of a non-reheat generator in case 1, the non-reheat generator leads to a smaller frequency deviation in the power system.

Case 3: In this case, the μ-synthesis technique is utilized for the power plant with transfer functions (2) and (5) and the uncertain parameters presented in Table III. The power system frequency deviation and the exerted control input signal, as well are illustrated in Fig. 6.

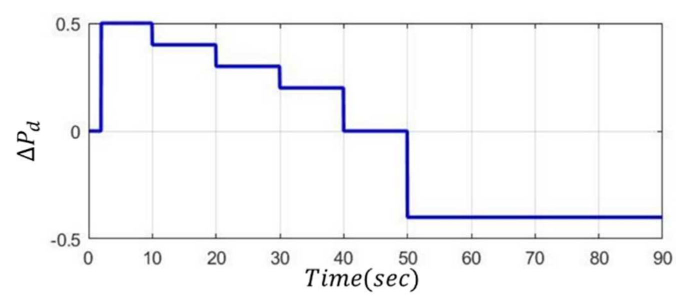

Fig. 3: Power fluctuation in the load demand.

TABLE I: Power system parameters' nominal values with uncertainty bounds-case 1.

Parameter	Value	Parameter	Value
T_G	0.08 s	R	$2.4 \pm 50\%$ Hz/p.u.MW
T_T	0.3 s	K_P	$120 \pm 50\%$ s
T_P	6 s		

Case 4: In this case, the μ-synthesis technique is used to stabilize the plant with transfer functions (6) and (7) and the uncertain parameters presented in Table IV. The power system frequency deviation and the exerted control input signal as illustrated in Fig. 7. Fig. 7 reveals that if a mechanical-hydraulic governor replaces the conventional hydraulic one, the amplitude of the frequency deviation is reduced, effectively.

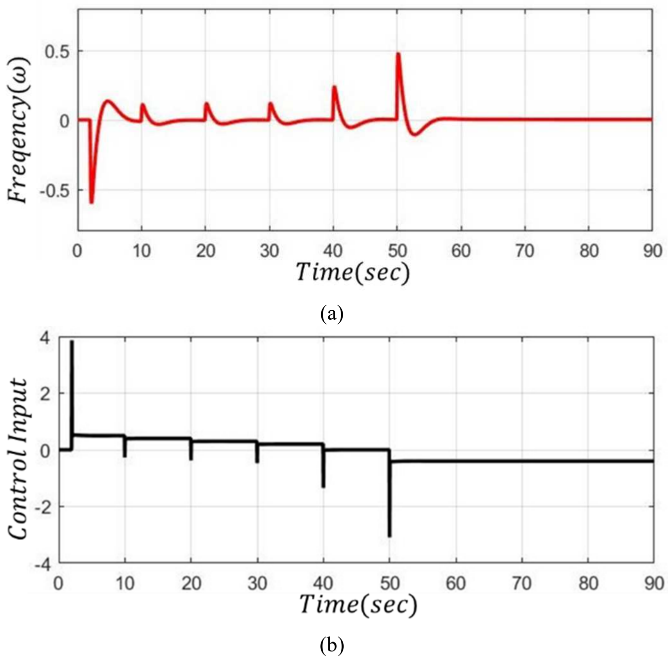

Fig. 4: Case 1 (a). Frequency response and (b). control input.

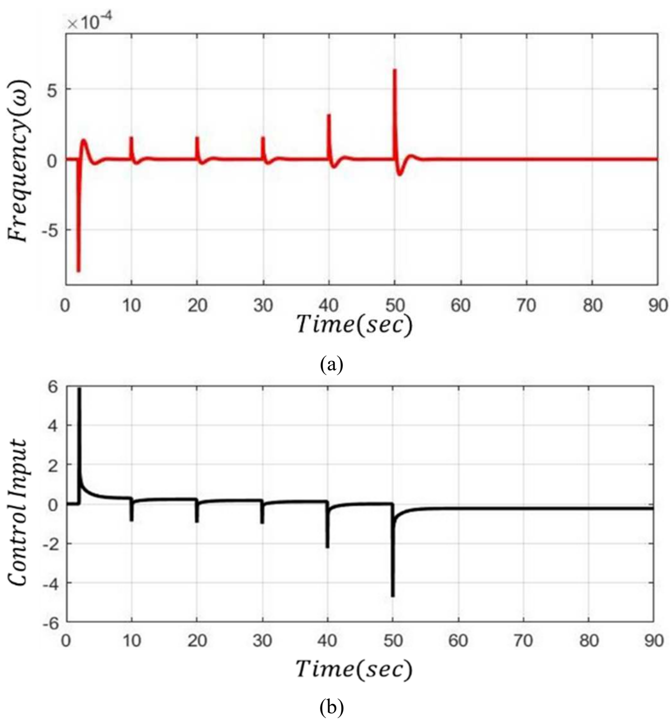

Fig. 5: Case 2 (a). Frequency response and (b). control input.

TABLE II: Power system parameters' Nominal values with Uncertainty bounds- case 2.

Parameter	Value	Parameter	Value
T_r	4.2 s	R	$2.4 \pm 40\%$ Hz/p.u.MW
T_T	0.3 s	K_P	$120 \pm 40\%$ s
T_P	20 s	c	0.35

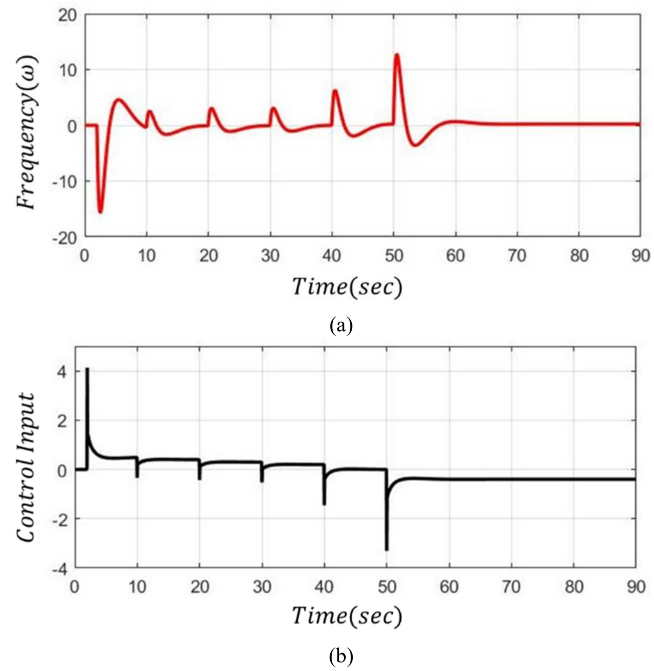

Fig. 6: Case 3 (a). Frequency response and (b). control input.

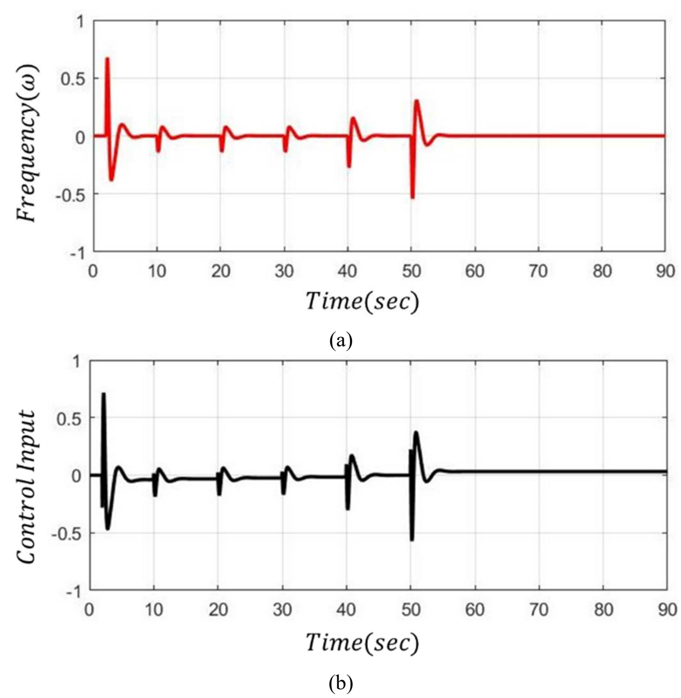

Fig. 7: Case 4 (a). Frequency response and (b). control input.

TABLE III: Power system parameters' Nominal values with Uncertainty bounds- case 3.

Parameter	Value	Parameter	Value
T_G	0.08 s	T_W	1 s
T_T	0.3 s	R	$2.4 \pm 50\%$ Hz/p.u. MW
T_P	6 s	K_P	$120 \pm 50\%$ s

TABLE IV: Power system parameters' Nominal values with Uncertainty bounds- case 4.

Parameter	Value	Parameter	Value
T_{GH}	0.513 s	T_R	5 s
T_{RH}	48.7 s	R	$2.4 \pm 50\%$ Hz/p.u. MW
T_P	20 s	K_P	$120 \pm 50\%$ s

V. Conclusion

In this paper, the problem of robust LFC in a typical single-area AC power application was studied. Three performances such as the robust stability, disturbance rejection, and good tracking were used in the μ-synthesis to design the controller offline. Four cases of single-area AC power systems including (mechanical)hydraulic governors and (non)reheated/hydro turbines are considered. These components are modeled by non-minimum first- or second-order transfer functions. Simulation results showed the merits of the developed robust controller. They revealed that a mechanical-hydraulic governor improves the system response over a hydraulic governor. Additionally, the transient responses of the non-reheated and the reheated turbine are almost the same. For future work, considering two-area and more-area power plants could be interesting.

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