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Design of Sliding-mode Controller via Model Reduction for Automatic Generation Control of Micro Hydropower Plants: Isolated-mode Case

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Abstract— **Compared with large hydro power plants, micro hydropower plants are emerging as a major renewable energy resource because they do not encounter the problems of population displacement and environmental problems. Micro hydropower plants are conducted in two different configurations. One is isolated mode and the other is grid-connected mode. Under any mode, controller plays a vital role for automatic generation control (AGC) of micro hydropower plants. Especially, frequency and load are regulated entirely by the controller under the isolated mode. But the controller design becomes challenging because the number of measurable state variables is usually less than the number of system state variables. This paper addresses a sliding-mode controller for the AGC problem of micro hydropower plants under the isolated mode. After modeling the AGC system, a reduced-order model is obtained from the initial model via the method of model reduction. Then, the sliding-mode controller is designed on basis of the reduced-order model, and is applied to the initial model for simulations. The simulation results illustrate the feasibility and robustness of the sliding-mode controller under the isolated mode for the AGC problem of micro hydropower plants.**

I. INTRODUCTION

Micro hydropower is a kind of a clean, renewable, and predictable energy source. It is one of the best alternatives to the highly polluting and very costly diesel generation in most remote communities, and plays an important role in rural electrification. Similar to larger traditional hydroelectric systems, micro hydropower generation systems also produce electricity by converting the mechanical energy in the running water into electric energy in an alternator. But a great benefit we can earn is that micro hydropower does not encounter the problems of population displacement and environmental problems associated with larger traditional hydroelectric systems. Over the last few decades, there has been a growing realization in developing countries that the clean power source has an important role to play in the economic development of remote rural areas, especially mountainous ones.

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Generally speaking, micro hydropower plants are conducted in two different configurations. One is isolated mode and the other is grid-connected mode. As known to all, consumers in an electric power system fed by a micro hydropower plant require uninterrupted power at rated frequency and voltage under any operating mode. To maintain these parameters within the prescribed limits, controls are required on the system. Voltage is maintained by the control of excitation of the generator and frequency is maintained by eliminating the mismatch between generation and load demand. As far as the problem of automatic generation control (AGC) is concerned, it is synonymous with load frequency control (LFC) of a power system. The main objective of AGC or LFC is to control the real power output of generating units in response to changes in system frequency within specified limits under the isolated mode, and system frequency and tie-line power interchange within specified limits under the grid-connected mode. Under any operating mode, controller usually plays a vital role for the problem of AGC.

With the prosperity of micro hydropower systems, applications of advanced control methods to design a variety of controllers for the AGC problem have been reported in the last few decades. Hanmandlu and Goyal in [1] developed a governor by combining an adaptive fast transversal filter, a normalized LMS (nLMS) algorithm, a fuzzy PI controller and a neural network together. The simulation results in [1] demonstrated the feasibility of this novel hybrid controller. In [2], Salhi and his colleagues focused on the modelling problem of a micro hydraulic turbine generating system and presented a series of Takagi-Sugeno (TS) models to describe the nonlinear system, then an electrical load TS fuzzy governor was employed to control the micro hydropower system. Doolla and Bhatti in [3]-[5] developed a multiple flow control system for the LFC technique of micro hydro power plants. Their control system with on/off control logic was able to reduce the size of the dump load up to 50%. Other reports in the field of AGC or LFC of micro/small hydropower plants were also studied in [6]-[11]. See [12] for a complete review on recent philosophies about isolating operation and control for distribution network connected with small/micro hydro power plants.

Sliding-mode control (SMC), with its discontinuous state-feedback control law, is a form of variable structure control (VSC) [13]. It is a nonlinear feedback control method that alters the dynamics of a nonlinear system by application of a high-frequency switching control. It switches from one continuous structure to another based on the current position in state space so that the system trajectories always move toward a switching condition and the ultimate trajectory will slide along the boundaries of the control structures. The geometrical locus consisting of the boundaries is called the sliding (hyper)surface. The motion taking place on the surface is called a sliding mode. The main strength of SMC is its robustness. It is insensitive to parameter variations and extraneous disturbance that enter into the control channel. Additionally, the sliding mode is reached in finite time, *i.e.*, better than an asymptotic behavior. This nonlinear method is an alternative to solve the AGC problem of small/micro hydro power plants.

Recently, there has been an increasing interest in applying the advanced control technology to control problems of hydro power systems. Qian and his colleagues [14] designed a sliding-mode governor for large hydropower plants with an up-stream surge tank. Zargari *et al* [15] designed a fuzzy sliding-mode governor to realize the frequency control of an isolated small hydropower system. In [15], the particle swarm optimization algorithm was adopted to regulate the membership functions of fuzzy system more accurately, and an estimator was suggested for estimating and identifying the system variables to reduce the costs of implementing the control method. Tripathy and Bhardwaj [16] pointed out dynamics and control for AGC of micro hydropower plants were conducted in two different configurations, i.e., isolated mode and grid-connected mode, where the isolated mode was the basic but important one because frequency and load were simultaneously regulated by one AGC controller.

This paper addresses a sliding-mode controller for AGC of micro hydropower plants under the isolated mode. After modelling the AGC system, we find the number of measurable state variables is less than the number of system state variables. This case indicates that it is hard or difficult to design a full-state-feedback controller for such a control problem. To deal with the problem, the initial system is simplified by the method of model reduction, then a reduced-order system is obtained for control design. According to the methodology of sliding mode, a AGC controller is designed on basis of the reduced-order model, and is applied to the initial system for simulation. The simulation results illustrate the feasibility and robustness of the presented method. The remainder of this paper is organized as follows. In Section 2, dynamics of the AGC system under the isolated mode are depicted. The sliding-mode AGC controller is designed in Section 3. The presented method in Section 4 is taken into practical accounts to verify the controller's feasibility and robustness for the problem of AGC. Finally, conclusions are drawn in Section 5.

II. System Dynamics

The AGC model of micro hydropower plants usually includes the following components, i.e., turbine & its feeding penstock, valve & its servomotor, and generator. Transfer function block diagram in Fig. 1 shows the system dynamics under the isolated mode. Since the AGC problem of micro hydropower plants under consideration is expressed only to relatively small changes, the block diagram in Fig. 1 is obtained on basis of small signal analysis. Tripathy and Bhardwaj [16], Hanmandlu and Goyal [1] modeled the system and presented the model of each component in the form of transfer function.

1) Turbine & penstock: The approximate transfer function of the turbine and penstock component for the analysis in [16] is given as

$$G_t(s) = \frac{\Delta P_G(s)}{\Delta X(s)} = \frac{-T_w s + 1}{\frac{T_w}{2}s + 1} \tag{1}$$

here T_w (s) is nominal starting time of water in penstock, s is Laplace transform complex variable operator, ΔP_G (per unit) is incremental power (torque) output of turbine, ΔX (per unit) is incremental power input to turbine (valve position). Note that (1) is a non-minimum phase system due to the effect of water hammer in penstock. This case indicates there is an initial tendency for the torque to change in a direction opposite to the change of water flow.

2) Valve & servomotor: Usually, a DC servomotor with closed-loop armature control is employed to regulate the water flow rate in penstock. The flow of water is regulated by controlling the valve position. The transfer function of the mechanical and electrical parts in [1] is displayed as

$$G_v(s) = \frac{1}{T_e s + 1}\frac{1}{T_m s + 1} \tag{2}$$

here T_m (s) is mechanical time constant, T_e (s) is electrical time constant. In addition, unity gain is applied as a feedback to depict the closed-loop armature control of this DC servomotor. At last, the transfer function of this component in [1] is written as

$$\frac{\Delta X(s)}{\Delta P_c(s) - \frac{1}{R}\Delta F(s)} = \frac{G_v(s)}{1 + G_v(s)} \tag{3}$$

here R is a constant of steady state speed regulation, ΔX (per unit) is gate position deviation, ΔF (Hz) is frequency deviation, ΔP_c (per unit kW) is incremental speed changer position.

3) Generator: Due to the load/frequency characteristic, we include a load damping term to the swing equation of a synchronous generator. By taking Laplace transform for the equation, the generator dynamics is able to be obtained as

$$\frac{\Delta F(s)}{\Delta P_G(s) - \Delta P_L(s)} = \frac{K_p}{T_p s + 1} \tag{4}$$

here ΔP_L is step function load disturbance, K_p is generator gain constant, defined as $K_p = \frac{1}{D} = 1/\frac{\partial P_L}{\partial F}$, T_P (s) is generator time constant, defined as $T_p = \frac{2H}{f^0 D}$, where H is inertia constant of synchronous generator, f^0 (Hz) is nominal system frequency.

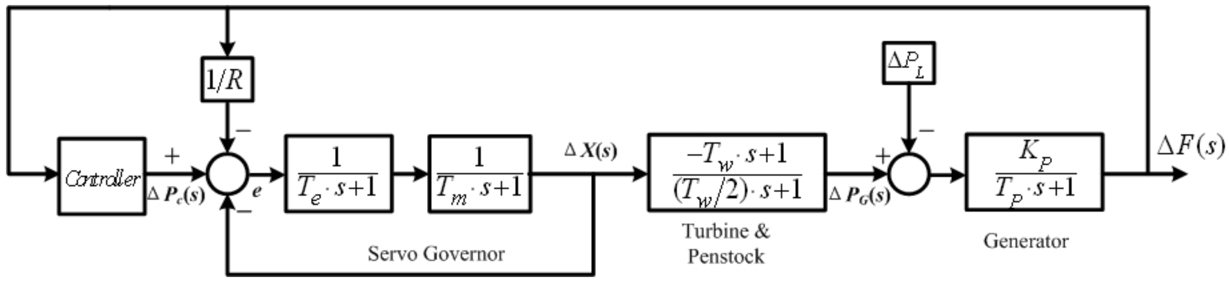

Fig. 1. Transfer function block diagram for Automatic generation control of micro hydropower plants under isolated mode.

III. Control Design

With the development of sensor and measuring technology, the methods of getting data of an industrial process have been raised up. This encourages us to employ the inner information of a system to achieve control objective. As far as the sliding-mode controller for the AGC problem is concerned, we can directly obtain incremental power (torque) output of turbine ΔP_G, incremental power input to the turbine (valve position) ΔX, and frequency deviation ΔF for our control design. The block diagram displayed in Fig. 2 indicates the isolated operating mode of micro hydropower plants. To force the steady state of ΔF to tend to zero [17], the integral of ΔF is utilized as an additional state x^i_{add} with a known gain K^i_E for , shown by dash lines in Fig. 2.

$$x^i_{add}(t) = K^i_E \int_0^\infty \Delta F(t)\ \mathrm{d}t \tag{5}$$

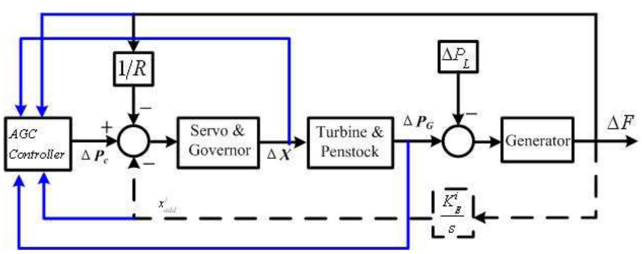

Fig. 2. Block diagram for AGC of micro hydropower plants under isolated mode (solid lines) with an additional state (dash lines).

In Fig. 2, the system is a 5-order one, but here only four measurable state variables, ΔP_G, ΔX, ΔF and x_{add}, are available for control design. Thus, it is hard or difficult to apply a full-state-feedback controller in practice. To solve the issue, we need to simplify the system by the method of model reduction, and achieve the control design on basis of this reduced-order model. From Fig. 1, the valve and governor component is the only part that needs to be simplified. In (2), the electrical time constant T_e is usually 10 times smaller than the mechanical time constant T_m, so that (2) can be simplified as

$$G_{vs}(s) = \frac{1}{(T_e+T_m)s+1} \tag{6}$$

Assume the parameters $T_e = 0.01$ and $T_m = 0.001$ given in [1], then we can have the frequency response curves of the simplified and prototype systems in Fig. 3. Fig. 3 show the two plots are almost the same type as each other at low frequencies. This case means the simplified system is able to depict the dynamics of the prototype one when the system is at low frequencies. Fortunately, the condition is easy to be satisfied because the load disturbance ΔP_L is always low-frequency step signal in practice so that the simplified system is accurate enough to be adopted for control design for rejecting the step load disturbance ΔP_L.

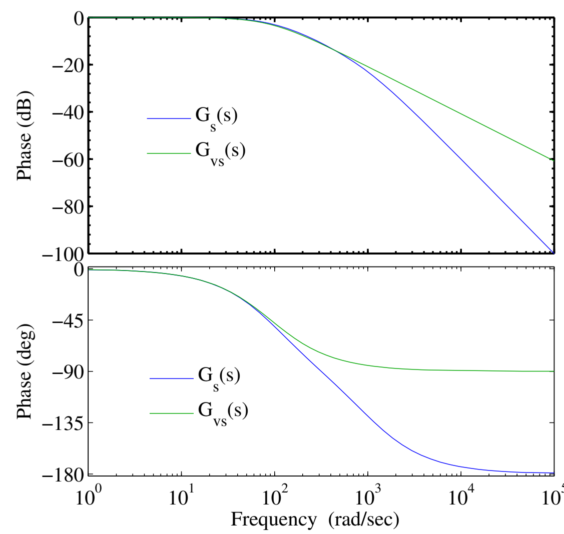

Fig. 3. Frequency response curves of the simplified and prototype systems.

With the additional state, its nominal state expression to depict the reduced-order system under the isolated mode can be written as

$$\begin{aligned} \dot{\mathbf{x}}_i &= \mathbb{A}_i\mathbf{x}_i + \mathbb{B}_i u + \mathbb{F}_i d_i(t) \\ y &= \mathbb{C}_i^T \mathbf{x}_i \end{aligned} \tag{7}$$

here $\mathbf{x}_i = [\Delta F(t), \Delta P_G(t), \Delta X(t), x^i_{add}(t)]^T$ is state vector, $d_i(t)$ is disturbance sign, State matrix $\mathbb{A}_i$, input vector $\mathbb{B}_i$, output vector $\mathbb{C}_i$, and disturbance vector $\mathbb{F}_i$ are shown in Appendix.

To design the sliding-mode controller, a sliding surface S_i in (8) should be defined at first.

$$S_i = \mathbf{c}_i^T \mathbf{x}_i \tag{8}$$

here $\mathbf{c}_i$ is constant and it is with the same dimension as $\mathbf{x}_i$. The SMC law usually includes two parts: switching control law and equivalent control law [13]. The former is employed to drive the system states moving towards a predefined sliding surface. The latter guarantees the system states keep sliding on the sliding surface and converge to the surface. During the control design, we still adopt such an approach and define the control law u as

$$u = u_{eq} + u_{sw} \tag{9}$$

Here u_{sw} is the switching control and u_{eq} is the equivalent control law, their expressions are deduced below.

When the system states keep sliding on the sliding surface, only the equivalent control u_{eq} acts. Differentiating S_i with respect to time t and letting $\dot{S}_i = 0$ obtain

$$\dot{S}_i = \mathbf{c}_i^T \dot{\mathbf{x}}_i = \mathbf{c}_i^T (\mathbb{A}_i \mathbf{x}_i + \mathbb{B}_i u_{eq}) = 0 \tag{10}$$

Substituting the nominal system (7) into (10), we have

$$u_{eq} = -(\mathbf{c}_i^T \mathbb{B}_i)^{-1} \mathbf{c}_i^T \mathbb{A}_i \mathbf{x}_i \tag{11}$$

In order to ensure the total control law (9) makes the sliding surface (8) asymptotically stable, we define a Lyapunov function as

$$V_i(t) = \frac{1}{2} S_i^2 \tag{12}$$

Differentiating V_i with respect to time t and substituting (7), (8), (9) and (11) into it obtain

$$\begin{aligned} \frac{\mathrm{d}V_i}{\mathrm{d}t} &= S_i \dot{S}_i = S[\mathbf{c}_i^T \dot{\mathbf{x}}_i] \\ &= S_i[\mathbf{c}_i^T (\mathbb{A}_i \mathbf{x}_i + \mathbb{B}_i u + \mathbf{c}_i^T \mathbb{F}_i d_i(t)\ )] \\ &= S_i\{\mathbf{c}_i^T [\mathbb{A}_i \mathbf{x}_i + \mathbb{B}_i (u_{eq} + u_{sw}) + \mathbf{c}_i^T \mathbb{F}_i d_i(t)]\} \\ &= S_i[\mathbf{c}_i^T (\mathbb{A}_i \mathbf{x}_i + \mathbb{B}_i u_{eq}) + \mathbf{c}_i^T \mathbb{B}_i u_{sw} + \mathbf{c}_i^T \mathbb{F}_i d_i(t)] \\ &= S_i[\mathbf{c}_i^T \mathbb{B}_i u_{sw} + \mathbf{c}_i^T \mathbb{F}_i d_i(t)] \end{aligned} \tag{13}$$

Let $\mathbf{c}_i^T \mathbb{B}_i u_{sw} = -\kappa_i S_i - \eta_i sgn(S_i)$ where κ_i and η_i are positive constants and $sgn(\cdot)$ is sign function, then the switching control law u_{sw} is obtained as

$$u_{sw} = -(\mathbf{c}_i^T \mathbb{B}_i)^{-1} [\kappa_i S_i + \eta_i sgn(S_i)] \tag{14}$$

The control law can be obtained as

$$u = u_{eq+} u_{sw} = -(\mathbf{c}_i^T \mathbb{B}_i)^{-1} [\mathbf{c}_i^T \mathbb{A}_i \mathbf{x}_i + \kappa_i S_i + \eta_i sgn(S_i)] \tag{15}$$

Note that u in (15) is determined by the reduced-order system (7). In the following simulations, we will employ this control input to regulate the prototype system shown in Fig. 1.

IV. Simulation Results

In this section, a set of typical parameters of an micro hydro power plant is considered for simulation. The following data [1] is considered for constructing the model as follows. Total rated capacity of the generation unit is 50 kW, normal operating load is 25 kW, regulation coefficient R is 10 $Hz/pu \cdot kW$. Provided that load-frequency dependency is linear, and nominal load is 48% of the rated load, ΔP_L=3%. The nominal starting time of water in penstock T_w is 4 s. The generator parameters are determined as $K_p = 50\ Hz/pu \cdot kW$ and $T_p = 64.64\ s$. The governor & servo parameters are given as $T_e = 0.01\ s$ and $T_m = 0.001\ s$.

A. Load Rejection

Under the isolated mode, the micro hydro unit serves an exclusive source to feed the area. No other source is able to be adopted to regulate the frequency in the area. The sliding-surface parameters of the SMC controller are selected as $c_i = [9.0\ 2.0\ 6.0\ 0.1]^T$ according to Ackermann's formula. Other controller parameters are picked up as $\kappa = 1$ and $\eta = 0.01$. Gain of the additional state K_E^i is 0.002. As shown in Fig. 5, the blue plots are the results by a conventional PID AGC controller [1]. The PID controller takes the form $u(t) = K_p X(t) + K_i \int X(t) \mathrm{d}t + K_d \dot{X}(t)$, the parameters of which are determined as $K_p = 0.056$, $K_i = 0.002$, and $K_d = 0$.

The load disturbance $\Delta P_L = 3\%$ is applied to the system at $t = 0$. The simulation results are shown in Fig. 5. Compared with the results by the conventional controller, the sliding-mode AGC controller is smaller on the indexes of overshooting and settling time. On the other hand, it is obvious that the designed controller is with the larger overshooting on the indexes of ΔP_G and ΔX. But this fact does indicate the conventional controller is superior. The reason of this phenomenon is that the designed controller can open the valve and increase the turbine output the moment that the load disturbance ΔP_L applies on the AGC control system. It ensures the designed controller is with the better performance to regulate the frequency of this power system.

B. Robust Testing

Due to uncertainties of load in control area, exact values of system parameters are actually known in a certain interval in practice. To test the robustness of the presented method, we assume the variation is not beyond 20% so that the following parameter intervals are taken into account, $K_p \in [40,\ 60]$, $T_p \in [51.71,\ 77.57]$, and $T_w \in [3.2,\ 4.8]$. In the simulation, the controller parameters are kept unchanged. They are the same ones as they are tuned for the nominal power system dynamics. The same load disturbance of magnitude 3% is injected to the AGC system at $t = 0$ for the two extreme cases.

Displayed in Fig. 5, the control system under the isolated mode is sensitive for the parameter variation above the nominal system, but the aviation below the nominal will lead to a better performance. But this fact does not effect the feasibility of the presented method. The reason is as follows. The nominal parameters under the isolated mode are usually rated. For an isolated power system, the opportunity of operating above its rating is rather rare. Further, the reason that we consider the 20% variation is that the system dynamics in Section 2 is gotten by small signal analysis. 20% parameter variation is enough to cover the range of the small signal analysis. More variation may lead to other system dynamics and be beyond the paper's scope.

V. Conclusions

Automatic generation control (AGC) of micro hydro plants is a powerful tool to stabilize the frequency of a power system. According to operating mode, the AGC problem of micro hydro plant is able be classified as isolated mode

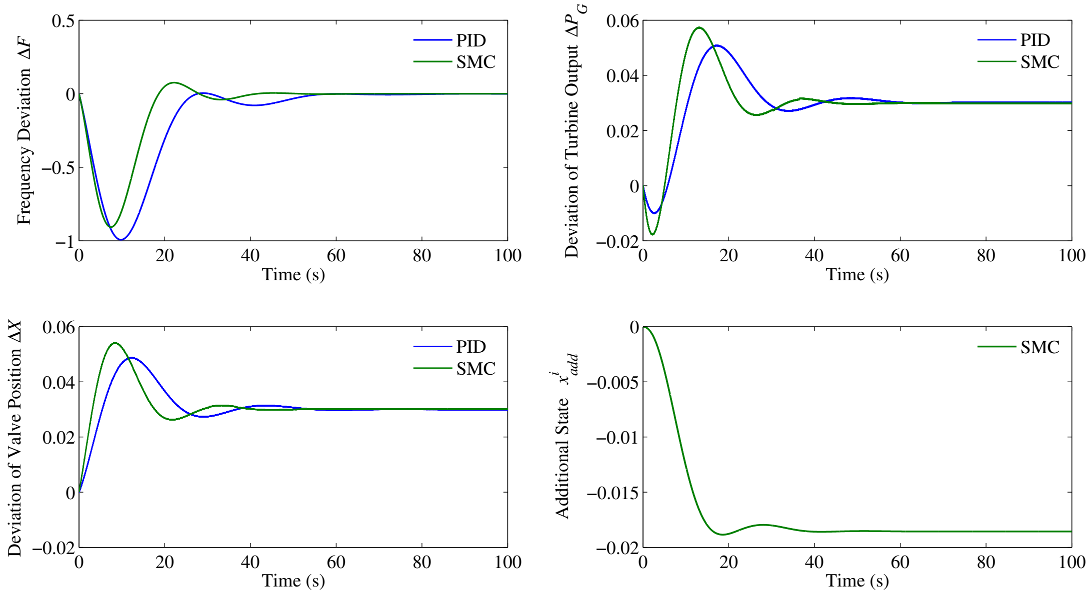

Fig. 4. Comparison of the simulation results under the isolated mode by the SMC controller and the conventional controller in [1].

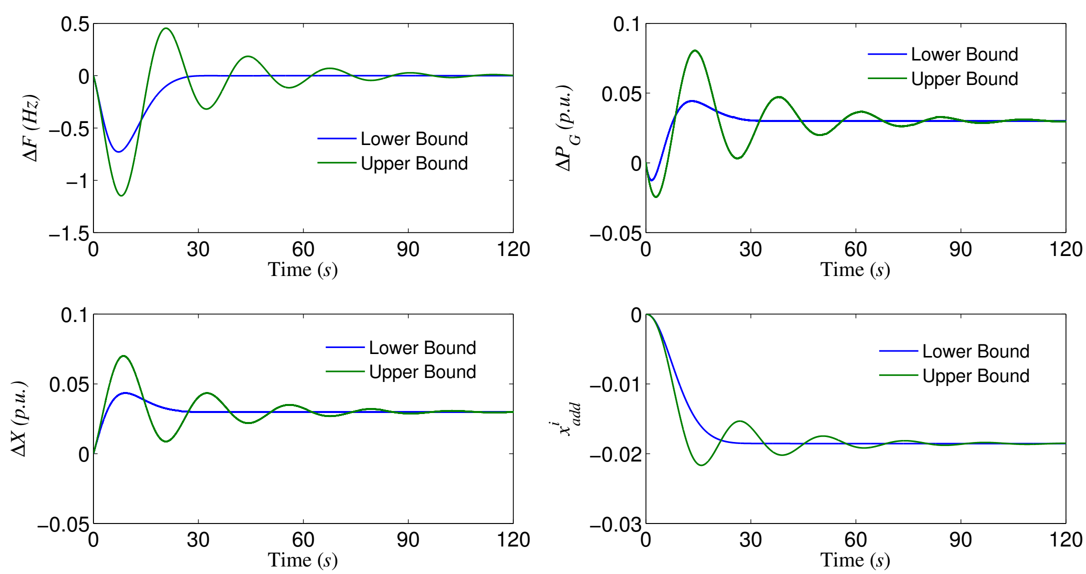

Fig. 5. Robustness testing under the isolated mode. **a** Frequency deviation ΔF ; **b** Deviation of power output ΔP_G; **c** Deviation of valve position ΔX; **d** Additional state x^i_{add}..

and grid-connected mode, where the isolated mode is basic but important. In this paper, a sliding-mode controller is addressed for the AGC problem of micro hydropower plants. Under the isolated mode, integral of the frequency deviation is introduced as an additional state to force the frequency deviation to zero. The mathematic model of the servo & governor component is simplified via model reduction for control design. Along this route, a sliding-mode controller is designed on basis of the reduced-order model to control the prototype system. To verify the feasibility of the presented control approach, typical parameters of micro hydro power plants are adopted to model this system. Compared with the conventional AGC controller, simulation results show the presented control method possess better transient responses. Moreover, $\pm 20\%$ variation of the system parameters are considered to verify the controller's robustness. The results show the control system is insensitive to the parameter variation when the system operates below the nominal parameters.

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APPENDIX

$$\Gamma = \frac{1}{T_e + T_m}$$

$$\mathbb{A}_i = \begin{bmatrix} -\frac{1}{T_p} & \frac{K_p}{T_p} & 0 & 0 \\ \frac{2\Gamma}{R} & -\frac{2}{T_w} & \frac{2}{T_w} + 2\Gamma & 2\Gamma \\ -\frac{\Gamma}{R} & 0 & -\Gamma & -\Gamma \\ K_E^i & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbb{B}_i = [0\ \ -2\Gamma\ \ \Gamma\ \ 0]^T \quad \mathbb{C}_i = [1\ 0\ 0\ 0]^T$$

$$\mathbb{F}_i = [-\frac{K_p}{T_p}\ 0\ 0\ 0]^T$$

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