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Frequency Control of Isolated Wind-Diesel Microgrid Power System by Double Equivalent-Input-Disturbance Controllers

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ABSTRACT In a wind-diesel isolated microgrid, the fluctuating output power of wind turbine generator (WTG) and the perturbation of the load demand will lead to power imbalance and frequency deviation in the system. Appropriate frequency control schemes are indispensable to guarantee power quality through maintaining the power balance. In view of the outstanding performance of Equivalent-Input-Disturbance (EID) method, it is taken to the task of load frequency control (LFC) problem of this microgrid. In this paper, novel double EID controllers are proposed for the frequency control of a wind-diesel isolated microgrid. In this integrated control design, one single EID controller is applied to the pitch angle control system to smooth output power of WTG by controlling the pitch angle. At the diesel generator side, another single EID controller is applied to adjust the output power of the diesel generator to maintain the power balance of the system and finally preserve frequency in the normal range. Battery energy storage system is connected as auxiliary regulation. The simulation studies show superior flexibility and control performance of the proposed strategy compared to the conventional PI method in a wind-diesel isolated microgrid in MATLAB.

INDEX TERMS Equivalent-input-disturbance, frequency control, pitch angle control, renewable energy, wind-diesel microgrid.

I. INTRODUCTION

Presently, generating systems in isolated remote areas mostly depend on diesel generation as a stable and controllable power resource [1]. Heavy oils for diesel generation incur fuel and transportation costs. Therefore, the utilization of renewable energy has attracted a lot of attention as clean electricity sources, especially in microgrid and smart grid. Microgrid comprises distributed generators and associated loads [2]. For distributed utilization, depending on the environment and realistic conditions, renewable energy, regarded as clean and economical energy sources, such as wind, solar, sea, biomass, are selected to be connected to isolated microgrid systems [3], [4]. The connection of renewable energy can help afford part of the power supply thus reducing the transportation costs and consumptions of fuel for diesel generators. The microgrid system with renewable energy provides a flexible power supply mode [5] for areas remote but rich in renewable energy. Wind energy is one of the prospective choices [6] to be connected to microgrid systems for distributed utilization. However, wind power is vulnerable to the environment condition such as weather and seasons, making the output of the wind turbine generator (WTG) not constant and varied with wind speed fluctuation [7]. Therefore, power imbalances, which further result in frequency deviation, will be caused by intermittent output power of WTG and the perturbation of the load demand, when WTG connect to microgrid and supply the power demand with diesel generators together.

In order to ensure the stable operation and power quality of the isolated microgrid, numerous studies about frequency control [8]–[10] for wind-diesel isolated microgrid have already been undertaken. One kind of existing method focus on control strategies [11] of micro distributed generators in microgrids which includes P/Q control, V/F control and droop control [12]. Various advanced intelligent methods have been introduced recently, such as sliding mode con-

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trol (SMC) [13], [14], robust control [15], [16], artificial neural network [17], [18], fuzzy logic [19], [20], advanced droop control [21], [22] and distributed model predictive control [23], [24]. Yet, conventional PI and PID control method are still the most widely employed in practical microgrid because of their simple structure and low cost. Conventional PI/PID method are usually tuned by Hit and trial and Ziegler-Nichols method [25] which is difficult to adapt the complexity of microgrids such as the varied load demand, wind speed and disturbance. Moreover, inappropriate choice of integral gain may even destabilize the overall system. So artificial intelligence based tuning method is adopted such as particle swarm optimization (PSO) [26] and genetic algorithm (GA) [27]. As in Ref. [28], Load Disturbance Rejection is used for tuning of proposed PID controller gains to reduce the frequency oscillation in an autonomous isolated microgrid. In Ref. [29], four PID controllers based on genetic algorithm were utilized to diesel generator, WTG system, solar photo voltaic system, energy storage system (ESS) in a hybrid microgrid. However, these advanced tuning methods have a large amount of calculation and complex structure which is not easy to implement in practical microgrid system [30]. Therefore, it is necessary to propose a method which simple in structure and calculation which also has better effect in frequency control of microgrid.

Another kind of method focus on adding new devices to the microgrid, such as ESS [31], plug-in hybrid electric vehicles [32], electrolyzer [33], Superconducting Magnetic Energy Storage [34] and controllable loads [23]. The ESS, such as batteries and supercapacitors, has earned much attention and been accepted as an efficient solution because of its fast response [35] which can adjust the sudden part of frequency fluctuation. The coordinated control of the distributed generations and ESS equipment is researched with two operation modes in Ref. [36]. Yet, poor areas and countries can't afford them as most ESS are expensive to equip and it should be given consideration to investment cost for. Moreover, the battery size and environmental costs should also be taken into account. Due to above reasons, in most designs, ESS are connected only as an auxiliary frequency regulation [37] which will be also utilized in this paper.

However, up until now, the limitation of the aforementioned design methods is that they usually generate the control signal only by utilizing bus frequency fluctuation which does not take the information of varied wind speed and load fluctuations into account. The main reason is in wind diesel microgrid, load demand and wind speed are too random to be measured beforehand. This neglect has brought some limitations to the further improvement of control methods as wind speed and load demand are important parts of microgrid.

In fact, the frequency control problems of microgrid mainly focus on small load perturbation under the nominal operating condition of the power system. From this point of view, we can regard varied wind speed and load fluctuation

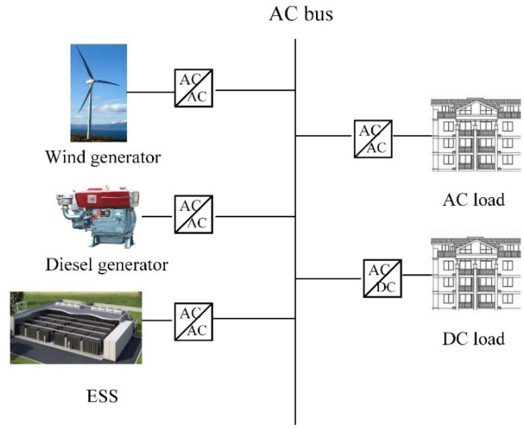

FIGURE 1. The system diagram of isolated microgrid.

as an external disturbance of wind-diesel microgrid. Thus, the problem of frequency control can be further changed to improve disturbance rejection of the system. Based on this consideration, by regarding the load demand variation and wind speed variation as disturbances, this paper applies Equivalent-Input-Disturbance (EID) approach to wind-diesel microgrid systemin response to the above limitation. EID method can estimate an equivalent wind speed variation and equivalent load variation, and that can be utilized to generate new control signals, better for reducing the impact of these fluctuations on the microgrids and so to preserve frequency balance. Besides that, it has a simple structure and does not require the prior information on disturbance [38]. In vehicular steering control, EID has been successfully applied [39], and shows superior disturbance-rejection performance when compared with other methods like SMC [40].

The system diagram of isolated microgrid proposed in this paper is shown as Fig.1 which consists of WTG, diesel generator, ESS and loads. They are connected to the AC bus by converters. WTG, diesel generator and ESS meet the load demand together. On one hand, diesel generator with long-time constant is controlled to suppress the slowly varying and large deviation of supply error. ESS, as an auxiliary frequency regulation, can release and storage power fast and is controlled to suppress the sudden variation of supply error. On the other hand, by smoothing output power of WTG connected to the microgrid, the impact of fluctuated wind energy on the microgrid is further reduced. Double EID controllers apply to WTG system and load frequency control (LFC) model of microgrid for diesel generator system respectively to suppress disturbances including the load demand variation and wind speed variation, so that preserve frequency in a normal range.

The remaining part of this paper is organized as follows. Section II establishes the whole wind-diesel isolated microgrid and the linearized model of WTG, battery ESS and LFC. The double EID method for the system is proposed in Section III. Section IV presents case studies on WTG, LFC and the whole system and discusses the experimental results. Finally, the conclusions are summarized in Section V.

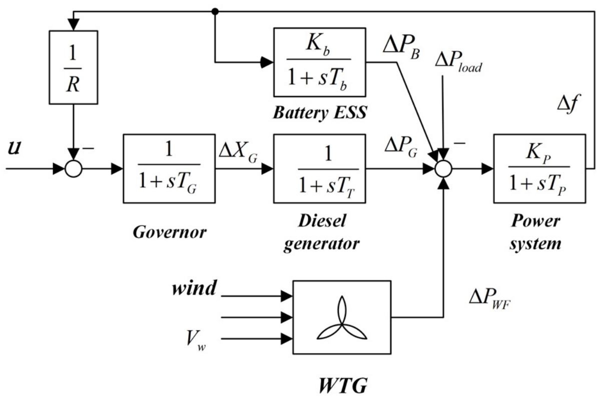

FIGURE 2. LFC model of Wind-diesel isolated system.

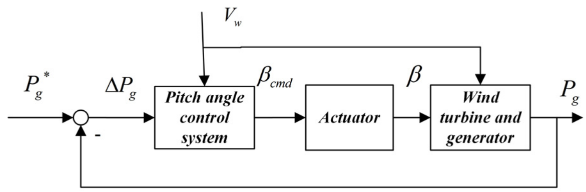

FIGURE 3. The WTG system.

II. SYSTEM DESCRIPTION AND MODELING

A. DESCRIPTION OF THE PROPOSED MICROGRID SYSTEM

The LFC system linearized model of the wind-diesel isolated microgrid [41], [42], referring to Fig.2. Δf, ΔP_G, ΔP_{load}, ΔP_{WF}, ΔP_B, u, is deviation of frequency, power fluctuation of diesel generator, load, WTG, battery ESS and control input respectively around the normal operating point; T_G, T_T, T_b are time constants of governor, diesel generator, battery ESS respectively; R is adjustment coefficient; V_W is wind speed.

Control of frequency and active power is referred to as LFC [43]. The LFC is intended to balance relationship between the active power output of WTG, battery ESS, the diesel generator and the load demand. If generating power varies, then the frequency fluctuates depending on variation of generating power. The transfer function between the power variation and the frequency variation in power system is given as follows [44]:

$$G(s) = \frac{K_p}{T_p s + 1} \tag{1}$$

where K_P is the system gain, T_P is system time constant.

The power supplied to the load demand side is the sum of output power from WTG, battery ESS and diesel generator. However, the output power of WTG is fluctuating and intermittent. Moreover, the load demand changes constantly with time, which will lead to the imbalance between supply and demand of active power. The power deviation can be expressed as:

$$\Delta P = P_G + P_{WF} \pm P_B - P_{load} \tag{2}$$

The system can be subdivided into the design and construction of two subsystems: WTG pitch angle control system and LFC system. The assumed system constraints and definitions for this design are as follows:

- It's assumed that the rated output power of WTG is always less than the load demand and WTG always works at the rated operating point.
- On the diesel generator side, the variation of load demand and WTG output power caused by varied wind speed are regarded as a total disturbance, which is suppressed by applying the EID-LFC controller.
- On the WTG side, the varied wind speed is regarded as the external disturbance to be rejected by the EID-WTG controller.

B. BATTERY ESS

Due to very good technical characteristic, such as fast response and modular flexibility, the battery ESS has been an effective way to help regulate the frequency control. In order to analyze the influence of battery ESS, a simple equivalent transfer function model is proposed as

$$G_{battery}(s) = \frac{K_b}{1 + T_b s} \tag{3}$$

Time constant T_b means its action delay. K_b is gain to show the relationship between output power variation ΔP_B of battery ESS and frequency deviation Δf. This paper focuses on verifying the effectiveness of the EID control method, so the size of the battery, the number of charges and discharges, and the specific dynamic frequency response are neglected. The effectiveness of battery ESS will be validated and discussed in the section IV.

C. WTG LINEARIZED MODEL

Direct-drive Wind Turbine Generator can directly couple wind turbines with generators, which minimal maintenance is required for long periods of operation. In this design, we consider this kind of WTG with a 275kW induction generator. This paper focus on pitch angle control, so only the control when the wind speed exceeds the rated wind speed is considered. A linearized theoretical model of WTG pitch angle control system is to be developed for this design. Pitch control can maintain constant power by adjusting pitch angle in the high wind speed area of rated wind speed. The WTG system is as shown in Fig. 3, including wind turbine, actuator, generator and pitch angle control system.

Where P_g, P_g^*, β, β_{cmd} are the output power of WTG, the reference input of WTG, the pitch angle, the pitch angle control command respectively.

To apply the EID controller, a linear approximate model of WTG is derived by linearizing the plant at rated power point. According to hydrodynamics and Betz law, the kinetic energy that wind turbine can obtain from wind is as follows [41]:

$$P = \frac{1}{2}\rho V_w^3 S C_P \tag{4}$$

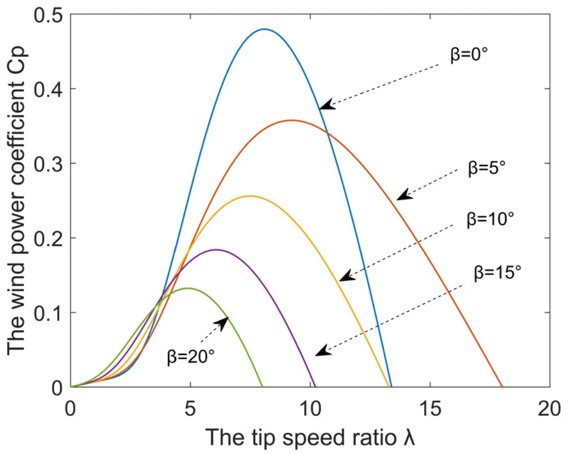

FIGURE 4. The characteristic curve C_P.

where ρ is the air density, S is the area swept of blade and C_P is the wind power coefficient.

The tip speed ratio λ represents the state of the wind turbine at different wind speeds, which can express as

$$\lambda = \frac{2\pi R_a n}{V_w} = \frac{\omega_a R_a}{V_w} \tag{5}$$

where ω_a is angular velocity of the wind turbine and R_a is the radius of the blade.

The wind power coefficient selected in this study is [45]:

$$C_P(\lambda, \beta) = 0.5173(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{6}$$

where $\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$.

The characteristic curve C_P is shown in Fig. 4. From Fig. 4, it can be seen that we can maintain the obtained wind power around the rated power by changing β to get a required C_P.

The shafting model of wind turbine is adopted and simplified as a single mass block model. The dynamic process of transmission chain and power electronic converter is neglected in the modeling. The output torque of the wind turbine is:

$$T_w(\beta, V_w, \omega_a) = \frac{C_P(\lambda, \beta) V_W^3 \rho S}{2\omega_a} \tag{7}$$

The rated power point ($\beta_{op}, V_{Wop}, \omega_{aop}$) is selected as the linearized operating point when WTG is under the rated wind speed. The linearized model is obtained through Taylor expansion

$$\Delta T_w = \bar{A}\Delta\omega_a + \bar{B}\Delta\beta + \bar{C}\Delta V_W \tag{8}$$

where

$$\bar{A} = \frac{\rho S V_W^2}{2\omega_a}(-C_P\frac{V_W}{\omega_a} + R_a\frac{\partial C_P}{\partial \lambda})|_{op}$$
$$\bar{B} = \frac{1}{2}\frac{V_W}{\omega_a}\rho S\frac{\partial C_P}{\partial \beta}|_{op}$$
$$\bar{C} = \frac{\rho S V_W}{2}(3C_P\frac{V_W}{\omega_a} - R_a\frac{\partial C_P}{\partial \lambda})|_{op}$$

The dynamic equation of WTG can be expressed as:

$$J\frac{d\omega_a}{dt} = T_w - T_g \tag{9}$$

where T_g is electromagnetic torque, J is moment of inertia. T_g is regarded as constant since this paper mainly study the pitch angle controller, and the viscous coefficient of the transmission shaft is neglected.

Combining (8) and (9), the linearized model of WTG at rated operating point is as follows:

$$\Delta\dot{\omega}_a = \frac{\bar{A}}{J}\Delta\omega_a + \frac{\bar{B}}{J}\Delta\beta + \frac{\bar{C}}{J}\Delta V_W \tag{10}$$

This state-space representation of the linear WTG model is used to design the control system. The pitch actuator can be modeled as a first-order system:

$$Q(s) = \frac{1}{T_a s + 1} \tag{11}$$

where T_a is time constant.

D. THE LFC SYSTEM MODEL

Since the frequency balance is easily destroyed when microgrid is isolated, diesel generator is usually used to establish isolated microgrid as a stable power source for compensating the fluctuation power from wind output and load demand. And moreover, in this microgrid the battery ESS is added as auxiliary regulation. The state space equations of system model [44] is as:

$$\begin{aligned}
\Delta\dot{f}(t) &= -\frac{1}{T_P}\Delta f(t) + \frac{K_P}{T_P}\Delta P_G(t) - \frac{K_P}{T_P}\Delta P_{load}(t) \\
&\quad + \frac{K_P}{T_P}\Delta P_{WF}(t) + \frac{K_p}{T_p}\Delta P_B \\
\Delta\dot{P}_G(t) &= -\frac{1}{T_T}\Delta P_G(t) + \frac{1}{T_T}\Delta X_G(t) \\
\Delta\dot{X}_G(t) &= -\frac{1}{RT_G}\Delta f(t) - \frac{1}{T_G}\Delta X_G(t) + \frac{1}{T_G}u(t) \\
\Delta\dot{P}_B(t) &= \frac{K_b}{T_b}\Delta f(t) - \frac{1}{T_b}\Delta P_B
\end{aligned} \tag{12}$$

Then transform the above formula into the form of state space-equation as follows

$$\dot{x}(t) = Ax(t) + Bu(t) + H[\Delta P_{WF}(t) - \Delta P_{load}(t)] \tag{13}$$

where $x(t) = \begin{bmatrix} \Delta f(t) \\ \Delta P_G(t) \\ \Delta X_G(t) \\ \Delta P_B(t) \end{bmatrix}$, $A = \begin{bmatrix} -\frac{1}{T_P} & \frac{K_P}{T_P} & 0 & \frac{K_b}{T_b} \\ 0 & -\frac{1}{T_T} & \frac{1}{T_T} & 0 \\ -\frac{1}{RT_G} & 0 & -\frac{1}{T_G} & 0 \\ \frac{K_b}{T_b} & 0 & 0 & -\frac{1}{T_b} \end{bmatrix}$,

$B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_G} \\ 0 \end{bmatrix}$, $H = \begin{bmatrix} \frac{K_P}{T_P} \\ 0 \\ 0 \\ 0 \end{bmatrix}$.

In this microgrid, the output power of battery ESS and diesel generator is the controllable. The EID-LFC is proposed to compensate the power fluctuation from load demand and WTG. Then the system can maintain frequency balance.

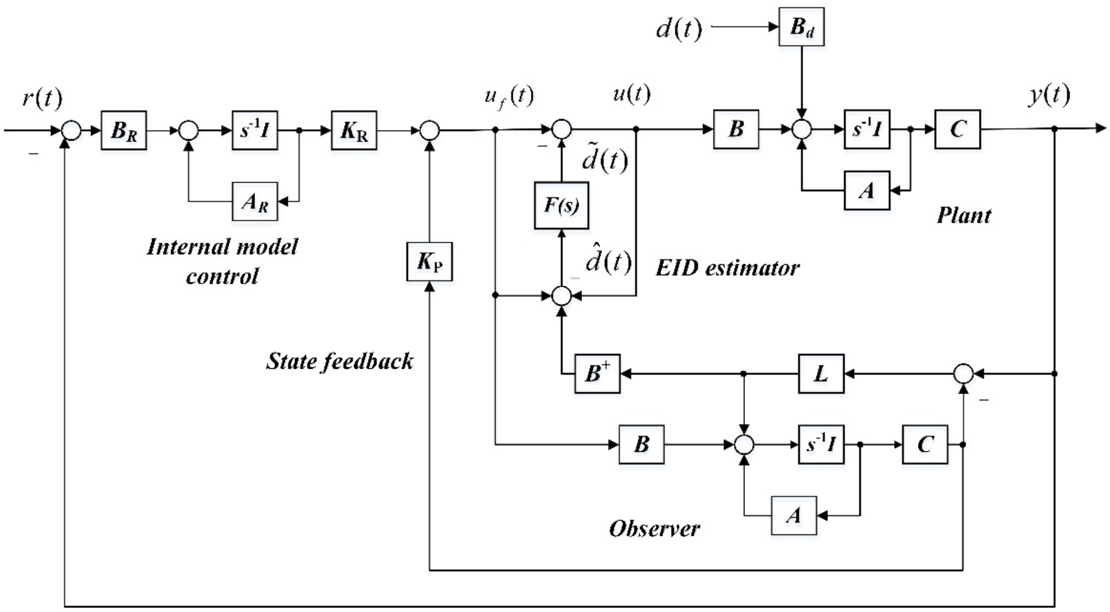

FIGURE 5. The EID control system.

The EID-LFC controller and EID-WTG controller is designed in next section.

III. PROPOSED FREQUENCY CONTROL METHOD BASED ON EID

A. METHODOLOGICAL THEORY OF EID METHOD

As shown in Fig. 5, the EID control system consists of an internal model controller, an EID estimator, a state observer, a controlled plant, and a state feedback controller. The core idea of EID is to find an equivalent disturbance $\tilde{d}(s)$ which make the same influence to the output on the control input channel as real disturbance $d(t)$ does. Then use it to make reverse compensation to the control input channel.

The state feedback control law is:

$$u_f(t) = K_p\hat{x}(t) + K_R x_R(t) \tag{14}$$

where $\hat{x}(t)$ is observer state, $x_R(t)$ is internal model state, K_p is state feedback gain of $\hat{x}(t)$, K_R is state feedback gain of $x_R(t)$.

Consider the following linear time-invariant plant:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + B_d d(t) \\ y(t) = Cx(t) \end{cases} \tag{15}$$

where $A \in R^{n\times n}$, $B \in R^{n\times p}$, $B_d \in R^{n\times q}$, $C \in R^{m\times n}$. $d(t)$ is a disturbance.

As explained in [46], we can obtain estimate of an EID as follows

$$\hat{d}(t) = B^+LC[x(t) - \hat{x}(t)] + u_f(t) - u(t) \tag{16}$$

where $B^+ = (B^TB)^{-1}B^T$. In this paper, EIDs of the varied wind speed and load fluctuations will be estimated respectively and become part of the control signal.

Since the output $y(t)$ contains a measurement noise, $\hat{d}(t)$ need a filter which is chosen to be a first-order $F(s)$ for simplicity:

$$F(s) = \frac{1}{Ts + 1} \tag{17}$$

where T is the time constant of the filter. The filtered disturbance estimation can be described as following

$$\tilde{D}(s) = F(s)\hat{D}(s) \tag{18}$$

where $\tilde{D}(s)$ and $\hat{D}(s)$ are Laplace transforms of $\tilde{d}(t)$ and $\hat{d}(t)$, respectively.

So an new imposed control law including EID is:

$$u(t) = u_f(t) - \tilde{d}(t) \tag{19}$$

B. ANALYSIS OF SYSTEM STABILITY

According separation theorem, state-feedback control law and state observer gain can be designed independently as long as stability is the only concern. Since the external signals and disturbances have no effect on the internal stability of the system, let them be zero. As explained in [46], the transfer function $G_d(s)$ from $\tilde{d}(s)$ to $\hat{d}(s)$ is

$$G_d(s) = B^+(sI - A)[sI - (A - LC)]^{-1}B \tag{20}$$

Based on small-gain theory, the closed-loop EID-based system under the control law (19) is stable if

$$||G_d(s)||_\infty < 1/||F(s)||_\infty \tag{21}$$

for the design of observer.

As the filter is constructed, $\boldsymbol{L}$ is the only parameter should be design which need to satisfy (21). And the optimal control method is a common way to obtain it. Choose the performance index properly, then we can calculate the $[\,K_P\;\;K_R\,]$ and satisfiable $\boldsymbol{L}$.

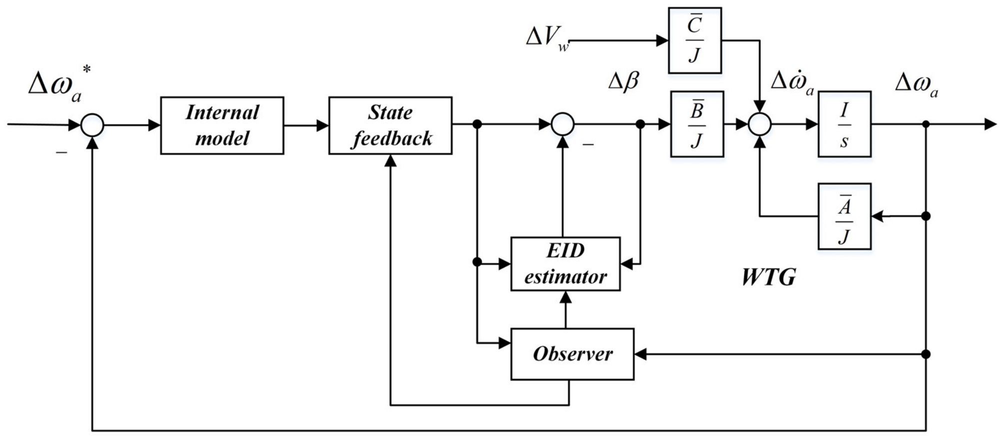

FIGURE 6. WTG system based on EID method.

C. EID INTEGRATED STRATEGY DESIGN FOR THE WHOLE MICROGRID SYSTEM

The EID method is applied to WTG pitch angle control system and microgrid LFC system respectively. The state-space representation of the linear WTG model is expressed above as (10). As shown in the Fig. 6, on WTG side, the ΔV_W is regarded as an external disturbance, $\Delta\beta$ is the control input equivalent to $u(t)$ and $\Delta\omega_r$ is the state variable. As explained in the above section, an equivalent signal of ΔV_W is defined by the EID estimator, and is included in the control input $u(t)$ as a reverse compensation. That is, adjust the pitch angle by this control signal to control the speed of the wind turbine, so as to stabilize the output power of WTG.

For the microgrid LFC side, the changing load demand and the output power fluctuation of WTG are regarded as an external disturbance which will be estimated to an equivalent value and then included in control input as a reverse compensation. EID-LFC controller is applied to suppress this disturbance to control the output power of battery ESS and diesel generator, and then to maintain the frequency.

The whole block diagram of microgrid control system based on EID is as shown in Fig. 7.

IV. SIMULATION RESULTS AND ANALYSIS

The actual stable small power system requires that the frequency deviation range is ±0.2 Hz which chosen to be a standard in this paper. In this section, effectiveness of the proposed method is examined by the simulation results in MATLAB.

All the parameters [13] used in the microgrid are given in the Table 1.

Note that, when wind speed reaches 18 m/s, the obtained power is rated power 275 kw/s. From

$$C_P(\lambda_0, \beta_0) = \frac{2P_{gop}}{\rho S V_{Wop}^3} \tag{22}$$

and (5), (6), we can obtain that the pitch angle at operating point is $\beta_{op} = 35.6°$. And then according to (8), the WTG

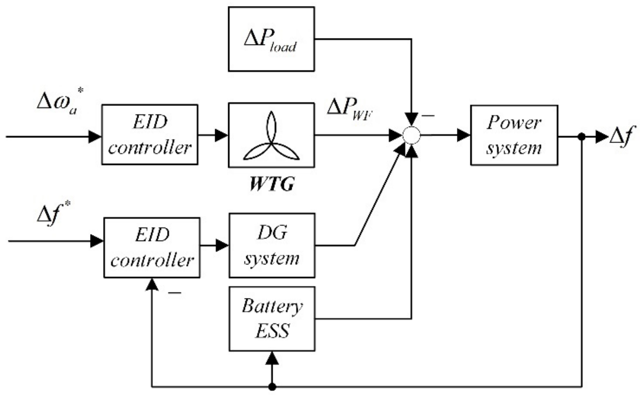

FIGURE 7. The block diagram of microgrid control system based on EID method.

system parameters can be obtained

$$\bar{A} = -0.3589, \quad \bar{B} = -0.101, \quad \bar{B}_d = 0.0921 \tag{23}$$

For linearized model (10) of WTG pitch angle control system, we can get the state feedback gain $K_{WTG} = \begin{bmatrix} -105.5505 & 10 \end{bmatrix}$ and state observer gain $L_{WTG} = -9.994$ which satisfy the stability condition by the optimal control method.

And the state feedback gain

$$K_{LFC} = \begin{bmatrix} -0.5286 & -0.6314 & -0.055 & 0.1023 & 3.1623 \end{bmatrix}$$

and

$$L_{LFC} = 10^4 \times \begin{bmatrix} 8.2597 & 0.4517 & 0.0267 & -0.006 \end{bmatrix}^T$$

for LFC system obtained by the same method.

The wind speed as shown in Fig. 8 is modeled by four-component modeling method, which contains basic wind, gust, step wind and random wind. Load variation is simulated by random signal in MATLAB as shown in Fig. 9. In order to verify the effectiveness of the EID control method, only 600s simulation data are used.

Five cases are simulated in MATLAB. The results are presented and discussed in following part.

TABLE 1. System parameters.

Symbol	Quantity
V_{Wop}	18 m/s
ω_{aop}	4.616 rad/s
P_{gop}	275 kw
ρ	1.225 kg/m^3
J	62993 kg·m^2
R_a	14 m
T_g	59.575 N·m
T_a	0.05 s
T_G	0.0728 s
T_T	0.273 s
R	2 Hz/p.u MW
T_P	15 s
K_P	120 Hz/p.u MW
A_R	0
B_R	1
T	0.01 s
K_{P1}	27
K_i	0.4

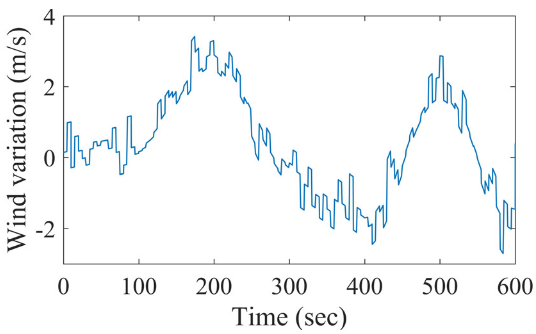

FIGURE 8. Wind speed variation.

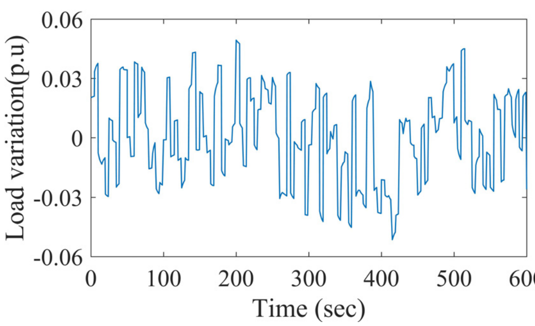

FIGURE 9. Random load variation.

Case 1: In this basic case, there is no battery equipped with the isolated microgrid. The WTG system and diesel generator system are both controlled by PI method. The simulation results are shown in Fig. 10, it shows that the frequency deviation exceeds ±0.2Hz because of the load variation and wind power fluctuation.

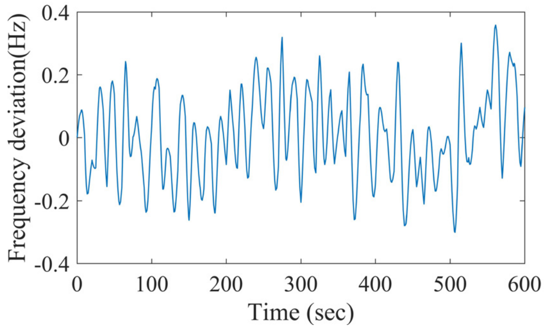

FIGURE 10. Frequency deviation under PI method.

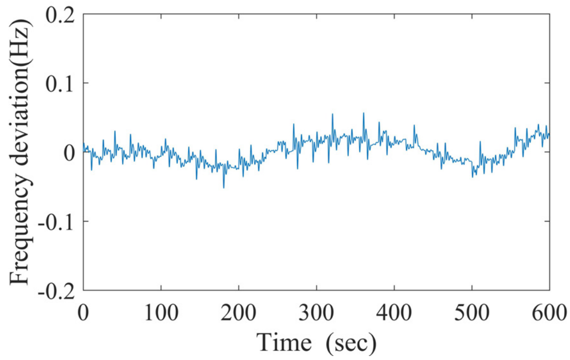

FIGURE 11. Frequency deviation with battery.

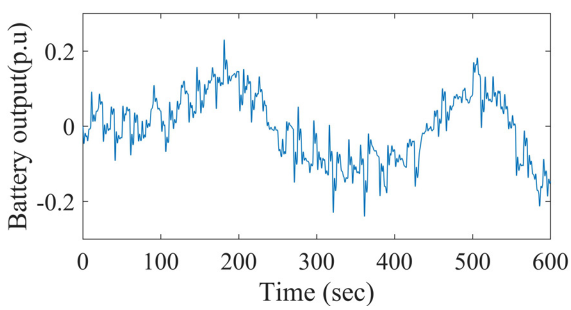

FIGURE 12. Battery output.

The result of this basic case will be compared with the following case to verify the effectiveness of battery ESS and the proposed method.

Case 2: Based on case 1, the battery is added to the microgrid as an auxiliary regulation. There is still no EID method in this case. After the battery ESS connecting to the microgrid, the frequency deviation is limited within ±0.05Hz from Fig.11 which shows that battery ESS can effectively adjust the frequency problem. Comparing with the basic case 1, the suppression performance of frequency fluctuation is increased by 75%.

However, as we have mentioned in the introduction section, the capacities of batteries must be taken into account. The battery output from Fig.12 shows that according to the large wind power and load fluctuation, it may be need large capacity battery to get the effective adjustment. The result shows that when the load demand variation is $-0.06 \sim +0.06$ p.u,

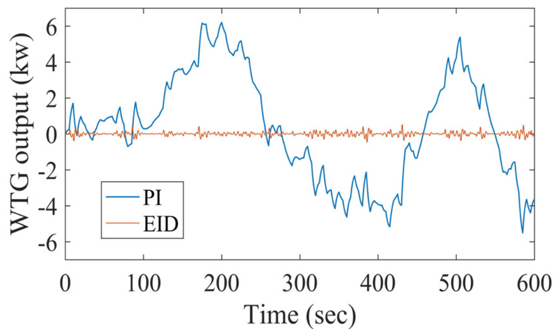

FIGURE 13. WTG output.

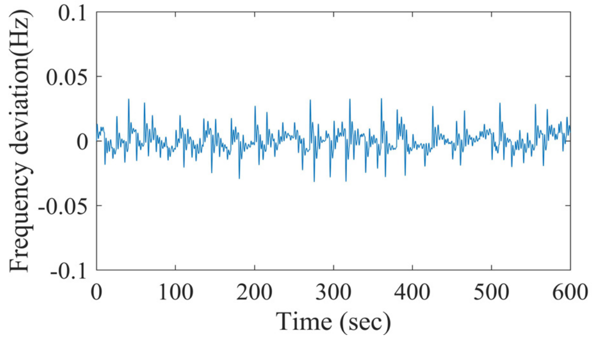

FIGURE 14. Frequency deviation with single WTG-EID controller.

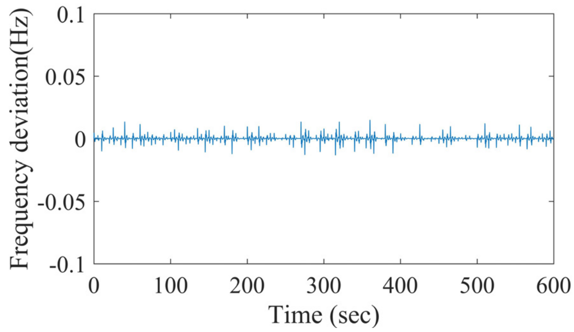

FIGURE 15. Frequency deviation with single EID-LFC controller.

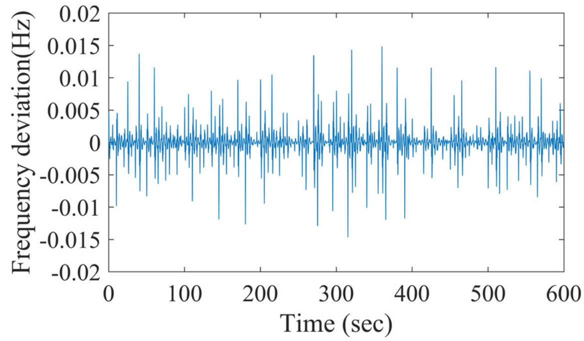

FIGURE 16. Frequency deviation under double EID controllers with battery.

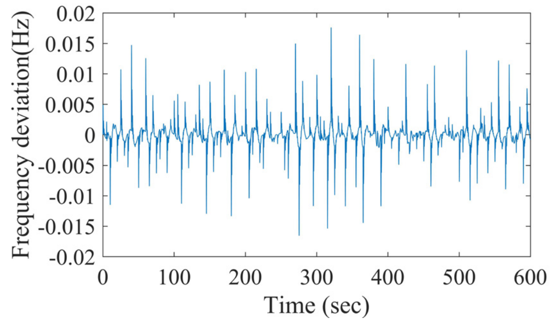

FIGURE 17. Frequency deviation under double EID controllers without battery.

it needs to match the battery ESS with $-0.2 \sim +0.2$ p.u. Therefore, the size of the battery ESS and the regulation performance must be considered comprehensively in practical system

Actually, to further enhance ESS reliability, compared with single battery ESS, the design of versatile ESS including batteries, superconducting magnetic energy storage, and kinetic energy storage in flywheels can adapt to more complex situations.

Case 3: In this case, based on case 2 which connected battery ESS, consider adding single EID controller to WTG pitch angle control or microgrid LFC system dividedly. Fig. 13 $\sim$ Fig. 15 shows the results. The output of WTG is more stable under EID controller than PI control.

Figure 14 shows that when apply single EID controller to WTG in microgrid. The frequency deviation is limited in ± 0.05Hz and is more stable since the WTG output is more smooth. This means the connection of wind power under EID controller will have smaller impact on the microgrid.

Figure 15 shows the system frequency deviation is limited to ± 0.015Hz which far less than ± 0.2Hz in case 1, by using the single EID-LFC for diesel generator. This result also shows that controlling the output of diesel generator and battery ESS are the main parts to suppress the frequency fluctuation compared with controlling WTG only.

Case 4: In this case, the designed double EID controllers frequency control method is applied to WTG and microgrid LFC system with battery. It can be seen from Fig. 16 that the frequency deviation is limited in ± 0.015Hz. The method proposed in this paper has been proved to be more effective than other case above.

In order to further study the contribution of battery ESS to frequency control under the proposed method, another comparative experiment was taken. Under double EID controllers, we consider disconnecting the battery ESS and the frequency deviation is a little out ± 0.015Hz in Fig. 16 while still limited in ± 0.015Hz with battery ESS in Fig. 17. However, within such a narrow range, the suppression effectiveness of these two cases can be regarded as almost the same. This obviously shows that when there is no battery ESS, the designed double EID frequency control method also can preserve frequency deviation in a minor range. The double EID controllers reduces the dependence on auxiliary regulation of battery ESS and improves the reliability of the controllers.

Case 5: In this case, we consider when the LFC system subjected to the step load perturbation to show instantaneous

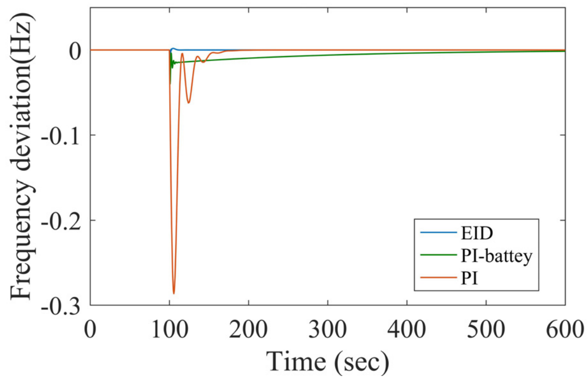

FIGURE 18. Frequency deviation under step load perturbation.

dynamic regulation performance under PI method, PI method with battery and EID method respectively. The step load perturbation added at $t = 100$ s is 0.1p.u. The result is shown in Fig. 18. It shows that all three methods can also make the frequency deviation reach to zero, but the EID method has the fast response and little chattering which is more effective than other two method.

The step load in this case can represent the cut-in and cut-off of user load in real life which also have sudden impact on small-capacity microgrids. Therefore, further information can be obtained from case 4 and case 5, that is, whether it's random or step fluctuations the proposed method can achieve better instantaneous dynamic regulation performance than only utilizing battery ESS.

V. CONCLUSION

The new frequency control method for wind-diesel isolated microgrid based on double EID method has been presented. Double EID controllers are applied to WTG system and LFC for diesel generator dividedly in this paper. Moreover, Battery ESS is added as auxiliary regulation. The generated control signal by EID method includes the estimated equivalent wind speed and equivalent load variation. Thus it greatly improves the system's ability to suppress frequency fluctuation compared with PI method which does not incorporate the information of wind speed and load variation. Through the above simulation and analysis, we can draw the following main three conclusions:

- By applying EID controller to WTG, the output power of WTG can be controlled to fluctuate in a very small range under the fluctuation of wind speed. This can reduce the impact on microgrid when wind power connected and play an active role in frequency regulation of wind-diesel microgrid.
- The system frequency deviation can be properly controlled within a very small range under the proposed integrated double EID controllers method and also has better instantaneous dynamic regulation performance.
- Moreover, satisfactory results can be achieved even when the battery ESS is disconnected which means we can reduce dependence on battery ESS and other related concerns about it in real system.

To summarize, the proposed integrated double EID controllers method for frequency control of wind-diesel microgrid can achieve flexible and superior frequency control performance.

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