

Dynamic Frequency Regulation of Wind Turbine Generators via Kinetic Energy Trajectory-based Control

Ziyang Huang, *Member, IEEE, Member, CSEE*, Zihan Wang, *Member, IEEE, Member, CSEE*, Xiaonan Zhang, *Student Member, IEEE, Member, CSEE*, Gengyin Li, *Member, IEEE, Member, CSEE*, Jianxiao Wang, *Senior Member, IEEE, Member, CSEE*, and Tiance Zhang, *Member, IEEE, Member, CSEE*

Abstract—To mitigate the deterioration of the system frequency response (SFR) caused by the increasing penetration of wind power, wind turbine generators are required to release their kinetic energy during frequency events to provide dynamic frequency support. Existing additional frequency control (AFC) primarily focuses on simulating output power with insufficient attention given to actual energy variations, thus posing challenges in optimizing energy management while maintaining control continuity. Moreover, abrupt control switching to avoid over-deceleration has a negative impact on the SFR. To address these issues, this paper proposes a novel AFC based on the kinetic energy trajectory (KET). An explicit smooth KET is first designed to serve as the energy reference. Specifically, the KET generates a positive power deviation when frequency drops and stores as much energy as possible when frequency rises. Then, the KET recovers energy to its initial state as frequency stabilizes. An adaptive sliding mode control is also employed to ensure the convergence of energy towards the KET, while enhancing robustness against various errors. Finally, the effectiveness and superiority of the proposed control are verified through an extended SFR model and a modified IEEE 9-bus system.

Index Terms—Additional frequency control, kinetic energy trajectory, system frequency response, wind turbine generator.

NOMENCLATURE

A. Acronyms

(A)SMC	(Adaptive) sliding mode control.
(A)TPC	(Adaptive) temporary power control.
DFIG	Double fed induction generator.
(E)AFC	(KET-based) additional frequency control.
KET	Kinetic energy trajectory.
FE	Frequency extremum.
(MO)SIC	(Multi-objective) synthetic inertia control.
MPPT	Maximum power point tracking.

ROCOF	Rate of change of frequency.
SFD	Secondary frequency dip.
SFR	System frequency response.
SG	Synchronous generator.
UUB	Uniformly ultimately boundedness.
WGN	White gaussian noise.
WTG	Wind turbine generator.

B. Time-Invariant Parameters

H_{sg}, H_{wtg}	Inertia coefficients of SG and WTG (s).
D_{sg}, D	Damping coefficients of SG and load.
$G_{sg}(s)$	Turbine governor system dynamics of SG.
ρ_{sg}, ρ_{wtg}	Generation coefficients of SG and WTG.
ΔP_0	Power disturbance (p.u.).
ρ	Air density (kg/m ³).
R	Wind turbine blade radius (m).
v	Wind speed (m/s).
H_x, D_y	Virtual inertia (s) and damping coefficient of x or y , $x \in \{sic, eafc1, eafc2\}$, $y \in \{sic\}$.
ΔP_z	Over-production (p.u.) of z , $z \in \{tpc, atpc, eafc1\}$.
t_0	Frequency event starting time (s).
t_1, t_2	Times of first FE and control switching (s).
σ	Inflection points change rate of $\tanh(\cdot/\sigma)$.
k_1, k_2, k_3	Positive gains of ASMC.

C. Time-Varying Variables

ω_{sys}	System frequency (p.u.).
ΔP_{sg}	Governor power deviation of SG (p.u.).
ω_{wtg}	Rotor speed of WTG (p.u.).
E_{wtg}	Rotor kinetic energy of WTG (s).
P_{wtg}	Output power of WTG (p.u.).
P_{mec}	Mechanical power of WTG (p.u.).
e_0	Frequency control start-stop signal (0/1).
λ	Tip speed ratio of wind turbine.
c	Wind energy capture coefficient of wind turbine.
d	Aggregated disturbance (p.u.).
e	Tracking error of energy (s).
s_0	Sliding surface (s).
δ	Upper bound of error (p.u.).
$\Delta x, \dot{x}$	Deviation of variable x from its initial state, and its time derivative.

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Z. Y. Huang, Z. H. Wang, X. N. Zhang, G. Y. Li and T. C. Zhang (corresponding author, email: ncepuztc@ncepu.edu.cn) are with the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China.

J. X. Wang is with the National Engineering Laboratory for Big Data Analysis and Applications, Peking University, Beijing 100871, China.

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D. Superscripts

db	Deadband of variable.
ini	Initial value of variable.
min/max	Limits or time-domain extremes of variable.
nom	Nominal value of parameter or variable.
opt	Optimal value of parameter or variable.
pre	Preset value of variable.
ref	Reference value of variable.
−/+	Instants preceding and succeeding a specific time.

I. INTRODUCTION

DYNAMIC frequency stability [1] can be commonly evaluated using three metrics in the SFR: ROCOF, FE, and frequency recovery time. For general source-load mismatch scenarios where frequency remains within limits, the first two metrics, which reflect the severity and duration of frequency events, are typically of greater concern. With the increasing integration of power electronics, particularly due to the substantial growth in renewable energy penetration dominated by large-scale WTGs, grid inertia and damping characteristics have significantly deteriorated. This results in a higher ROCOF and a worse FE in the frequency event. When operating in MPPT mode, a WTG's rotor becomes decoupled from SGs, with its output power solely dependent on wind speed [2]. In this case, WTG cannot provide dynamic frequency support.

To address deteriorating frequency dynamics, system operators require WTGs to emulate frequency response characteristics similar to those of SGs [3], essentially through the utilization of kinetic energy. Existing studies have identified two primary utilization methods. The first method is deloading control, where WTG reduces its mechanical power and operates suboptimally by increasing rotor speed [4], adjusting blade pitch angle [5], or coordinating the two [6]. During the frequency drop event, WTG energy is released through the transition from a suboptimal state to an optimal state. However, this method can only provide slow power regulation for FE improvement and steady-state frequency support, while being less effective for emulating inertia to improve ROCOF [7]. In addition, deloading operation damages both power generation and economy of WTGs. The second method is AFC, which relies on fast converter dynamics to provide fast support across multiple timescales. Power reference of a WTG can originate from either an upper-level wind farm optimization controller [8]–[11] or a local speed controller. This paper focuses on the local speed controller, which emphasizes the energy utilization and frequency regulation capabilities of WTG and provides an explicit, parameter-tunable power reference [12]–[24]. AFC can be further classified into frequency-based and energy-based types according to relevant control variables.

The most representative frequency-based AFC is SIC [12]. SIC takes frequency deviation and ROCOF as inputs to the speed controller, enabling WTGs to emulate inertia response and primary frequency regulation, similar to that of SGs. For fixed inertia and damping coefficients, an SFD may occur following over-deceleration. To address this, adaptive gains have been proposed that are proportional to rotor speed [13],

available energy [14], or decay over time [15]. However, rapid power reference reduction contradicts effective energy release. The steady-state damping contribution in SIC prevents energy from recovering to its initial state. To mitigate this, a washout filter cascaded with the damping loop is introduced in [16] to eliminate low-frequency components of the SFR, whereas in [17], a PI supplementary term regarding rotor speed deviation is incorporated into the power reference. Both methods, however, risk inducing energy oscillations. Recent studies prioritize enhanced energy release during large disturbances. In [18], a fuzzy-logic-based damping coefficient is designed, which is adjusted by rotor speed and frequency deviation. In [19], a conservative estimation of the maximum damping coefficient is established. Although the above SIC modifications demonstrate effectiveness, implicit energy variations during the frequency event critically restrict the control performance of SIC. There still exists substantial potential for energy utilization in the above studies.

Due to its rapid response, speed-based AFC is alternatively termed TPC. During a frequency drop event, TPC follows a predefined shape function for energy release and recovery to generate a power reference independent of frequency. In the early study, a small, fixed overproduction [20] is adopted as the shape function, which faces limitations including insufficient support and the SFD caused by the abrupt termination of overproduction. Subsequent studies focus on eliminating the SFD. In [21], a power reference proportional to rotor speed is introduced to mitigate control switching imbalances, while an optimal switching time to balance the first FE and SFD is sought in [22]. To accelerate energy recovery and improve operational economics, conic curves are adopted as recovery trajectories in [23] and [24]. Despite the progress of TPC in shape function design, the inherent dynamic decoupling between energy and frequency impedes its applicability and full energy utilization under different grid conditions and disturbances.

In conclusion, to efficiently support dynamic frequency with WTG energy and enhance the control applicability of AFC, it is necessary to establish explicit energy variations coupled to frequency. From the perspective of WTG energy, a novel EAFC is proposed. The main contributions are as follows.

1) The energy dynamics of WTG are derived and integrated into the system models. By analyzing the limitations in energy utilization of generic AFC, the concept of EAFC is introduced, and the corresponding speed controller is designed.

2) A two-stage KET involving energy offset and recovery is designed to provide enhanced dynamic frequency regulation.

3) An ASMC is proposed to converge energy to the KET while improving robustness against diverse errors. The effectiveness of the adaptive law of ASMC is rigorously proven through Lyapunov analysis using the UUB condition.

The rest of this paper is organized as follows: Section II derives the WTG energy dynamics; Section III analyzes the limitations of generic AFC and introduces the concept of EAFC; Section IV designs a two-stage KET for energy offset and recovery; Section V proposes the ASMC for energy convergence; Section VI presents case studies; and Section VII concludes this work.

II. WTG MODELING WITH ENERGY DYNAMICS

An aggregated WTG is employed to simplify discussions, focusing on dynamic behaviors relevant to frequency regulation rather than differences in operational state among multiple WTGs. The rotor shaft of WTG is modeled as an ideal mass without torsional vibration or deformation. The following swing equation gives its mechanical dynamics.

$$2H_{\text{wtg}}\omega_{\text{wtg}}\dot{\omega}_{\text{wtg}} = P_{\text{mec}} - P_{\text{wtg}} \quad (1)$$

where the per-unit mechanical power P_{mec} is determined by aerodynamic efficiency.

$$P_{\text{mec}}P_{\text{wtg}}^{\text{nom}} = 0.5\rho\pi R^2 v^3 c \quad (2)$$

with

$$P_{\text{wtg}}^{\text{nom}} \triangleq 0.5\rho\pi R^2 (v^{\text{nom}})^3 c^{\text{max}}$$

where $P_{\text{wtg}}^{\text{nom}}$ denotes the WTG nominal power (in MW) defined when the nominal wind speed v^{nom} is reached and WTG operates at maximum wind energy capture efficiency c^{max} .

c is a function of the tip speed ratio λ and the blade pitch angle β_{wtg} . For v below v^{nom} , β_{wtg} remains at 0 [25], making c solely dependent on λ , which itself is a dual-variable function of ω_{wtg} and v defined as (3). c is thus represented as $c(\omega_{\text{wtg}}, v)$.

$$\lambda \triangleq \frac{\omega_{\text{wtg}}\omega_{\text{wtg}}^{\text{nom}} R}{v} \quad (3)$$

where $\omega_{\text{wtg}}^{\text{nom}}$ is the nominal rotor speed (in rad/s). To achieve c^{max} , the optimal tip speed ratio λ^{opt} must be maintained. Consequently, the initial rotor speed $\omega_{\text{wtg}}^{\text{ini}}$ and the initial wind speed v^{ini} under MPPT satisfy

$$\frac{\omega_{\text{wtg}}^{\text{ini}}\omega_{\text{wtg}}^{\text{nom}} R}{v^{\text{ini}}} = \lambda^{\text{opt}} \triangleq \frac{\omega_{\text{wtg}}^{\text{nom}} R}{v^{\text{nom}}} \Rightarrow \omega_{\text{wtg}}^{\text{ini}} = \frac{v^{\text{ini}}}{v^{\text{nom}}} \quad (4)$$

Substituting $c(\omega_{\text{wtg}}, v)$ into (2) yields P_{mec} as the following function of ω_{wtg} and v .

$$P_{\text{mec}} = \left(\frac{v}{v^{\text{nom}}}\right)^3 \frac{c(\omega_{\text{wtg}}, v)}{c^{\text{max}}} \quad (5)$$

Due to the difficulty in accurately obtaining the true value of P_{mec} online, an estimation of P_{mec} is introduced. To start with, v is assumed fixed at its initial value v^{ini} during the SFR; then, the second-order Taylor series expansion of c at $\omega_{\text{wtg}} = \omega_{\text{wtg}}^{\text{ini}}$ is used to estimate P_{mec} , denoted as $\hat{P}_{\text{mec}}$. $\hat{P}_{\text{mec}}$ is widely adopted in the subsequent control design. For practical applications, it is recommended to configure $\hat{P}_{\text{mec}}$ using empirical formula (5).

$$\hat{P}_{\text{mec}} = (\omega_{\text{wtg}}^{\text{ini}})^3 \left[1 + \frac{1}{2c^{\text{max}}} \frac{d^2 c}{(d\omega_{\text{wtg}})^2} \bigg|_{\omega_{\text{wtg}}^{\text{ini}}} (\omega_{\text{wtg}} - \omega_{\text{wtg}}^{\text{ini}})^2 \right] \quad (6)$$

The following typical empirical formula [26] for c is adopted to calculate the second derivative.

$$c = \left(\frac{39.53}{\lambda} - 3.09 \right) e^{-\frac{12.5}{\lambda}} \Rightarrow \frac{d^2 c}{(d\omega_{\text{wtg}})^2} \bigg|_{\omega_{\text{wtg}}^{\text{ini}}} \approx -\frac{4c^{\text{max}}}{(\omega_{\text{wtg}}^{\text{ini}})^2} \quad (7)$$

The energy dynamics must match the timescale of the SFR. Therefore, the most relevant WTG components are its mechanical dynamics and the speed controller. The latter primarily generates a power reference $P_{\text{wtg}}^{\text{ref}}$ for the rotor-side converter. Under stability constraints, the rotor-side and grid-side converter dynamics are sufficiently fast to justify the approximation $P_{\text{wtg}} \approx P_{\text{wtg}}^{\text{ref}}$. Substituting (5) and $P_{\text{wtg}} \approx P_{\text{wtg}}^{\text{ref}}$ into (1) and introducing the kinetic energy definition, the WTG energy dynamics are derived as

$$\begin{aligned} \dot{E}_{\text{wtg}} &= P_{\text{mec}} - P_{\text{wtg}}^{\text{ref}} \\ &= \left(\frac{v}{v^{\text{nom}}}\right)^3 \frac{c(\sqrt{E_{\text{wtg}}/H_{\text{wtg}}}, v)}{c^{\text{max}}} - P_{\text{wtg}}^{\text{ref}} \end{aligned} \quad (8)$$

with

$$E_{\text{wtg}} \triangleq H_{\text{wtg}}\omega_{\text{wtg}}^2$$

Essentially, equation (8) constitutes a nonlinear state equation with E_{wtg} , $P_{\text{wtg}}^{\text{ref}}$, and v as the state variable, control variable, and disturbance, respectively. This formulation applies a nonlinear definition domain mapping $\omega_{\text{wtg}} = (E_{\text{wtg}}/H_{\text{wtg}})^{0.5}$ to (1), thereby facilitating c to be a composite function of E_{wtg} .

Two WTG modeling methods are considered based on converter dynamics approximation, as shown in Fig. 1. Model 1 is a detailed full-order grid-connected DFIG model [27] that includes complete converter dynamics, ensuring high simulation fidelity. Model 2 is a simplified reduced-order model excluding grid topology. In this model, the power-frequency response of WTG is integrated as an additional feedback loop to the classic SFR model [28], with millisecond-level converter dynamics ignored [29]. This model is primarily used for preliminary analysis of control performance.

III. NOVEL ADDITIONAL FREQUENCY CONTROL

A. Limitations of Generic AFC

This subsection discusses the limitations of the generic AFC applicable to WTG. To embed diverse generic AFC while ensuring compatibility with system models that integrate energy dynamics, the speed controller adopts the structure shown in Fig. 2(a), which includes the following modules:

- Start-stop logic. Set e_0 to 1 to activate AFC if $\Delta\omega_{\text{sys}}$ exceeds the deadband $[-\Delta\omega_{\text{sys}}^{\text{db}}, \Delta\omega_{\text{sys}}^{\text{db}}]$. Set e_0 to 0 without reactivation to terminate AFC if $\Delta\omega_{\text{sys}}$ returns to the deadband or energy reaches operational limit ($E_{\text{wtg}}^{\text{min}}$ or $E_{\text{wtg}}^{\text{max}}$).
- Generic AFC. Conventional SIC and TPC are tested. SIC retains MPPT while incorporating the inertia and damping terms of $\Delta\omega_{\text{sys}}$ into over-production [12]. TPC temporarily suspends MPPT to provide fixed over-production based on the sign of $\Delta\omega_{\text{sys}}$ [20]. Their power references during the frequency event are given by

$$P_{\text{wtg}}^{\text{ref}} = \begin{cases} -2H_{\text{sic}}\dot{\omega}_{\text{sys}} - D_{\text{sic}}\Delta\omega_{\text{sys}} + P_{\text{wtg}}^{\text{opt}}, & \text{SIC} \\ -\text{sgn}(\Delta\omega_{\text{sys}})\Delta P_{\text{tpc}} + P_{\text{wtg}}^{\text{ini}}, & \text{TPC} \end{cases} \quad (9)$$

with

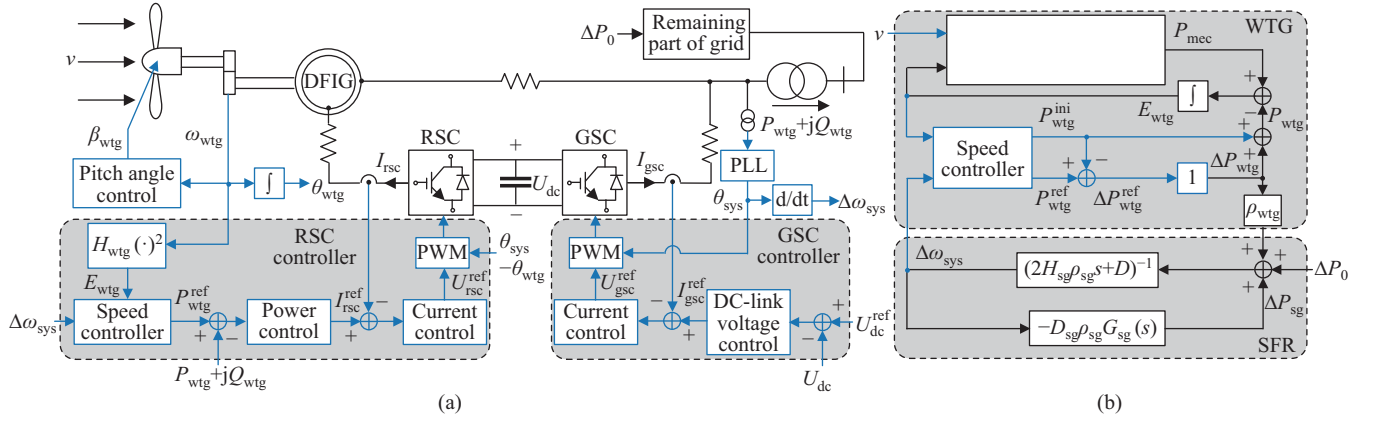


Fig. 1. System models with WTG providing frequency support. (a) Model 1: Grid-connected DFIG. (b) Model 2: Extended SFR model with WTG.

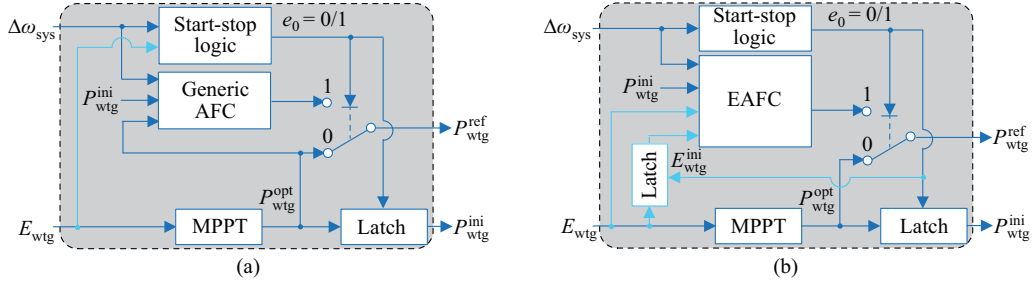


Fig. 2. Basic structure of speed controller. (a) Speed controller for generic AFC. (b) Speed controller for EAFC.

$$P_{wtg}^{opt} = \min \left\{ \left(\frac{E_{wtg}}{H_{wtg}} \right)^{1.5}, 1 \right\}$$

where P_{wtg}^{opt} and P_{wtg}^{ini} represent the optimal and initial MPPT power, and $\text{sgn}(\cdot)$ is the sign function.

- Latch. Saves and holds P_{wtg}^{ini} for the AFC module.
- MPPT. Determine P_{wtg}^{opt} via the MPPT curve.

Using (9), Fig. 2(a), and Model 2, tests are conducted under $\Delta P_0 = -0.1$ p.u., with other parameters listed in Table I. For simplicity, $H_{sic} = D_{sic}/2$ is set for SIC. The dynamic responses of $\Delta\omega_{sys}$ and E_{wtg} with varying H_{sic} and ΔP_{tpc} are shown in Fig. 3.

As shown in Fig. 3(b), larger control parameters increase power reference and energy release rate. When energy reaches $E_{min\ wtg}$, AFC forcibly switches back to MPPT to prevent over-deceleration, accompanied by an abrupt ROCOF change in Fig. 3(a). For SIC with small control parameters ($H_{sic} \leq 20$ s), no switching occurs as energy remains above $E_{min\ wtg}$. For large control parameters ($H_{sic} = 30$ s or $\Delta P_{tpc} \geq 0.1$ p.u.), the control switching occurs after FE and triggers an SFD.

The discontinuity in the ROCOF is theoretically explained. As per Fig. 1(b), the SFR part of Model 2 is described by

$$2H_{sg}\rho_{sg}\dot{\omega}_{sys} + D\Delta\omega_{sys} = \rho_{sg}\Delta P_{sg} + \rho_{wtg}(P_{wtg}^{ref} - P_{wtg}^{ini}) + \Delta P_0 \quad (10)$$

with

$$\rho_{sg} + \rho_{wtg} = 1$$

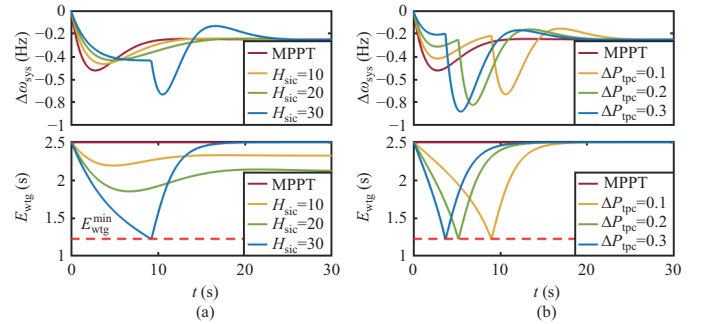


Fig. 3. Simulation results of generic AFC. (a) SIC. (b) TPC.

Substituting the WTG energy dynamics (8) into (10) yields mixed dynamics of frequency and energy.

$$2H_{sg}\rho_{sg}\dot{\omega}_{sys} + \rho_{wtg}\dot{E}_{wtg} = -D\Delta\omega_{sys} + \rho_{sg}\Delta P_{sg} + \rho_{wtg}P_{mec} - \rho_{wtg}P_{wtg}^{ini} + \Delta P_0 \quad (11)$$

Neither frequency nor energy can undergo an abrupt change, which also constrains the right side of (11). Hence, the numerical mutations in $\dot{\omega}_{sys}$ and $\dot{E}_{wtg}$ are subjected to algebraic constraints. Taking the difference of (11) at the instants preceding and succeeding the control switching time t_2 yields

$$2H_{sg}\rho_{sg}(\dot{\omega}_{sys}(t_2^+) - \dot{\omega}_{sys}(t_2^-)) + \rho_{wtg}(\dot{E}_{wtg}(t_2^+) - \dot{E}_{wtg}(t_2^-)) = 0 \quad (12)$$

As indicated in (12), any stepwise change in $\dot{E}_{wtg}$ will be mapped proportionally to a stepwise change in $\dot{\omega}_{sys}$, revealing

the limitations in energy utilization of generic AFC. Since the energy variations fail to be precisely controlled, energy reaches its limit in a non-tangential manner, i.e., $\dot{E}_{\text{wtg}}(t_2^-) \neq 0$. $\dot{E}_{\text{wtg}}(t_2^+)$ should be opposite to $\dot{E}_{\text{wtg}}(t_2^-)$ to avoid energy over-deceleration, which leads to SFR deterioration and potential SFD.

B. Proposed EAFC

Generic AFC primarily focuses on power simulation, pursuing a carefully-designed power reference regardless of energy variations. However, maximum energy utilization is accompanied by SFR deterioration. Given this, a novel AFC is proposed, whose concept involves generating a smooth energy reference $E_{\text{wtg}}^{\text{ref}}$ based on $\Delta\omega_{\text{sys}}$ and adjusting $P_{\text{wtg}}^{\text{ref}}$ accordingly by making E_{wtg} track $E_{\text{wtg}}^{\text{ref}}$. $E_{\text{wtg}}^{\text{ref}}$ is referred to as the KET and aims to utilize energy for improving dynamic frequency while avoiding SFR deterioration. As E_{wtg} converges to $E_{\text{wtg}}^{\text{ref}}$, a smooth $E_{\text{wtg}}^{\text{ref}}$ ensures that both $\dot{E}_{\text{wtg}}$ and $\dot{\omega}_{\text{sys}}$ are continuous.

To embed EAFC, the speed controller is redesigned as shown in Fig. 2(b). Its primary distinction from Fig. 2(a) is highlighted in light blue, where energy now plays a role only in generating $P_{\text{wtg}}^{\text{ref}}$ for frequency support, without affecting the start-stop logic.

The new speed controller includes the following modules:

- Start-stop logic. Simplified as a deadband of $\Delta\omega_{\text{sys}}$, removing energy considerations.
- EAFC. Generates $P_{\text{wtg}}^{\text{ref}}$ using both $\Delta\omega_{\text{sys}}$ and energy. The complete design is shown in Fig. 4 (detailed discussion will follow).
- Latches. Save and hold $P_{\text{wtg}}^{\text{ini}}$ and $E_{\text{wtg}}^{\text{ini}}$ for the AFC module.
- MPPT. Same as Fig. 2(a).

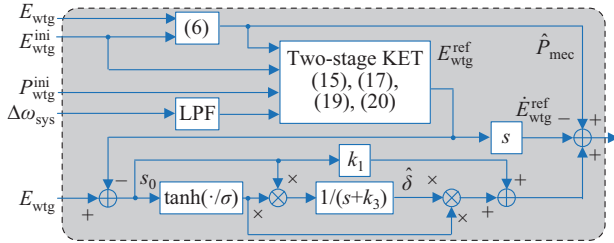


Fig. 4. Structure of the proposed EAFC.

IV. TWO-STAGE ENERGY UTILIZATION TRAJECTORY

In this section, it is assumed that the actual energy converges to the KET, that is, $E_{\text{wtg}} \approx E_{\text{wtg}}^{\text{ref}}$. The KET is designed to operate in two distinct stages: energy offset stage within the time interval $(t_0, t_2]$ and energy recovery stage within the time interval (t_2, ∞) .

A. KET for the Energy Offset Stage

As WTG deviates from its maximum power point during the SFR, both aerodynamic efficiency and mechanical power decrease. This corresponds to negative damping during the frequency drop event and positive damping during the frequency

rise event, respectively. Therefore, the KET within this stage must differentiate between event types.

1) KET during the frequency drop event ($\Delta\omega_{\text{sys}} < -\Delta\omega_{\text{sys}}^{\text{db}}$)

During the time interval $(t_0, t_1]$, $\Delta\omega_{\text{sys}}$ transitions from 0 to a minimum value, while WTG is expected to release its energy. In [30], a genetic algorithm is employed to tune the control parameters of conventional SIC, aiming to ensure $\Delta P_{\text{wtg}} \geq 0$ to avoid negative damping deteriorating the frequency nadir. With the implementation of the KET, this objective can be easily achieved. The time derivative of the KET is designed as

$$\dot{E}_{\text{wtg}}^{\text{ref}} = m \frac{2H_{\text{sg}}\rho_{\text{sg}}}{\rho_{\text{wtg}}} \dot{\omega}_{\text{sys}} + (\hat{P}_{\text{mec}} - P_{\text{wtg}}^{\text{ini}}) \quad (13)$$

where m is a positive multiplier factor. If the error between $\hat{P}_{\text{mec}}$ and P_{mec} is small, it can be further derived that:

$$\begin{aligned} \Delta P_{\text{wtg}} &= P_{\text{mec}} - E_{\text{wtg}} - P_{\text{wtg}}^{\text{ini}} \\ &\approx \hat{P}_{\text{mec}} - \dot{E}_{\text{wtg}}^{\text{ref}} - P_{\text{wtg}}^{\text{ini}} = -m \frac{2H_{\text{sg}}\rho_{\text{sg}}}{\rho_{\text{wtg}}} \dot{\omega}_{\text{sys}} \geq 0 \end{aligned} \quad (14)$$

Integrating two sides of (13) from t_0 to $t \in (t_0, t_1]$ yields

$$\begin{aligned} E_{\text{wtg}}^{\text{ref}} &= E_{\text{wtg}}^{\text{ini}} + m \frac{2H_{\text{sg}}\rho_{\text{sg}}}{\rho_{\text{wtg}}} (\Delta\omega_{\text{sys}} + \Delta\omega_{\text{sys}}^{\text{db}}) \\ &\quad + \int_{t_0}^t (\hat{P}_{\text{mec}} - P_{\text{wtg}}^{\text{ini}}) dt \end{aligned} \quad (15)$$

A larger m results in more energy being extracted. However, an excessively large m causes SFD. To formulate a conservative upper bound for m , the most severe conditions are applied to (15): i. $E_{\text{wtg}}^{\text{ref}}(t_1) = E_{\text{wtg}}^{\text{min}}$; ii. $\Delta\omega_{\text{sys}}(t_1) = -\Delta\omega_{\text{sys}}^{\text{max}}$, where $\pm\Delta\omega_{\text{sys}}^{\text{max}}$ are the prescribed limits of $\Delta\omega_{\text{sys}}$ set by system operators for low-frequency load shedding or over-frequency generator tripping; iii. $\hat{P}_{\text{mec}}$ decreases linearly over time from $P_{\text{wtg}}^{\text{ini}}$ to $\hat{P}_{\text{mec}}^{\text{min}}$, where $\hat{P}_{\text{mec}}^{\text{min}}$ is the minimum value of $\hat{P}_{\text{mec}}$.

$$m = \frac{[E_{\text{wtg}}^{\text{ini}} - E_{\text{wtg}}^{\text{min}} - 0.5\Delta t_{10}^{\text{pre}}(P_{\text{wtg}}^{\text{ini}} - \hat{P}_{\text{mec}}^{\text{min}})]\rho_{\text{wtg}}}{2H_{\text{sg}}\rho_{\text{sg}}(\Delta\omega_{\text{sys}}^{\text{max}} - \Delta\omega_{\text{sys}}^{\text{db}})} \quad (16)$$

where $\Delta t_{10}^{\text{pre}}$ is the preset value of $t_1 - t_0$, which replaces $t_1 - t_0$ since t_1 is unknown at time t_0 . $\Delta t_{10}^{\text{pre}}$ can be speculated from historical SFR data or simply taken as a value within 2~10 s. $\Delta t_{10}^{\text{pre}}$ is larger than Δt_{10} obtained when WTG does not participate in regulation.

During the time interval $(t_1, t_2]$, $\dot{E}_{\text{wtg}}^{\text{ref}}$ should be braked to 0 to terminate the energy release. A linearly decreasing relationship with time is adopted for $\dot{E}_{\text{wtg}}^{\text{ref}}$.

$$\begin{aligned} \dot{E}_{\text{wtg}}^{\text{ref}} &= \frac{t_1 + \Delta t_{21} - t}{\Delta t_{21}} (\hat{P}_{\text{mec}}(t_1) - P_{\text{wtg}}^{\text{ini}}) \\ \Rightarrow E_{\text{wtg}}^{\text{ref}} &= \frac{(t_1 + 2\Delta t_{21} - t)(t - t_1)}{2\Delta t_{21}} (\hat{P}_{\text{mec}}(t_1) - P_{\text{wtg}}^{\text{ini}}) \\ &\quad + E_{\text{wtg}}^{\text{ref}}(t_1) \end{aligned} \quad (17)$$

where $\Delta t_{21} = t_2 - t_1$ is the braking time, t_1 , $\hat{P}_{\text{mec}}(t_1)$, and the frequency nadir are obtained simultaneously, and $E_{\text{wtg}}^{\text{ref}}(t_1)$ is given by (15) at time t_1 .

Utilizing the condition $E_{\text{wtg}}^{\text{ref}}(t_2) \geq E_{\text{wtg}}^{\text{min}}, \Delta t_{21}$ is ultimately set to

$$\Delta t_{21} = \min \left\{ 2 \frac{E_{\text{wtg}}^{\text{ref}}(t_1) - E_{\text{wtg}}^{\text{min}}}{P_{\text{wtg}}^{\text{ini}} - \hat{P}_{\text{mec}}(t_1)}, \Delta t_{21}^{\text{pre}} \right\} \quad (18)$$

where $\Delta t_{21}^{\text{pre}}$ is the preset value of $t_2 - t_1$.

2) KET during the frequency rise event ($\Delta\omega_{\text{sys}} > \Delta\omega_{\text{sys}}^{\text{db}}$)

Since the decrease in mechanical power corresponds to positive damping, the KET does not require segmentation. Taking $t_2 = t_1$, the KET within the time interval $(t_0, t_2]$ is designed as follows to govern WTG to maximize energy storage during the extreme frequency rise event ($\Delta\omega_{\text{sys}}(t_2) = \Delta\omega_{\text{sys}}^{\text{max}}$).

$$E_{\text{wtg}}^{\text{ref}} = 2H_{\text{eafc1}}(\min\{\Delta\omega_{\text{sys}}, \Delta\omega_{\text{sys}}^{\text{max}}\} - \Delta\omega_{\text{sys}}^{\text{db}}) + E_{\text{wtg}}^{\text{ini}} \quad (19)$$

with

$$H_{\text{eafc1}} = \frac{E_{\text{wtg}}^{\text{max}} - E_{\text{wtg}}^{\text{ini}}}{2(\Delta\omega_{\text{sys}}^{\text{max}} - \Delta\omega_{\text{sys}}^{\text{db}})}$$

where H_{eafc1} is the equivalent inertia coefficient at this stage.

Here is the design concept of H_{eafc1} .

- To fully utilize the available WTG energy, H_{eafc1} ensures that $E_{\text{wtg}}^{\text{ref}}$ reaches its limit $E_{\text{wtg}}^{\text{max}}$ as $\Delta\omega_{\text{sys}}$ approaches $\Delta\omega_{\text{sys}}^{\text{max}}$.
- The “min” function in (19) is used to avoid exceeding $E_{\text{wtg}}^{\text{max}}$. If $\Delta\omega_{\text{sys}} > \Delta\omega_{\text{sys}}^{\text{max}}$, $E_{\text{wtg}}^{\text{ref}}$ will be clamped at $E_{\text{wtg}}^{\text{max}}$. When $\Delta\omega_{\text{sys}}$ is smaller than $\Delta\omega_{\text{sys}}^{\text{max}}$, $E_{\text{wtg}}^{\text{ref}}$ is a smooth function of $\Delta\omega_{\text{sys}}$.

B. KET for the Energy Recovery Stage

During the time interval (t_2, ∞) , $\Delta\omega_{\text{sys}}$ transitions from $\Delta\omega_{\text{sys}}(t_2)$ to a steady-state value, whereas $\dot{\omega}_{\text{sys}}$ transitions from $\dot{\omega}_{\text{sys}}(t_2)$ to 0. $\Delta\omega_{\text{sys}}(t_2)$, $\dot{\omega}_{\text{sys}}(t_2)$, and their associated time t_2 are available at the onset of this stage. Subsequently, $E_{\text{wtg}}^{\text{ref}}$, similar in form to (19), is established to recover energy.

$$E_{\text{wtg}}^{\text{ref}} = 2H_{\text{eafc2}}(\Delta\omega_{\text{sys}} - \Delta\omega_{\text{sys}}(t_2) - \eta_2^{-1}\gamma_2(t)\dot{\omega}_{\text{sys}}(t_2)) + E_{\text{wtg}}^{\text{ref}}(t_2) \quad (20)$$

with

$$H_{\text{eafc2}} = \frac{E_{\text{wtg}}^{\text{ini}} - E_{\text{wtg}}^{\text{ref}}(t_2)}{2(\gamma_1(t)\Delta\omega_{\text{sys}} - \Delta\omega_{\text{sys}}(t_2) - \eta_2^{-1}\dot{\omega}_{\text{sys}}(t_2))}$$

$$\gamma_i(t) = 1 - e^{-\eta_i(t-t_2)}$$

where $E_{\text{wtg}}^{\text{ref}}(t_2)$ is given by (17) or (19) at time t_2 , H_{eafc2} is the equivalent inertia coefficient at this stage, η_1 and η_2 are two positive constants to control the recovery rate of energy and the decay rate of $\dot{\omega}_{\text{sys}}(t_2)$, respectively.

For small η_1 , the recovery process is relatively slow, and $E_{\text{wtg}}^{\text{ref}}$ will maintain a trend consistent with $\Delta\omega_{\text{sys}}$ over an extended period. In the low-inertia system (i.e., hydro-dominated system), significant multi-swing effects in the SFR may induce undesired oscillations of $E_{\text{wtg}}^{\text{ref}}$. For a large η_1 , rapid energy recovery mitigates multi-swing impacts but risks deteriorating the frequency stabilization process due to higher recovery power. Thus, η_1 should be judiciously selected based on specific scenario requirements. Conversely, η_2 should be

maximized to prevent the denominator of H_{eafc2} from going through 0.

In the energy offset stage, the KET incorporating (15) and (17) provides positive power deviation during the frequency drop event, while the KET specified in (19) ensures full energy storage during the extreme frequency rise event. In the energy recovery stage, the KET specified in (20) aims to recover WTG energy to the optimal state determined by the wind speed within a specified time limit. The following relationships derived from (13), (15), (17), (19), and (20) demonstrate the smoothness (also continuity) and effectiveness of the KET.

$$\begin{cases} \lim_{t \rightarrow t_1^-} E_{\text{wtg}}^{\text{ref}} = E_{\text{wtg}}^{\text{ref}}(t_1) = \lim_{t \rightarrow t_1^+} E_{\text{wtg}}^{\text{ref}} \\ \lim_{t \rightarrow t_1^-} \dot{E}_{\text{wtg}}^{\text{ref}} = \dot{P}_{\text{mec}}(t_1) - P_{\text{wtg}}^{\text{ini}} = \lim_{t \rightarrow t_1^+} \dot{E}_{\text{wtg}}^{\text{ref}} \\ \lim_{t \rightarrow t_2^-} E_{\text{wtg}}^{\text{ref}} = E_{\text{wtg}}^{\text{ref}}(t_2) = \lim_{t \rightarrow t_2^+} E_{\text{wtg}}^{\text{ref}} \\ \lim_{t \rightarrow t_2^-} \dot{E}_{\text{wtg}}^{\text{ref}} = 0 = \lim_{t \rightarrow t_2^+} \dot{E}_{\text{wtg}}^{\text{ref}} \\ \lim_{t \rightarrow \infty} E_{\text{wtg}}^{\text{ref}} = E_{\text{wtg}}^{\text{ini}}, \lim_{t \rightarrow \infty} \dot{E}_{\text{wtg}}^{\text{ref}} = 0 \end{cases} \quad (21)$$

Notably, this paper presents an implementation of the KET. In practice, the KET can be customized into more sophisticated forms with additional constraints or variables. The core contribution of this paper emphasizes adopting an explicit frequency-coupled KET to enhance dynamic frequency regulation and avoid SFR deterioration from control switching, rather than proposing a unique KET formulation.

V. ADAPTIVE SLIDING MODE CONTROL

A. SMC with Mechanical Power Estimation

During frequency response regulation, it is critical to maintain sustained convergence of energy towards the KET for anticipated energy utilization. In addition, a transition from $E_{\text{wtg}}^{\text{ref}}$ to $P_{\text{wtg}}^{\text{ref}}$ must be established. Considering that WTG is a nonlinear system [31], these requirements necessitate introducing an appropriate auxiliary control loop

Conventional PI control may exhibit limitations such as long regulation and overshoot. SMC has demonstrated effectiveness and robustness for diverse dynamics, including linear, nonlinear, and incompletely modeled systems [32]. SMC also inherently supports energy tracking and power reference generation.

Considering the modeling error caused by parameter disturbances and uncertainties, the WTG energy dynamics are reformulated as

$$\dot{E}_{\text{wtg}} = P_{\text{mec}} - P_{\text{wtg}}^{\text{ref}} + d \quad (22)$$

where d is assumed to be upper bounded by an unknown time-varying positive constant. Such an assumption is familiar in SMC design [33].

Energy tracking error is defined as the sliding surface to describe the desired system dynamics.

$$s_0 = e \triangleq E_{\text{wtg}} - E_{\text{wtg}}^{\text{ref}} \quad (23)$$

The sliding mode equation (23) satisfies $s_0 = 0$ and $\dot{s}_0 = 0$ when the tracking error executes sliding motion on the sliding

surface. The equivalent control term u , which is a component of the power reference, can be derived as

$$u = P_{\text{mec}} - \dot{E}_{\text{wtg}}^{\text{ref}} + d \quad (24)$$

To accelerate the convergence of tracking error towards the sliding surface, an exponential approaching law is adopted. To mitigate control inaccuracy and transient instability induced by intense chattering, the hyperbolic tangent function $\tanh(\cdot/\sigma)$ replaces the conventional sign function $\text{sgn}(\cdot)$ as the sliding mode switching function.

$$\dot{s}_0 = -k_1 s_0 - k_2 \tanh(s_0/\sigma) \quad (25)$$

Combining (24) and (25), the complete power reference expression becomes

$$P_{\text{wtg}}^{\text{ref}} = P_{\text{mec}} - \dot{E}_{\text{wtg}}^{\text{ref}} + d + k_1 s_0 + k_2 \tanh(s_0/\sigma) \quad (26)$$

Due to the unavailability of d and potential inaccuracy in P_{mec} , the practical power reference is implemented as

$$P_{\text{wtg}}^{\text{ref}} = \hat{P}_{\text{mec}} - \dot{E}_{\text{wtg}}^{\text{ref}} + k_1 s_0 + k_2 \tanh(s_0/\sigma) \quad (27)$$

B. Stability Analysis Based on Adaptive Law

Substituting (27) into $\dot{s}_0$ yields

$$\dot{s}_0 = (P_{\text{mec}} - \hat{P}_{\text{mec}} + d) - k_1 s_0 - k_2 \tanh(s_0/\sigma) \quad (28)$$

Comparing (28) with (25), the total error term $P_{\text{mec}} - \hat{P}_{\text{mec}} + d$ causes the dynamics of s_0 to deviate from those governed solely by the approaching law. Given that $P_{\text{mec}} - \hat{P}_{\text{mec}}$ and d are both bounded, the total error satisfies

$$P_{\text{mec}} - \hat{P}_{\text{mec}} + d \leq |P_{\text{mec}} - \hat{P}_{\text{mec}}| + |d| \leq \delta \quad (29)$$

Since δ is also unknown and time-varying, the estimation of δ , denoted as $\hat{\delta}$, is further introduced. By replacing k_2 with $\hat{\delta}$, the proposed SMC transitions into an ASMC to exhibit robustness against $P_{\text{mec}} - \hat{P}_{\text{mec}} + d$. The dynamics of $\hat{\delta}$ are updated via the following adaptive law.

$$\dot{k}_2 = \dot{\hat{\delta}} = -k_3 \hat{\delta} + s_0 \tanh(s_0/\sigma) \quad (30)$$

The stability of ASMC can be proven through Lyapunov analysis. Firstly, a Lyapunov function V is constructed as

$$V = 0.5(s_0^2 + \tilde{\delta}^2) \quad (31)$$

where $\tilde{\delta} = \delta - \hat{\delta}$ represents the estimation error of δ . The time derivative of V is calculated as

$$\begin{aligned} \dot{V} &= s_0 \dot{s}_0 + \tilde{\delta} \dot{\tilde{\delta}} \\ &= s_0 (P_{\text{mec}} - \hat{P}_{\text{mec}} + d) - k_1 s_0^2 - s_0 \delta \tanh(s_0/\sigma) + k_3 \tilde{\delta} \dot{\tilde{\delta}} \\ &\leq \delta [|s_0| - s_0 \tanh(s_0/\sigma)] - k_1 s_0^2 + k_3 \tilde{\delta} \dot{\tilde{\delta}} \end{aligned}$$

Two classical inequalities [34] are applied, specifically,

$$|s_0| - s_0 \tanh(s_0/\sigma) \leq 0.28\sigma, \quad \tilde{\delta} \dot{\tilde{\delta}} \leq 0.5(\delta^2 - \tilde{\delta}^2) \quad (32)$$

Consequently, $\dot{V}$ can be further expressed as

$$\begin{aligned} \dot{V} &\stackrel{(32)}{\leq} (0.28\sigma\delta + 0.5k_3\delta^2) - \min\{k_1, 0.5k_3\}(s_0^2 + \tilde{\delta}^2) \\ &\stackrel{(31)}{\leq} \alpha - \beta V \Rightarrow 0 \leq V \leq \alpha/\beta + (V^{\text{ini}} - \alpha/\beta)e^{-\beta t} \end{aligned} \quad (33)$$

with

$$\alpha = 0.28\sigma\delta + 0.5k_3\delta^2, \quad \beta = \min\{2k_1, k_3\}$$

where V^{ini} is the initial value of V .

From (33), it follows that, regardless of the size of V^{ini} , V becomes bounded within a finite time. This demonstrates the UUB stability [35] of s_0 (and consequently e) and $\tilde{\delta}$, indicating their convergence to small neighborhoods around the origin with appropriate parameter tuning. Notably, e diminishes under small α and large β , necessitating small σ and large k_1 . However, large k_1 may induce an excessive power reference. Thus, a balance should be struck between enhancing transient performance and maintaining an admissible power reference.

The proposed ASMC, comprising (27) and (30), is integral to EAFC. The overall structure of EAFC is illustrated in Fig. 4.

VI. CASE STUDIES

Based on the system models in Fig. 1, two cases are established in MATLAB/Simulink. In Case 1, the effectiveness and robustness of the proposed EAFC are verified, including the selection of appropriate $\Delta t_{10}^{\text{pre}}$, $\Delta t_{21}^{\text{pre}}$, and η_1 . In Case2, the impacts of disturbance size, wind power penetration, and wind speed on control performance are examined. In both cases, four frequency regulation modes are tested, where MOSIC [36] and ATPC [24] are the latest works derived from SIC and TPC without inducing an SFD.

- **MPPT**: WTG does not participate in frequency regulation.
- **MOSIC**: WTG employs MOSIC, with $P_{\text{wtg}}^{\text{ref}}$ for energy release given by

$$\begin{aligned} P_{\text{wtg}}^{\text{ref}} &= -[\omega_{\text{wtg}}^2 - (\omega_{\text{wtg}}^{\text{min}})^2] \\ &\cdot \left(\frac{H_{\text{wtg}} \dot{\omega}_{\text{sys}}}{\Delta\omega_{\text{sys}}^{\text{max}} - |\Delta\omega_{\text{sys}}|} + K(t)\Delta\omega_{\text{sys}} \right) + P_{\text{wtg}}^{\text{opt}} \end{aligned} \quad (34)$$

where $K(t)$ is a positive time-varying damping coefficient.

- **ATPC**: WTG employs ATPC, with $P_{\text{wtg}}^{\text{ref}}$ for energy release given by

$$\begin{aligned} P_{\text{wtg}}^{\text{ref}} &= [P_{\text{wtg}}^{\text{ini}} + \Delta P_{\text{atpc}} - (\omega_{\text{wtg}}^{\text{min}})^3] \left(\frac{\omega_{\text{wtg}} - \omega_{\text{wtg}}^{\text{min}}}{\omega_{\text{wtg}}^{\text{ini}} - \omega_{\text{wtg}}^{\text{min}}} \right)^2 \\ &+ (\omega_{\text{wtg}}^{\text{min}})^3 \end{aligned} \quad (35)$$

- **EAFC**: WTG employs the proposed EAFC, with $P_{\text{wtg}}^{\text{ref}}$ given by (27).

A. Case 1: Extended SFR Model

Integrate the EAFC structure into the speed controller in Fig. 2(b), and then apply it to the WTG part of Model 2 to form the architecture of Case 1. For the SFR part, the turbine governor system adopts the simplest modeling as

$$G_{\text{sg}}(s) = \frac{1 + K_1 \tau_3 s}{1 + \tau_3 s} \quad (36)$$

The simulation duration is set to 30 s to focus solely on the dynamic frequency response. A disturbance with the size of 0.1 p.u. is applied at $t_0 = 0$ s. Other parameters are listed in Table I.

TABLE I
KEY SIMULATION PARAMETERS OF CASE 1

Models	Parameter	Symbol	Value
SFR	Maximum, deadband of $\Delta\omega_{sys}$ (p.u.)	$\Delta\omega_{sys}^{max}, \Delta\omega_{sys}^{db}$	0.01, 0.0001
	Inertia coefficient (s)	H_{sg}	6.25
	Damping coefficients	D_{sg}, D	25, 1
	Parameters of $G_{sg}(s)$	τ_3, K_1	8, 0.3
	Optimal tip speed ratio	λ^{opt}	6.32
WTG	Wind speed ($m \cdot s^{-1}$)	v^{nom}, v	12, 12
	Inertia coefficient (s)	H_{wtg}	2.5
	Generation coefficient	ρ_{wtg}	0.2
	Rotor speed limits (p.u.)	$[\omega_{wtg}^{min}, \omega_{wtg}^{max}]$	[0.7, 1.2]
	ATPC over-production (p.u.)	ΔP_{atpc}	0.5
	KET parameters	η_2	100
	ASMC parameters	σ, k_1, k_3	0.01, 100, 1

1) Scenario 1: Control Effectiveness Verification

The control parameters of the KET are derived as follows.

- For the energy recovery stage during the frequency drop event, Δt_{10}^{pre} is set to 5 s. m is calculated via (16).

$$\omega_{wtg}^{ini} = 12/12 = 1, \quad \hat{P}_{mec}^{min} = 1 - 2(0.7 - 1)^2 = 0.82$$

$$m = \frac{0.2[2.5(1 - 0.7^2) - 0.5 \times 5(1 - 0.82)]}{2 \times 6.25 \times 0.8(0.01 - 0.0001)} = \frac{5}{3}$$

Δt_{21}^{pre} is set to 5 s. The first term in (18) typically exceeds 5 s.

- For the energy recovery stage during the frequency rise event, H_{eafc1} is calculated as

$$H_{eafc1} = \frac{2.5(1.2^2 - 1)}{2(0.01 - 0.0001)} = 55.5 \text{ s}$$

- For the energy recovery stage, η_1 is set to 0.2.

Figure 5 presents the dynamic responses of $\Delta\omega_{sys}$, E_{wtg} , and P_{wtg} under different regulation modes. For the convenience of comparing energy variations, the available energy ΔE_{wtg} and its initial value $\Delta E_{wtg,ava}^{ini}$ are first defined here as follows.

$$\begin{cases} \Delta E_{wtg,ava} \triangleq \varepsilon(\Delta\omega_{sys})(E_{wtg}^{max} - E_{wtg}) \\ \quad + \bar{\varepsilon}(\Delta\omega_{sys})(E_{wtg} - E_{wtg}^{min}) \\ \Delta E_{wtg,ava}^{ini} \triangleq \varepsilon(\Delta\omega_{sys})(E_{wtg}^{max} - E_{wtg}^{ini}) \\ \quad + \bar{\varepsilon}(\Delta\omega_{sys})(E_{wtg}^{ini} - E_{wtg}^{min}) \end{cases} \quad (37)$$

where $\varepsilon(\cdot)$ is the unit step function, and $\bar{\varepsilon}$ is the opposite of ε .

During the frequency drop event, WTG operates in three segments under EAFC: during the time interval $(0, t_1)$ corresponding to OA, WTG releases its energy and provides positive power deviation via the KET specified in (15); during the time interval (t_1, t_2) corresponding to AB, WTG follows the KET specified in (17) to terminate energy release within 5 s; during the time interval $(t_2, 30 \text{ s})$, WTG achieves full energy recovery via the KET in (20).

Frequency nadirs for MOSIC, ATPC, and EAFC are -0.495 Hz , -0.500 Hz , and -0.428 Hz . In fact, the adaptive gains of MOSIC ($\omega_{wtg}^2 - 0.49$) and ATPC ($(\omega_{wtg} - 0.7)^2$) eliminate SFD but reduce energy utilization. Comparing (34) and (35) with (9), P_{wtg}^{ref} under MOSIC or ATPC decays rapidly with decreasing energy, hindering further energy release. Fig. 5(a) reveals that only 60.6% and 20.0% of $\Delta E_{wtg,ava}^{ini}$ is released,

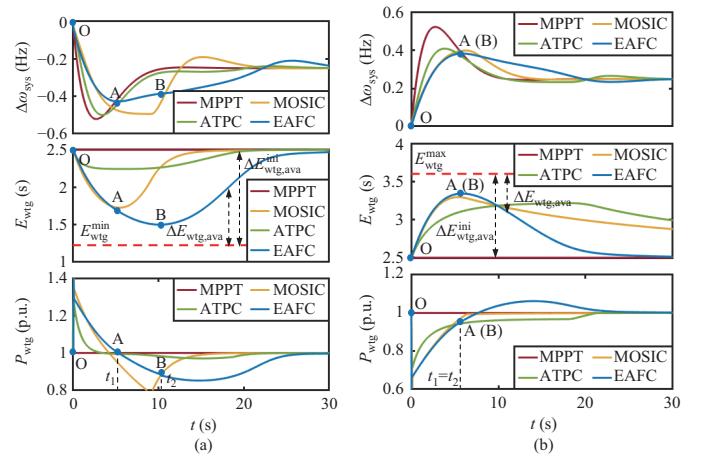


Fig. 5. Simulation results 1 for control performance comparison in Case 1. (a) $\Delta P_0 = -0.1 \text{ p.u.}$ (b) $\Delta P_0 = 0.1 \text{ p.u.}$

resulting in inferior nadir mitigation. In contrast, 78.5% of $\Delta E_{wtg,ava}^{ini}$ is released under EAFC due to the consideration of $\Delta E_{wtg,ava}^{ini}$ in m setting. Despite MOSIC's higher energy utilization efficiency compared to ATPC, its premature energy recovery fails to maintain a sustained positive power deviation before the frequency nadir, yielding inferior regulation compared to ATPC.

During the frequency rise event, WTG operates in two segments under EAFC: during the time interval $(0, t_1)$ corresponding to OA, WTG stores energy with negative power deviation via the KET specified in (19); during the time interval $(t_1, 30 \text{ s})$, WTG achieves full energy recovery via the KET specified in (20).

As shown in Fig. 5(b), EAFC achieves superior frequency peak suppression (0.383 Hz) compared to MOSIC (0.399 Hz) and ATPC (0.408 Hz). Energy utilization efficiencies are 72.2%, 65.0%, and 76.4% for MOSIC, ATPC, and EAFC. While all modes maintain constant negative power deviation during the time interval $(0, t_1)$, energy under EAFC has a faster and more reliable recovery process than MOSIC and ATPC.

Figure 6 illustrates the dynamic responses of P_{mec} and ω_{wtg} under EAFC to elaborate on the mechanism of energy dynamics. Since energy dynamics are reformulated from the swing equation, the dynamic responses of ω_{wtg} align precisely with E_{wtg} . As shown in Fig. 6(a), $P_{wtg} > P_{mec}$ maintains sustained energy release during the time interval (t_0, t_2) . At point B, energy release terminates ($P_{wtg} = P_{mec}$), corresponding to the minimum values of both E_{wtg} and ω_{wtg} . Subsequent energy recovery is driven by $P_{wtg} < P_{mec}$. Fig. 6(b) describes the

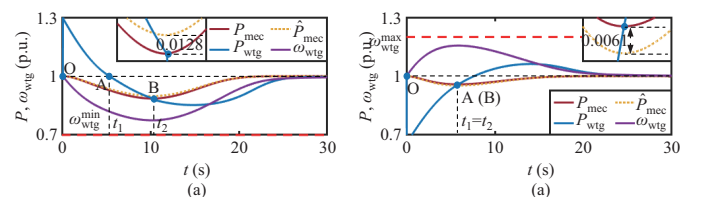


Fig. 6. Simulation results 1 for energy dynamics analysis in Case 1. (a) $\Delta P_0 = -0.1 \text{ p.u.}$ (b) $\Delta P_0 = 0.1 \text{ p.u.}$

symmetrical process. Furthermore, according to estimation (6), maximum estimation errors of 0.0128 p.u. and 0.0061 p.u. are observed at point B, corresponding to the maximum deviations of ω_{wtg} from $\omega_{wtg}^{ini} = 1$.

2) Scenario 2: Values Selection for Δt_{10}^{pre} , Δt_{21}^{pre} , and η_1

To verify the effectiveness of $\Delta t_{10}^{pre} = \Delta t_{21}^{pre} = 5$ s, sensitivity analyses are performed. Fig. 7(a) visualizes the frequency nadirs versus Δt_{10}^{pre} and Δt_{21}^{pre} via a 3D diagram. $\Delta t_{10}^{pre} = \Delta t_{21}^{pre} = 5$ s approximates the optimal configuration (yellow region of Fig. 7(a)), confirming its validity. Fig. 7(b) compares performance under extreme Δt_{10}^{pre} and Δt_{21}^{pre} , and indicates that small Δt_{10}^{pre} and Δt_{21}^{pre} (orange and light blue curves) induce sustained frequency drop, large Δt_{10}^{pre} (green curves) leads to insufficient energy release due to reduced m , and large Δt_{21}^{pre} (purple curves) decelerates energy recovery and frequency stabilization.

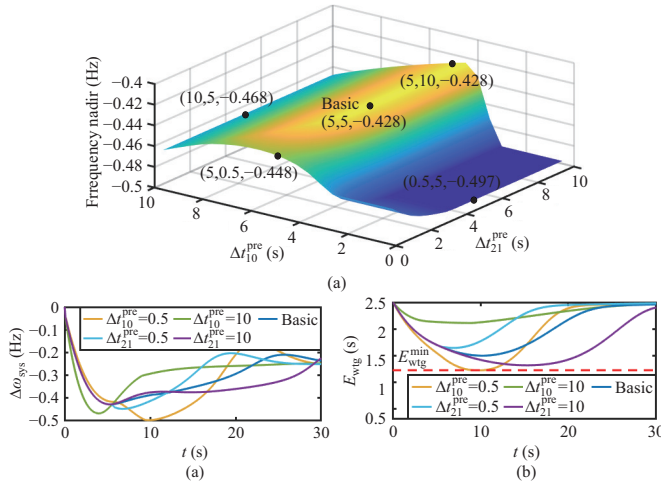


Fig. 7. Simulation results 2 for selecting Δt_{10}^{pre} and Δt_{21}^{pre} in Case 1. (a) Frequency nadir. (b) Frequency deviation and energy.

The energy recovery and frequency stabilization are governed by η_1 in (20). Fig. 8 presents the dynamic responses of $\Delta\omega_{sys}$ and E_{wtg} varying with η_1 . Small η_1 decelerates energy recovery, as indicated by the same trends between $\Delta\omega_{sys}$ and E_{wtg} for $\eta_1 = 0$ (green curves). As η_1 gradually grows, the energy recovery accelerates, and the WTG recovery power also grows, causing a violent frequency stabilization process with overshoot (purple curves). However, the overshoot hardly affects the rate and monotonicity of energy recovery. To balance the dynamic responses of $\Delta\omega_{sys}$ and E_{wtg} , $\eta_1 = 0.2$ is appropriate to be selected as a compromise.

3) Scenario 3: Robustness Verification of ASMC

Two operations of P_{wtg}^{ref} are combined to verify the robustness of the proposed control to errors: removing ASMC; adding a WGN signal φ with a signal-to-noise ratio of 50. The corresponding test structures are depicted in Fig. 9, with dynamic responses of E_{wtg} and P_{wtg} presented in Fig. 10.

The absence of ASMC allows cumulative errors in $P_{mec} - \hat{P}_{mec}$ to increase, causing energy to gradually deviate from the KET and preventing full energy recovery, as evident by the steady-state energy offset in Fig. 10(b). Therefore, ASMC is critical for enforcing energy convergence.

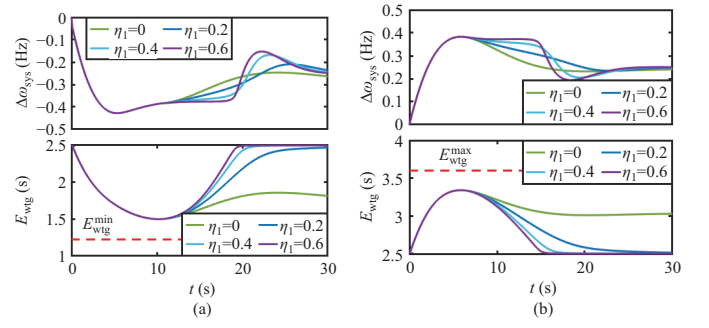


Fig. 8. Simulation results 2 for selecting η_1 in Case 1. (a) $\Delta P_0 = -0.1$ p.u. (b) $\Delta P_0 = 0.1$ p.u.

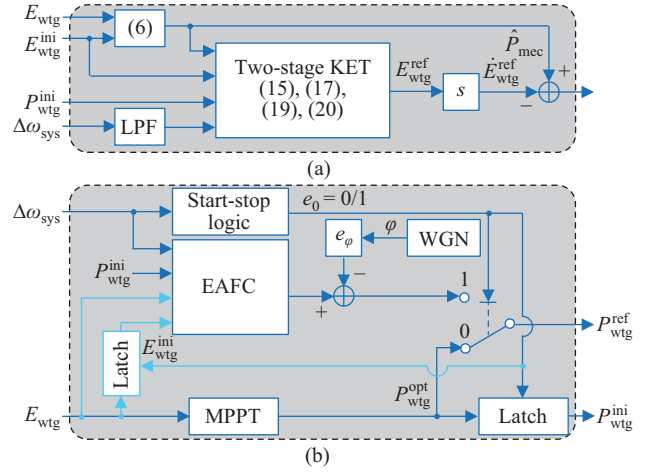


Fig. 9. Structures for robustness verification in Case 1. (a) EAFc w/o the adoption of AMSC. (b) Speed controller with the addition of WGN ($e_\varphi = 0/1$).

Considering the addition of φ to emulate d , the dynamic responses of P_{wtg} are shown in the blue curves in the lower half of Fig. 10, containing DC and noise components. Compared to the crimson curves, the blue curves indicate that the addition of φ in the power closed loop introduces both noise and a DC offset. When ASMC is adopted, energy maintains sustained convergence towards the KET in Fig. 10(a), verifying the effectiveness of the UUB condition and the robustness against $P_{mec} - \hat{P}_{mec} + d$.

B. Case 2: Modified IEEE 9-bus System

As shown in Fig. 11, Case 2 is a modified 9-bus system incorporating WTGs. The original IEEE 9-bus system comprises 3 conventional SGs, 3 loads, and 9 branches. Characteristics of the studied system include:

- SGs are equipped with governors for primary frequency regulation and power system stabilizers, which use rotor speed as an input to dampen frequency oscillations. SG1 and SG3 are thermal-based SGs, while SG2 is a hydro-based SG. Their turbine governor systems are modeled as

$$G_i(s) = \begin{cases} \frac{K_1(1+s\tau_3)(1+s\tau_4)+K_2(1+s\tau_4)+K_3}{(1+s\tau_1)(1+s\tau_2)(1+s\tau_3)(1+s\tau_4)}, & i = \text{sg1/sg3} \\ \frac{(D_{sg2}-2H_{sg2}s)G_t(s)G_{pi}(s)}{D_{sg2}[D_{sg2}(1+s\tau_1)+G_t(s)G_{pi}(s)]}, & i = \text{sg2} \end{cases} \quad (38)$$

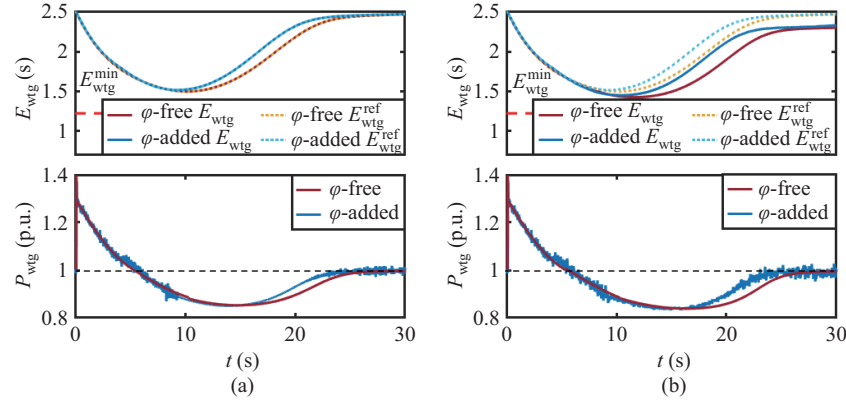


Fig. 10. Simulation results 3 for robustness verification in Case 1. (a) ASMC is adopted. (b) ASMC is bypassed.

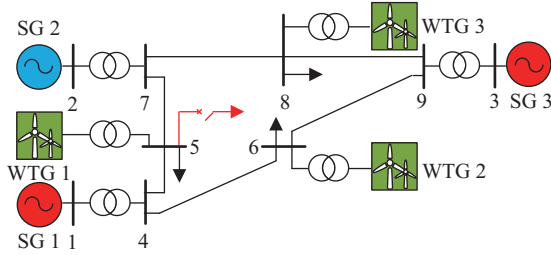


Fig. 11. Modified IEEE 9-bus system with distributed WTGs.

with

$$G_t(s) = \frac{1 - P_{sg2}^{pref} \tau_5 s}{1 + 0.5 P_{sg2}^{pref} \tau_5 s}, \quad G_{PI}(s) = K_P + \frac{K_I}{s}$$

- WTGs 1~3 are spatially distributed across buses 5, 6, and 8, respectively. Each WTG is equivalent to a DFIG in Model 1, with the rotor-side converter controller applying the same speed controller as in Case 1.

The simulation duration is set to 30 s with a disturbance applied at $t_0 = 10$ s. Five scenarios are tested. In Scenario 1, all WTGs operate at an initial wind speed of 12 m/s; wind power penetration is 30%; disturbance size is 35 MW (10% of total load). Scenarios 2~4 are derived by individually adjusting disturbance size, wind power penetration, and initial wind speeds based on Scenario 1. In Scenario 5, a centralized configuration of 105 MW is formed by aggregating the capacities of WTGs 2~3 into WTG1. For Scenarios 1~3, WTGs 1~3 share identical initial wind speeds, and only WTG1's energy and power variations are displayed due to

their consistent operational state. Table III summarizes FEs and energy utilization efficiencies for Scenarios 1~4.

1) Scenario 1: Control Effectiveness Verification

In Scenario 1, m applicable for WTGs 1~3 are calculated as 5/9, 35/36, 25/18, respectively, while $H_{eafc1} = 55.5$ s. Fig. 12 presents the dynamic responses of $\Delta\omega_{sys}$, E_{wtg1} , and P_{wtg1} .

During the frequency drop event, EAFC achieves the largest improvement in frequency nadir. Unlike MOSIC, it avoids premature energy recovery and negative power deviation. Compared to ATPC, it prevents power reduction and insufficient energy release. The full energy controllability of EAFC

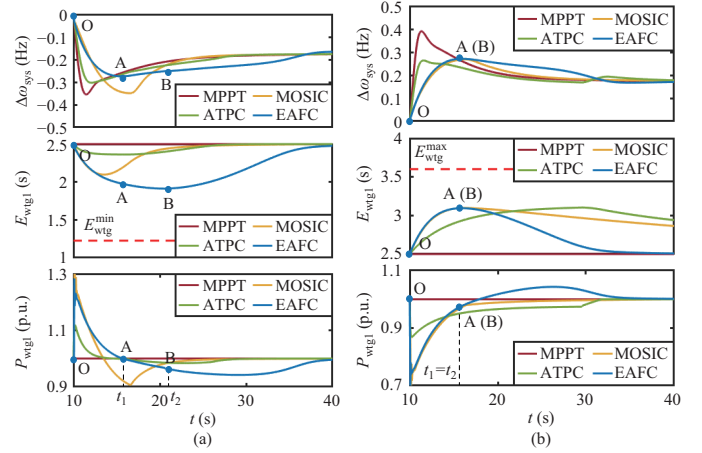


Fig. 12. Simulation results 1 for control performance comparison in Case 2. (a) $\Delta P_0 = -0.1$ p.u. (b) $\Delta P_0 = 0.1$ p.u.

TABLE II
SIMULATION PARAMETERS OF CASE 2

Source	Parameter	Symbol	Value
SGs 1~3	Nominal power (MVA)	$S_{sg1}^{nom}, S_{sg2}^{nom}, S_{sg3}^{nom}$	200, 100, 50
	Power reference (p.u.)	$P_{sg1}^{pref}, P_{sg2}^{pref}, P_{sg3}^{pref}$	0.7, 0.7, 0.7
	Inertia coefficient (s)	$H_{sg1}, H_{sg2}, H_{sg3}$	5, 2.5, 5
	Damping coefficient	$D_{sg1}, D_{sg2}, D_{sg3}$	20, 50, 20
	Turbine governor system time constant (s) and gain	$\tau_{1\sim4}$ of SG1 & SG3	0.2, 0.3, 7, 0.5
		$K_{1\sim3}$ of SG1 & SG3	0.3, 0.3, 0.4
		τ_1, τ_5, K_P, K_I of SG2	0.2, 1, 14, 4
WTGs 1~3	Nominal capacity (MVA)	$S_{wtg1}^{nom}, S_{wtg2}^{nom}, S_{wtg3}^{nom}$	20, 35, 50
	Inertia coefficient (s)	$H_{wtg1}, H_{wtg2}, H_{wtg3}$	2.5, 2.5, 2.5

Note: Other unlisted control parameters are the same as case 1.

TABLE III
SIMULATION RESULTS OF CASE 2

Scenario	Event	Index	MPPT	MOSIC	ATPC	EAFC
Scenario 1	$\Delta\omega_{sys} < 0$	FE (Hz)	-0.352	-0.349	-0.302	-0.273
		E_{wtg1} efficiency (%)	0	32.1	10.8	46.3
	$\Delta\omega_{sys} > 0$	FE(Hz)	0.392	0.271	0.267	0.274
		E_{wtg1} efficiency (%)	0	54.6	54.8	54.3
Scenario 2	$\Delta\omega_{sys} < 0$	FE(Hz)	-0.457	-0.452	-0.385	-0.348
		E_{wtg1} efficiency (%)	0	43.9	13.4	65.5
	$\Delta\omega_{sys} > 0$	FE(Hz)	0.527	0.356	0.363	0.352
		E_{wtg1} efficiency (%)	0	68.4	58.1	70.0
Scenario 3	$\Delta\omega_{sys} < 0$	FE(Hz)	-0.420	-0.384	-0.376	-0.317
		E_{wtg1} efficiency (%)	0	42.2	10.8	52.9
	$\Delta\omega_{sys} > 0$	FE(Hz)	0.470	0.326	0.384	0.327
		E_{wtg1} efficiency (%)	0	65.3	54.8	65.0
Scenario 4	$\Delta\omega_{sys} < 0$	FE(Hz)	-0.374	-0.358	-0.327	-0.288
		E_{wtg} efficiency (%)	0/0/0	37/36/35	12/11/11	57/54/48
	$\Delta\omega_{sys} > 0$	FE(Hz)	0.415	0.326	0.319	0.262
		E_{wtg} efficiency (%)	0/0/0	27/27/64	5/14/55	52/52/52

ensures rational utilization over extended periods.

During the frequency rise event, although the frequency peak suppression of EAFC is slightly weaker than that of MOSIC and ATPC, it ensures reliable energy recovery. In contrast, MOSIC and ATPC exhibit prolonged recovery processes, which align with the trends shown in Fig. 5.

Figure 13 presents the dynamic responses of P_{mec1} and ω_{wtg1} under EAFC to elaborate the mechanism of energy dynamics that is identical to Fig. 6. At the same time, Fig. 14 validates through sensitivity analysis that $\Delta t_{10}^{pre} = \Delta t_{21}^{pre} = 5$ s and $\eta_1 = 0.2$ remain appropriate for Scenario 1. It is assumed that this configuration is also applicable to Scenarios 2~5.

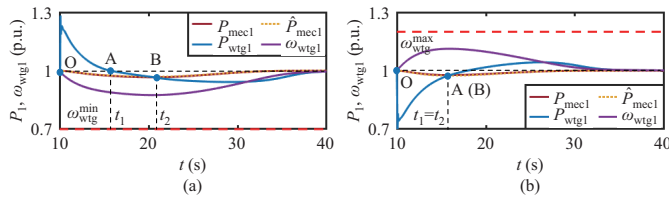


Fig. 13. Simulation results 1 for energy dynamics analysis in Case 2. (a) $\Delta P_0 = -0.1$ p.u. (b) $\Delta P_0 = 0.1$ p.u.

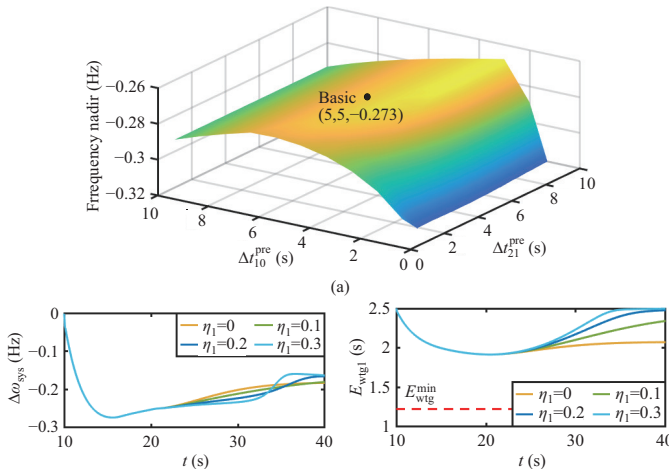


Fig. 14. Simulation results 1 for selecting Δt_{10}^{pre} , Δt_{21}^{pre} and η_1 in Case 2. (a) Frequency nadir with varying Δt_{10}^{pre} , Δt_{21}^{pre} . (b) $\Delta\omega_{sys}$ and E_{wtg1} with varying η_1

2) Scenario 2: Increasing Disturbance Size to 45 MW

m applicable for WTGs 1~3 and H_{eafc1} remain identical to Case 1. Dynamic responses under increased disturbance size are shown in Fig. 15. For all regulation modes, FEs deteriorate, but energy utilization efficiencies improve compared to Fig. 12.

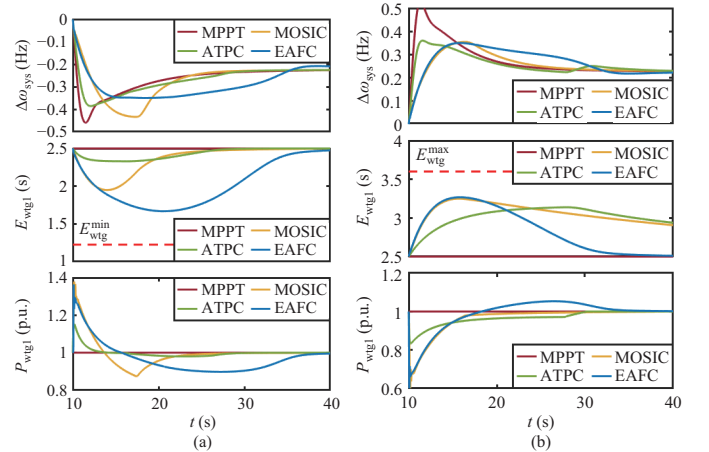


Fig. 15. Simulation results 2 for control performance comparison in Case 2. (a) $\Delta P_0 = -0.1$ p.u. (b) $\Delta P_0 = 0.1$ p.u.

During the frequency drop event, EAFC maintains superior frequency nadir improvement by effectively utilizing energy in diverse stages of dynamic frequency response, avoiding premature energy recovery or insufficient energy release.

During the frequency rise event, EAFC outperforms MOSIC and ATPC in energy utilization efficiency, frequency peak suppression, and energy recovery, demonstrating strong adaptability to large disturbances.

3) Scenario 3: Reducing Wind Power Penetration to 20%

The capacities of WTGs 2~3 are both reduced to 20MVA (m of WTGs 2~3 are unified to 5/9), accompanied by a 45 MW load reduction. Wind power penetration decreases from 30% to 20%. Fig. 16 presents the dynamic responses of $\Delta\omega_{sys}$, E_{wtg1} , and P_{wtg1} .

During the frequency drop event, EAFC remains the optimal regulation mode, aligning with the conclusions drawn from

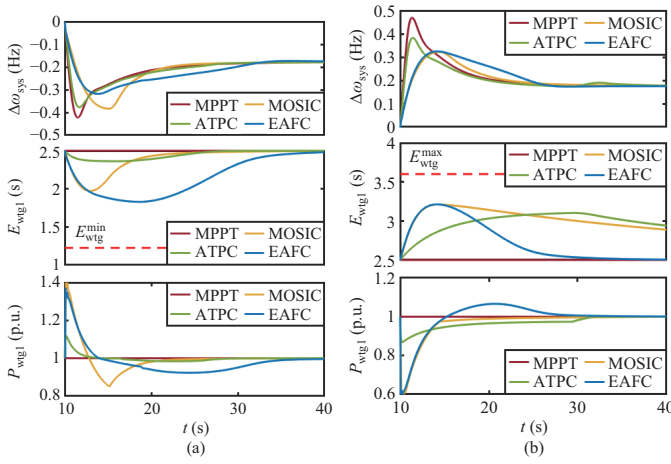


Fig. 16. Simulation results 3 for control performance comparison in Case 2. (a) $\Delta P_0 = -0.1$ p.u. (b) $\Delta P_0 = 0.1$ p.u.

Scenarios 1 and 2. During the frequency rise event, EAFC is close to MOSIC in terms of energy utilization efficiency and frequency peak suppression, and outperforms ATPC. In addition, due to the similar inertia coefficients of the EAFC and MOSIC in the energy offset stage (see H_{eafc1} and (34)), EAFC and MOSIC exhibit similar control performance within the time interval (t_0, t_2) , as evidenced by almost overlapping dynamic responses in Figs. 5(b), 12(b), 15(b), and 16(b).

4) Scenario 4: Adjusting Initial Wind Speeds to 10, 11, 12 m/s

Initial wind speeds are adjusted to account for the differences in operational state among WTGs. Correspondingly, WTGs 1~2 output power reductions necessitate a 15 MW load reduction. Taking WTG1 as an example, m and H_{eafc1} are calculated as

$$\begin{cases} \omega_{\text{wtg1}}^{\text{ini}} = 10/12 = 5/6 \\ \hat{P}_{\text{mec1}}^{\text{min}} = (5/6)^3 [1 - 2(0.7/(5/6) - 1)^2] = 0.549 \\ m_1 = \frac{20[2.5((5/6)^2 - 0.7^2) - 0.5 \times 5((5/6)^3 - 0.549)]}{2 \times (200 \times 5 + 100 \times 2.5 + 50 \times 5)(0.01 - 0.0001)} = 0.294 \\ H_{\text{eafc11}} = \frac{2.5(1.2^2 - (5/6)^2)}{2(0.01 - 0.0001)} = 94.1 \text{ s} \end{cases}$$

where m and H_{eafc1} for WTG2 can be calculated as 0.778 and 75.72 s, respectively. m and H_{eafc1} for WTG3 still remain unchanged. The dynamic responses of $\Delta\omega_{\text{sys}}$, E_{wtg1} are presented in Fig. 17.

For MOSIC and ATPC, during the frequency drop event, the issues analyzed persist, i.e., premature energy recovery and insufficient energy release. In contrast, during the frequency rise event, WTG3, with a larger energy capacity than WTGs 1 and 2, typically exhibits slow recovery. In contrast, EAFC provides the largest improvement to both frequency nadir and frequency peak, as $\Delta E_{\text{wtg1,ava}}^{\text{ini}}$, $\Delta E_{\text{wtg2,ava}}^{\text{ini}}$, and $\Delta E_{\text{wtg3,ava}}^{\text{ini}}$ are taken into consideration via the setting of m and H_{eafc1} . Each WTG can adaptively provide regulation based on individual initial wind speeds. EAFC also ensures all WTGs undergo full energy recovery simultaneously.

5) Scenario 5: Centralized WTG Integration

Figure 18 presents the dynamic responses of WTG1 before and after capacity aggregation, where almost overlapping responses of $\Delta\omega_{\text{sys}}$ and E_{wtg1} indicate the independence of

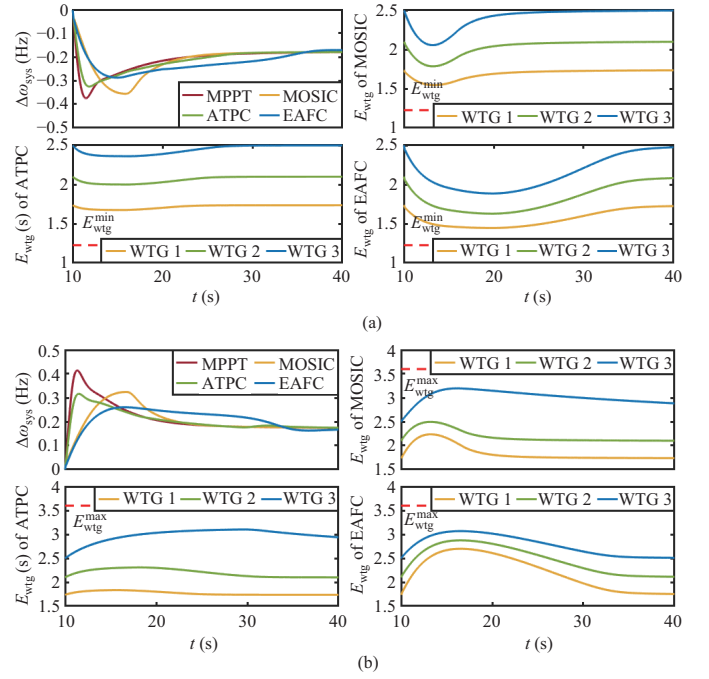


Fig. 17. Simulation results 4 for control performance comparison in Case 2. (a) $\Delta P_0 = -0.1$ p.u. (b) $\Delta P_0 = 0.1$ p.u.

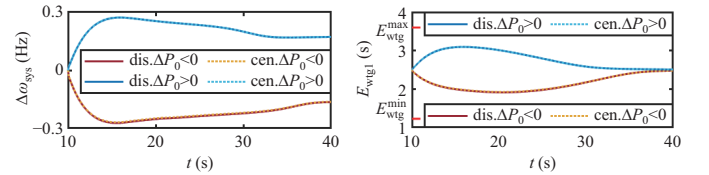


Fig. 18. Simulation results 5 for control performance comparison in Case 2.

WTG output powers and confirm that a centralized WTG can emulate the control performance of distributed WTGs under EAFC.

VII. CONCLUSION

To enhance the dynamic frequency regulation capabilities of WTGs under diverse disturbances, it is critical to utilize their energy to provide fully continuous regulation. This paper proposes an EAFC. The designed KET specifies an explicit frequency-coupled energy reference. An ASMC ensures energy convergence towards the KET throughout the SFR.

Case studies involving an extended SFR model and a modified IEEE 9-bus system demonstrate that the proposed EAFC achieves smooth energy offset and recovery. Energy utilization is fully controllable to meet customized frequency regulation requirements at various stages of SFR. EAFC demonstrates robustness against errors in mechanical power estimation and modeling while also exhibiting superior FE improvement across varying disturbance sizes, wind power penetrations, and initial wind speeds.

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Ziyang Huang received the B.S. degree in Electrical Engineering from North China Electric Power University, Beijing, China, in 2017, where he is currently pursuing the Ph.D. degree. His research interests include fast frequency regulation of new energy power system.



Zihan Wang received his B.S. and Ph.D. degrees in Electrical Engineering from North China Electric Power University, Beijing, China, in 2019 and 2025, respectively. He is currently an Engineer in Electric Power Research Institute of State Grid Zhejiang Electric Power Company. His research interests include stability and control of power electronics-dominated power systems and renewable energy conversion systems.





Xiaonan Zhang received the B.S. degree in Electrical Engineering from North China Electric Power University, Beijing, China, in 2021. She is currently working toward the Ph.D. degree in Electrical Engineering at North China Electric Power University, Beijing, China. Her main research interests include stability analysis and control of renewable energy power systems.



Jianxiao Wang received his B.S. and Ph.D. degrees in Electrical Engineering from Tsinghua University, Beijing, China, in 2014 and 2019. He was a visiting student researcher at Stanford University, CA, USA. He is currently an Assistant Professor with Peking University, Beijing, China. His research interests include smart grid operation and planning, hydrogen and storage technology, transportation and energy systems integration, electricity market, and data analytics. He has authored publications in high-impact journals, including *Nature Communications*, *Energy & Environmental Science*, etc. He received IEEE PES Outstanding Volunteer Award, Young Elite Scientists Sponsorship Program by CAST, and Beijing Young Talent Award.



Gengyin Li received his B.S., M.S., and Ph.D. degrees from North China Electric Power University, Beijing, China, in 1984, 1987, and 1996, respectively, all in Electrical Engineering. Since 1987, he has been with the School of Electrical and Electronic Engineering, North China Electric Power University, where he is currently a Professor. His research interests include HVDC transmission, power quality analysis and control, and emerging transmission and distribution technologies.



Tiance Zhang received his B.S. and Ph.D. degrees in Electrical Engineering from North China Electric Power University, Beijing, China, in 2018 and 2023, respectively. Since 2023, he has been with the School of Electrical and Electronic Engineering, North China Electric Power University, where he is currently an Assistant Professor. His research interests include renewable energy forecast, power system operation, distribution network planning and operation, etc.