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Improving Electric-Grid Frequency Stability: An In-depth Examination Windmills-partaking in-Frequency stability

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ABSTRACT: *As wind energy gains prominence as a significant power source, the capacity of the (windmills) Doubly-fed Induction Generator (DFIG) to respond to load variations in the power grid is restricted by decoupled active power control, posing a noteworthy concern. This study delves into the windmill's (DFIG) capabilities in aiding frequency regulation (FR). We explore mathematical relationships between the rate of wind energy incorporation, windmills regulation capabilities, frequency modulation (FM), and wind energy efficiency. This paper introduces innovative control strategies that enhance the proactive role of adjustable windmills, endowed with augmented virtual inertia, in stabilizing grid frequency. Our research scrutinizes how wind energy influences grid frequency stability under changing conditions – from fluctuating wind velocities and steady operational states to sudden shifts in load demand. Utilizing data from Yunnan-Power-Grid, alongside MATLAB/Simulink and a windmill model. We demonstrate the effectiveness of windmills (DFIG) in maintaining grid frequency. Our analysis also incorporates windmill models designed for FR into a comprehensive two (02)-areas, four (04)-machines electricity-network grid design, pinpointing the optimal percentage of tunable windmills required for maintaining grid frequency equilibrium. The simulation findings underscore the importance of prioritizing windmills (DFIG) operating at standard velocities within windmill fields for effective frequency control.*

Key Words: *DFIG; wind energy; frequency regulation (FR); frequency modulation (FM); windmill;*

1. Introduction:

Electricity is now a cornerstone of modern life [1]. The environmentally friendly nature of wind power, a renewable energy source subject to weather conditions, is increasingly acknowledged [2]. Globally, there's a surge in the development of wind energy, despite engineering challenges [3]. In certain Chinese local power grids, wind power accounts for several percentages of the energy mix [4]. Its sustainability and zero-emission attributes make wind power an exemplary green energy source [5]. To combat frequency and voltage fluctuations caused by variable power sources and loads, energy resources are linked to grids through advanced controllers [6,7]. Nevertheless, the inherent unpredictability and intermittent nature of wind power can adversely affect the vibrant solidity, FM, and in high capacity wind farms. Presently, the DFIG has risen to prominence in the wind energy market as a variable-speed wind generator (VSWG) [8]. VSWGs contribute to frequency modulation by implementing inertia control, power control, and integrating power storage systems [9–11]. Significant research has focused on primary and secondary frequency responses [12]. Modern wind farms are under increasing pressure to adapt to the evolving demands of the grid [13,14]. However, the DFIG's control system, being decoupled from grid frequency, and the limited 'implied inertia' from rotor kinetic energy, marginally contribute to grid stability [15]. Thus impacting, sometimes negatively, the grid's frequency regulation capabilities [16]. As wind power penetration in the grid heightens, this becomes a glaring issue, threatening the safe operation of the entire grid system [17, 18]. This underscores the importance of studying large-scale wind power grid connections and their influence on power grid frequency characteristics [19].

Recent research has intensively examined DFIG's involvement in grid FM [20], proposing various control strategies. Due to the distinct frequency response characteristics of windmills compared to traditional synchronous generators [21], the grid's frequency response post DFIG integration has been simulated and analyzed [22, 23]. A proposal to manage rotor speed changes and regulate output involves controlling the rotor flux position in DFIG [24]. The integration of a frequency response link into the doubly-fed induction wind turbine control system is also explored [25]. By controlling output, wind turbines can generate a simulated inertia 'H', allowing them to contribute to FR [26]. Studies indicate that excess simulated inertia control might destabilize the windmill [27]. A method coordinating the frequency governor of modifiable windmills with the old one's emphases on referend inertia (H) for principal regularity variation, but it does not fully address subordinate regularity physiognomies [28, 29]. Implementing droop control by incorporating windmills into FM follows traditional synchronous generator control modes [30, 31]. Comparisons between different windmill speed control methods reveal potential issues with a fixed droop coefficient, leading to recommendations for its adjustment [32–34]. Recent research advancements in control strategies and energy evaluation for wind power's role in system FM are also highlighted [35, 36]. Studies on the impact of DFIG access on grid transient stability using simulation methods focus on the adverse effects of high wind power permeability and propose improvement measures [37–40].

1.1 A critical analysis and comparison with existing literature to establish the rationale and significance of this research:

- **General Recognition of Wind Energy:** Acknowledged globally for its environmentally friendly nature Wind power is increasingly a significant part of energy mixes, notably in certain Chinese local grids.
- **Challenges in Wind Power Integration:** Despite its sustainability, the integration of wind power into grids faces challenges due to its inherent unpredictability and intermittency, impacting grid stability, particularly frequency and voltage regulation.
- **Role of DFIG in Wind Farms:** The DFIG has gained prominence in wind energy for FM, but its decoupled control system from grid frequency and limited inertia contribute marginally to grid stability.
- **Frequency Response and Control Strategies:** Intensive research has focused on DFIG's role in grid FM, with various control strategies proposed to manage rotor speed changes, integrate frequency response links, and simulate inertia for FR.

- **Comparison with Traditional Generators:** Windmills, including those with DFIG, exhibit distinct frequency response characteristics compared to traditional synchronous generators, necessitating specific control strategies for integration and stability.
- **Rationale and Significance:** Our research addresses an essential gap, the wind energy effect on grid frequency stability, in scenarios of changing wind speeds and unexpected load demands. The rationale of the study is vital due to the growing dependence on wind energy and the need for effective frequency regulation.
- **Challenges in Simulated Inertia and Control Methods:** Excess simulated inertia control can destabilize turbines, highlighting the need for careful coordination of frequency control between adjustable wind turbines and traditional generators.

1.2 Key Contributions and Innovations

The key contributions and innovations of this study are as follows;

- **Research Focus and Novelty:** This research delves into the DFIG in farms of wind for grid FR. The paper introduces new control tactics for modifiable turbines with augmented effective inaction, aiming to stabilize grid frequency.
- **Literature Comparison:** Existing literature primarily addresses the challenges posed by the intermittent nature of wind power and its impact on grid stability. Our research extends this by specifically focusing on the role of windmills (DFIG) in maintaining grid frequency stability under varying conditions. Previous studies have also explored the frequency response characteristics of windmills and the integration of energy storage systems, which are pertinent to our research.
- **Mathematical Model:** It provides a detailed mathematical model analyzing the relationship between wind energy incorporation, turbine regulation capabilities, FM, and energy efficiency.
- **Simulation and Analysis:** Utilizing MATLAB/Simulink and a windmill (DFIG) model, the study demonstrates the effectiveness of DFIGs in maintaining grid frequency. This includes two (02)-areas four (04)-machines grid framework simulation to identify the optimal proportion of tunable windmills required for frequency equilibrium.
- **Real-World Application and Data Use:** The research incorporates real-world data from Yunnan-Power to validate the model and its applicability in practical scenarios.
- **Contribution to Knowledge:** Our findings contribute to understanding the optimal allocation of adjustable windmills within wind farms for effective frequency control. The research advances knowledge on the integration of wind power into grid systems, offering practical implications for energy policy and grid management.
- **Frequency Regulation Capability Analysis:** It examines the capabilities of windmills under various wind conditions, providing insights into their FR abilities, energy reserve capacities, and rejection rates at different wind velocities.
- **Future Research Directions:** Potential areas for future research could include exploring the scalability of control strategies in different grid configurations and geographical contexts. Investigating the long-term impacts of these strategies on grid reliability and sustainability would also be valuable.

In this paper, a mathematical model is presented in section 2. Section 3 formulates a frequency control framework based on primary grid frequency control method. Section 4 outlines a theoretical analysis and a controller approach for wind turbines in frequency regulation. Section 5's simulation results suggest that, in high wind power permeability scenarios, ensuring safe and economical wind farm operation requires strategically allocating adjustable units, prioritizing those with substantial comprehensive FR capability. Section 6 concludes the paper, followed by references.

2. Mathematical model :

2.1 Power frequency features

In recent years, there has been significant development in wind energy conversion systems (WECS). At the heart of any WECS lies the machine responsible for converting mechanical energy into electricity. The windmill (DFIG) stands as a primary technology utilized within WECSs. The Windmill (DFIG) essentially functions as a wound rotor induction device, historically employed for applications necessitating speed regulation [41]. Fig. 1 demonstrates the basic structure of the DFIG generator. To optimize wind energy capture, DFIG typically operates in the MPPT mode at rated wind speeds. In this mode, DFIGs are unable to reserve energy for grid frequency fluctuations. However, if the operational mode is shifted such that the DFIG rotor operates at a velocity above MPPT through an over-speed strategy, and the rotor's current excitation frequency remains constant; a different scenario unfolds [42]. Although DFIGs may not harness wind energy at its peak in this phase, the rotor can accumulate kinetic energy. This endows it with dynamic characteristics akin to a synchronous generator; thereby enabling its contribution to prime grid FR. Figure 1 demonstrates the standard Of-over-speed-control. The diagram, taking into account the operational features of turbine, maps the liaison among outcome power (P t) and speed (ω) beneath a continual terrain control across different wind speeds. The MPPT curve, representing optimal power generation, is formed by connecting maximum power points at varying wind speeds. While the over speed and slowing methods can offer

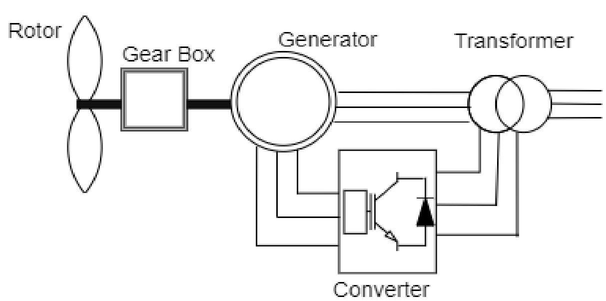

Fig. 1 DFIG basic structure

Standby energy, dropping the wind turbine's active output through lower rotational speeds might cause static instability and related challenges [17]. Consequently, the often preferred for adjustable velocity load detaching. At a specific wind speed, v_1, the runs smoothly at point a (as shown in Figure 2). If the velocity drops to v_2, the system's dynamic power declines, causing a frequency dip. Due to the significant inertia, its at ω_1 , avoiding abrupt changes.

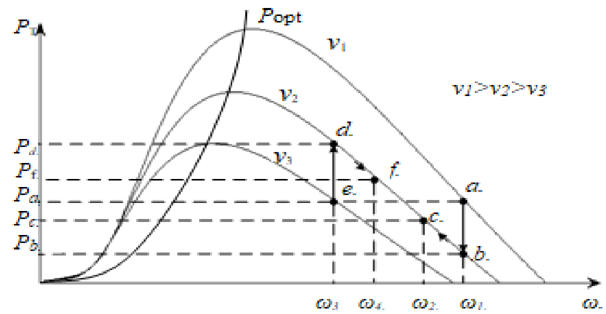

Fig. 2 Command principle for over speed controller

During this phase, the windmill's power output shifts from P_a at spot 'a to P_b at point b , analogous to the reduced velocity v_2 Simultaneously, the EM power of generator stays at P_a Any surplus power from the turbine is rerouted along the shaft. This diversion of mechanical power causes the unit's rotational speed to decrease. The turbine's mechanical power output follows the BC curve, increasing as it does. To boost system frequency and raise power, it's critical to modify the slipup angle velocity to match the windmill's reference speed with ω_2 After excess mechanical energy is unleashed, the windmill stabilizes at the c spot, stabilizing energy outcome at Pc, which in turn elevates the frequency. The control strategy for decreases in wind speed follows a similar pattern, as depicted by points e , d , and f in Fig. 2.

The electric energy induced by generating engine to the power network is:

$$P_{gen} = P_{s.} - P_{r.} \tag{1}$$

Where P_s is the actual power going out from the rotor and P_r is the actual power added by the rotor.

When DFIG deviates from MPPT, the EM (electromagnetic) power (P) of the is regulated by adjusting the rotor velocity and utilizing the KE (kinetic energy) deposited;

$$P = \frac{\Delta E_k}{\Delta t} = J\omega \frac{\Delta \omega}{\Delta t} \tag{2}$$

where E_k represents the rotating kinetic energy produced by wind turbine, J signifies rotating inertia, ω denotes rotating spin velocity. The "H" is;

$$E_k = 0.5\, J\, \omega..^2 \tag{3}$$

$$H = 0.5\, J\, \omega.^2 / S_{N.} \tag{4}$$

The ratio of active power to apparent power is expressed as:

$$\frac{P}{S} = 02H \ \frac{\omega}{\omega_s} \frac{\Delta\left(\omega/\omega_s\ \right)}{\Delta t} \tag{5}$$

Per unit is stated as,

$$P^* = 2H\, \omega^* \left(\Delta\, \omega^* / \Delta\, t\right). \tag{6}$$

The generator speed being essentially identical to the synchronous speed, denoted as ω^*= 1, also relates to the inertia time constant.

$$H = P^* / \left(2\Delta\, \omega^* / \Delta\, t\right). \tag{7}$$

This enables reaction to changes in grid frequency through the modification of rotor speed, thereby enabling the release or absorption of kinetic energy following shifts in grid frequency.

2.2 The basic norm of wind farms participating in the main FR

Upon integration of wind power denoted as P_{wt}, into the system, the power output from represented as P_G, and the energy consumed by the load is referred to as $P_{L;}$

$$P_{wt} + P_G = P_{wt} + \gamma P_{GN} = dP_L \tag{8}$$

Based upon the key network, when wind power participates in FR, there is a change in the system load, denoted as dP_L, and the following occurs;

$$dP_G + dP_w - dP_L = K_T df \tag{9}$$

In this scenario dP_G and dP_w represent the variations in the outcome of the synchronous machine and the windmill, df indicates the change in frequency, while (TC) transmission coefficient is K_T;

$$K_T = H_T / H_L \tag{10}$$

The coefficient is measured in the units of megawatts per hertz (MW/Hz).

(a) the permeability of the farm μ is defined as rate of total power output of the windmill to change in P_L. Expressed as;

$$\mu = P_{wt}/\Delta P_L \tag{11}$$

(b) The FM rate of-the windmill fields, represented as γ and expressed in a mathematical equation given below;

$$\gamma = dP_w/dP_{wt} \tag{12}$$

According to equation (6) ~ (11), it can be obtained

$$\frac{P_{GN}}{dP_L} = \frac{1-\xi}{\gamma}, \quad \frac{dP_{wt}}{P_{GN}} = \frac{\gamma\xi}{1-\xi} \tag{13}$$

Additionally,

$$\begin{cases} K_G = \frac{dP_G}{df} = \frac{P_{GN}}{f_N \sigma_G} \\ K_w = \frac{dP_w}{df} = \frac{dP_w}{f_N \sigma_w} = \xi\eta \frac{dP_L}{f_N \sigma_w} \\ K_L = \frac{dP_L}{df} = K_{L*} \frac{dP_L}{df_N} \end{cases} \tag{14}$$

In this context, f_N represents the nominal power frequency, which is 50Hz.

Moreover, the value of K_T and σ_T ; derived from LP (load-power).

$$K_{T*} = K_T \frac{f_N}{P_L} = \frac{1}{\sigma_T} \tag{15}$$

From equations (10) and (14) into equation (15), and subsequently organizing and simplifying the expressions;

$$\frac{1}{\sigma_T} = \frac{P_{GN}}{P_L \sigma_G} + \frac{\xi\eta}{\sigma_w} + K_{L*} \tag{16}$$

The components of the RHS in the formula have distinct interpretations:

The first part)", represents the differential adjustment function attributed to the synchronous generator, detailing how it adapts to changes in the grid.

The second part)", illustrates the effect of wind energy integration on the grid's differential adjustment coefficient. This aspect shows the dynamics, specifically in FM, but it does not alter the synchronous generator's differential adjustment function within the grid.

The third component)", corresponds to the usual worth of the load's frequency correction factor, highlighting how LP (load power) varies with frequency changes in the grid.

In this context, ΔP_w the power variation handled by the wind turbine, is determined as;

$$\Delta P_w = K_w \Delta f = \frac{\xi \gamma P_L}{f_N \sigma_w} \Delta f \tag{17}$$

Formula (17) indicates that an increase in the ratio of windmills partaking in FM (γ) and the higher level of wind power permeability (ξ), lead to a more significant change in wind power output (ΔP_w). According to equation (16), a lower adjustment coefficient (σ_T) enhances the FM impact of wind power. In conclusion, for effective integration of wind power into grid FM and to optimize wind energy production, it's essential to determine the minimum required ratio of modifiable given diverse levels of wind power permeability.

While there is a dynamic change in the system load, represented as ΔP_L, and the goal is to warrant that the resulting variation in the system frequency Δf remains within or below 0.2 Hz, the necessary parameters can be deduced using equation (6);

$$\Delta P_W \geq K_T \Delta f - \Delta P_G + \Delta P_L = (K_T - K_G)\Delta f + \Delta P_L \tag{18}$$

It is evident that when both the synchronous machine and the system's total FR coefficients, remain constant, any variation in the load, denoted as ΔP_L will be recompensed by the amendment in wind power output ΔP_w that can share in FM. The determined rate of vigorous change in the load is defined as ε which can be set as follows;

$$\varepsilon = \Delta P_L / P_L \tag{19}$$

(17) ~ (18) signifies that, with a fixed permeability ξ, both the minimum fraction γ of windmill partaking in the FM and the determined valuation of load vigorous alter ratio ε can be ascertained based on the frequency deviation ΔP_L.

2.3 Widespread FR ability of windmill

The equation for the windmill's rotor captured power can be expressed as follows:

$$P_w = 0.5\, \rho\, A\, C_p\, v..^3 \tag{20}$$

where ρ = air-density (kg/m^3), A = swept-area of the rotor, C_P is power coefficient (dimensionless), and v = wind speed (m/s).

(c) The utilization factor beta (β) is defined as;

$$\beta = dP_w / P_{wm.} \tag{21}$$

(d) The power reserve coefficient (K_p) is rate of the windmill's dP_w to its P_{wm}, in other words, it is;

$$K_{p.} = dP_w / P_{wm.} \tag{22}$$

In the formula, the typical range for K_P is between 10% and 20% [43]. This composed ene rgy is vital for the DFIG windmill to react to vibrant network. It ensures stable operation when the gen eration unit operates away from the MPPT mode.

Based on equations (20) and (22), it is observed that at lower wind speeds, wind turbines produce less power, leading to a smaller energy reserve available for participating in frequency modulation. This results in a reduced capability for frequency modulation under low wind speed conditions. Conversely, at higher wind speeds, the potential for wind turbines to contribute to frequency modulation increases. However, this also means a larger energy reserve and consequently a lower usage rate for the wind turbine, indicating a higher rate of energy rejection. Thus, wind turbines demonstrate varying abilities in frequency regulation, energy reserve capacities, and rejection rates at different wind speeds. This underlines the importance of carefully selecting wind turbines for involvement in frequency regulation.

$$\frac{1}{\beta} = 1 + \frac{\Delta P_W}{P_W} = 1 + \frac{2\Delta P_W}{\rho S C_P v^3} \tag{23}$$

Based on equation (17), once the permeability of the wind farm is determined and every turbine participates in frequency modulation, the entire windmill field can be considered as a solo windmill involved in modulating the grid frequency. In this scenario, ξ is treated as a constant (a fixed value) and η is assigned a value of 1. By incorporating equation (17) into equation (25) and rearranging the subsequent formula;

$$\beta=\left[1+\frac{2\xi P_L \Delta f}{\rho S C_P v^3 f_N \sigma_w}\right]^{-1} \tag{24}$$

Equation (24) shows that for a constant wind speed when there are variations in the system frequency, the of the windmill, represented by σ_w, is in direct proportion to its utilization coefficient β. This implies that the capacity of frequency is inversely proportional to its utilization ratio. To maximize the wind turbine efficiency while maintaining its ability to regulate frequency, a comprehensive frequency regulation coefficient, referred to as K, is established for the adjustable wind turbine at dissimilar velocities, as under;

$$K = \alpha_1 K_w(\gamma,\xi) + \alpha_2 \beta \tag{25}$$

here, K_w represents the FM coefficient that is intrinsically linked to the FM ratio γ and the permeability ξ of the wind farm. The coefficients α_1, α_2 are adjustable real numbers that should be finely tuned in harmony with the unique dynamics of the grid. If it's imperative to maintain the FM capability of the wind within the grid, then a higher proportion is assigned to α_1, thereby ensuring a greater utilization ratio for the wind turbine compared to α_2. Typically, the optimal values for α_1 and α_2 are derived through a meticulous evaluation of historical wind farm data, leveraging optimization techniques, empirical insights, or relevant mathematical formulations. The overriding objective is to attain the most efficient FM impact, utilizing the smallest number of FM and the lowest air denial rate.

Taking into account the widespread FM coefficient K, the optimum wind velocity of the turbine can be identified, ensuring both the utilization proficiency. The determination method for K_w and β of windmill is as below;

1. At the specified velocity, connect the conventional wind turbine to the system. Then, by escalating the load, reduce the frequency by zero point three hertz and measure the actual power output of the wind turbine.
2. In an identical setup, replace the conventional wind turbine with a frequency adjustable one. Measure the maximum frequency variation and the actual power output of the windmill before it initiates FM, confirming that these measurements are taken under the same load change conditions.
3. By incorporating equations outlined in sections 2.2 and 2.3 with the upward estimated values, it becomes possible to calculate the FM coefficient K_w and the utilization coefficient β at the definite wind velocity.

3 DFIG's control model's contribution to primary frequency regulation

Adhering to the controlling philosophy of wind energy role in frequency modulation, this paper conceptualizes a detailed and all-encompassing frequency control model, as visualized in Figure 3. This intricately designed model encompasses five pivotal components: (1) the speed control of rotor; (2) the analog inertia control module; (3) the drop control module; (4) the combined module for protection of speed and power evaluation; and (5) the pitch angle control module. Each of these modules plays a crucial role in harmonizing and optimizing the frequency control process, ensuring a seamless and efficient integration of wind power into the broader frequency modulation framework.

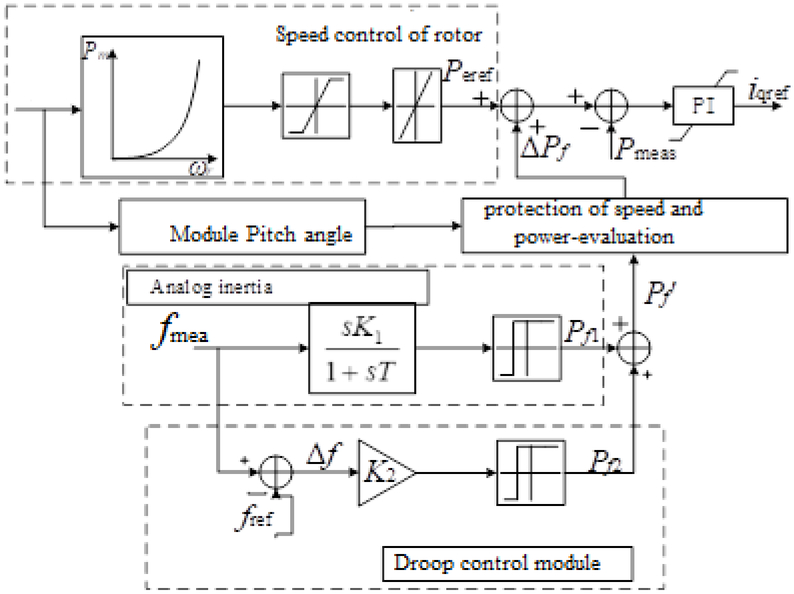

Fig. 3 DFIG's model contributing in FR

Figure 2 illustrates a speed protection mechanism designed to safeguard DFIG from over engaging in frequency modulation, which could result in the speed of the rotor falling below the critical minimum, ω_{min}. When the velocity goes to ω_{min}, it becomes necessary for the power-network to adjust the further actual energy ΔP_f to zero. Disengaging DFIG to share in grid FM. The energy evaluation section is to evade the energy P_f ' contributing in FM surpassing the ΔP allocated by the windmill. In the instance where P_f hits the determined value ΔP_{max} , the grid then requires to set the added actual power ΔP_f to ΔP_{max} and cease to participate in FM. The pitch angle control module, primarily utilized when wind speeds surpass the rated threshold, is depicted in its model form in Figure 4.

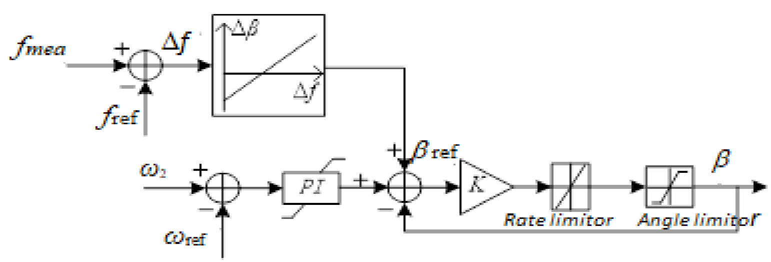

Fig. 4 Pitch perspective control unit

4 Wind farm's control strategy partaking in (FM) frequency modulation

The fundamental rationale for incorporating wind farms into the FM control strategy revolves around the objective of preserving both the system frequency and the wind farm's active power at stable levels, to reduce the involvement of turbines in the FM process as much as possible. Upon the earlier review of the fundamental principles of windmill-cluster in FR and their overall FR capacity, this article presents the following procedural flow for the management plan of windmill-cluster partaking in regulating the rate of cycles per second (frequency);

a: Evaluate the wind speed experienced by each wind turbine.

b: Determine the total windmill tally engaged in FR , taking into account the smallest ratio of modifiable turbines required at varying permeability conditions.

c: Prioritize the involvement of the wind turbines that demonstrate the best overall regulation of frequency ability and optimal wind speed for FR purposes.
d: If the necessary quantity is not achieved, select wind turbine units based on a sequential decrease in wind speed from the best operating wind velocity.
e: In case the required number of turbines is still not attainable, proceed to select turbine units based on a principle that involves operating at speeds above the optimal level, with a gradual increase in wind speed. This procedure is illustrated in Figure 5.

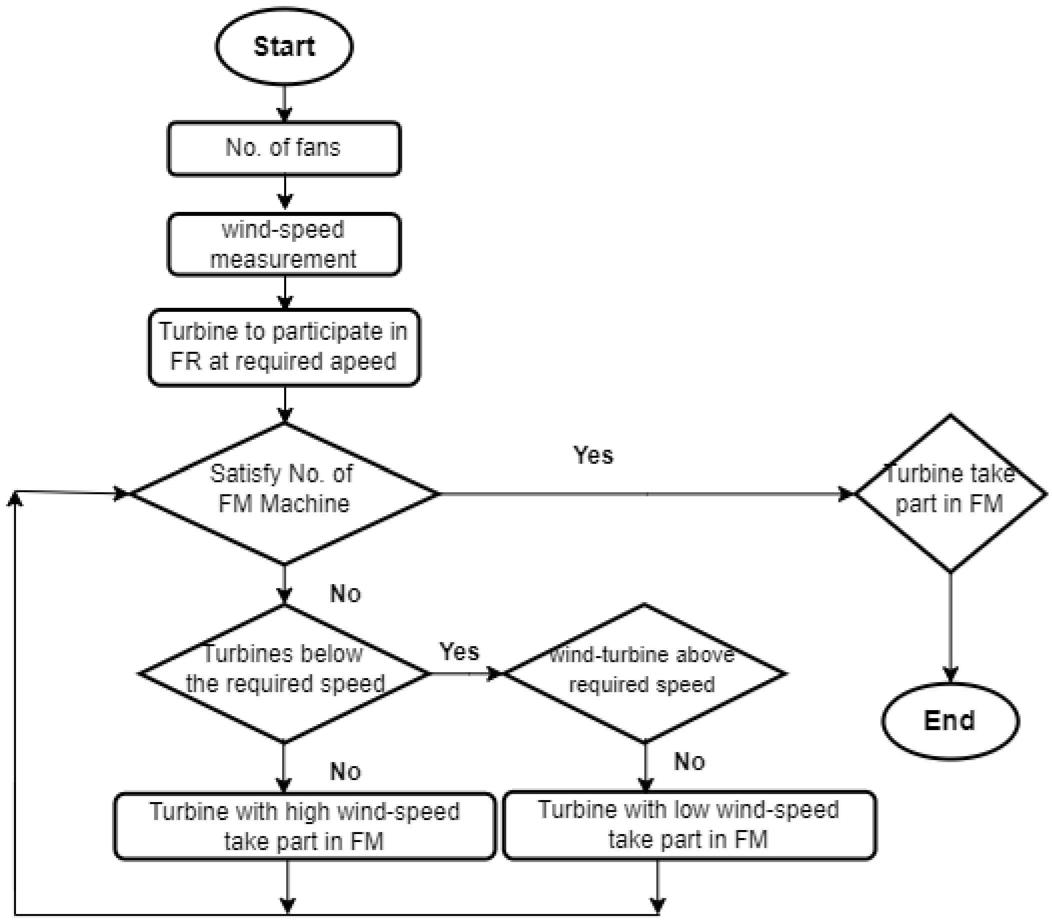

Fig. 5 Optimization control strategy's flow chart for wind farm contributing

5 Simulation's Results

5.1 1st Case-Study

Under the guidelines of the state standard of China GB 15946-1995, the power system's frequency control within the range of (50 ± 0.2) Hz should exceed 98% of the time [4]. Using the grid in a specific region of Province of Yunnan as a case study, Figure 6 displays the primary wiring diagram of the grid. Within this setup, the wind farms at Luopingshan, Ma'an, and Dalongtan have capacities of 55 (40 × 1.38) MW, 50 (33 × 1.51) MW, and 50 (35 × 1.43) MW. Meanwhile, the hydropower stations at Luosiwan, Lanping, Longdi, and Xuebangshan have capacities of 210MW, 75MW, 12MW, and 16MW respectively. This indicates that the total established capacity of wind energy is closer to 150MW, which represents about 24% of the total installed capacity, indicating a relatively high level of permeability in this area. If the wind turbines from all three farms are consolidated into a single unit, this would result in three equivalent wind turbines. The input wind speeds for equivalent turbines are depicted in Figure 7.

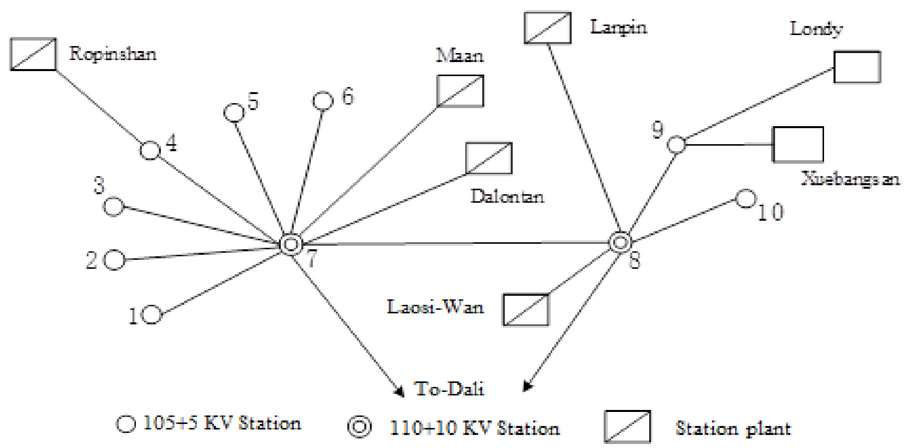

Fig. 6 Main Power Grid Layout for a Specific Section of Power Grid Area

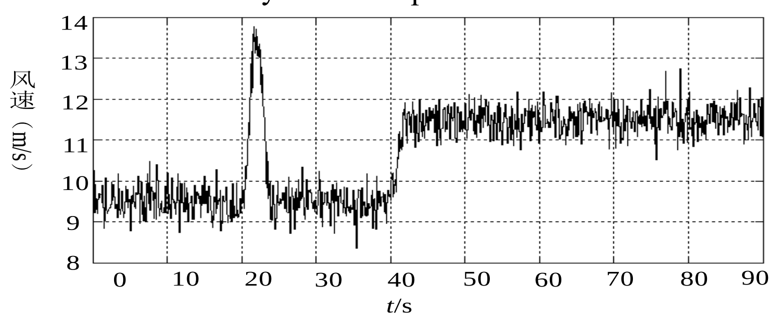

Fig 7 wind speed's wave pattern

5.1.1 Influence of high wind on the frequency of the grid

At the moment when t equals 70 seconds, there's a sudden load increase at node 6. To assess the effect of heightened wind energy permeability on-the-grid's-frequency, simulations are conducted with total load and output at 10%, 20%, and 30% respectively. The frequency behavior curve of the electricity network is demonstrated in Figure 8. From the graph, it's clear that at lower wind speeds, grid frequency is more significantly affected by gusts, leading to a slower recovery of frequency and heightened fluctuations due to variable wind speeds. In contrast, at higher wind speeds, the active power reaches its peak between 60 and 70 seconds, aligning with the determined entire outcome of system. In such instances, the wind turbine remains non participatory in frequency modulation, which leads to reduced grid inertia at higher wind power permeability. This scenario is not conducive for the grid's primary frequency modulation capacity.

5.1.2 Confirmation of FM controller model

By replacing the standard wind turbine with the one equipped to partake in FM, a comparative analysis is performed on the frequency variation characteristics at a wind turbine permeability of 20%, as depicted in Figure 9. It becomes apparent that the involvement of the turbine in FM substantially reduces the rate of change in the frequency of the grid and lowers the steady state frequency error. This effectively lessens the influence of casual wind speed oscillations on frequency. Nevertheless, there is a minor reduction in the utilization rate before the load increase, attributable to the power reserve requirement of the DFIG.

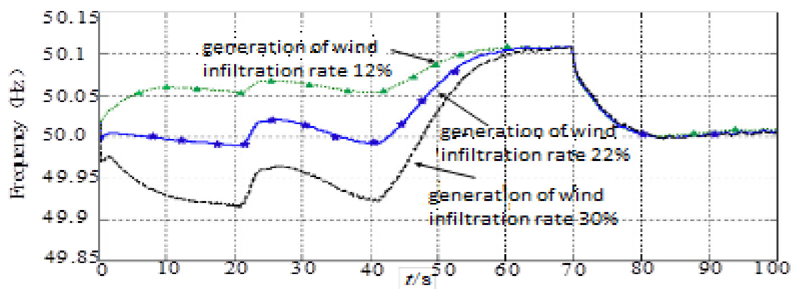

Fig. 8 Grid frequency response at various wind energy infiltration plugs

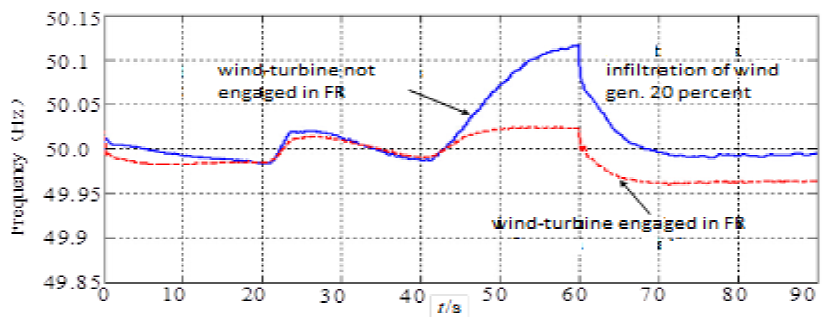

Fig. 9 Power grid frequency regulation impact of Partaking wind turbines

5.2 2nd Case-study

This study introduces four (04)-machines, two (02)-areas electricity-network design created using simulation software, publicized in Figure 10. There are four synchronous generators in the grid, each with wattage of about 910MW. A DFIG Windmill, labeled FW and with a corresponding assessed capability of 455MW (290 × 1.56 MW), is connected at bus 6. Elements La and Lb represents the loads of the grid for the two respective areas, cumulatively amounting to a load capacity of slightly more than three thousand megawatts.

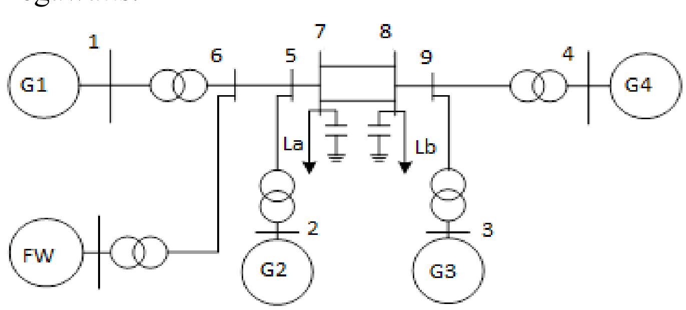

Fig. 10 System configuration for simulation

Upon the examination of the fraction of turbines at varying levels of permeability and their overall frequency regulation ability, the study makes the following assumptions:

1. The wind velocity during steady operations is set at the lowest acceptable level for the wind turbine's working.
2. The objective is to keep the grid frequency steady at 50 Hz, ensuring that fluctuations do not surpass ±0.3 Hz.
3. The velocity of incoming wind is maintained uniformly across all types of turbines.

5.2.1 Fraction of wind turbine in changed permeability

The primary goal of integrating wind power into the regulation of grid frequency is to guarantee the stability of frequency on the generation side. However, the regulatory effects on the load side are also addressed, using a coefficient K_L as presented in equation 7. The strategies described aim to enhance the integration of wind power in grid frequency modulation, maximize wind energy utilization, and establish the lowest rate of regulating wind turbines necessary underneath various wind power permeability conditions. The approaches used are detailed below;

1. Escalation the wind velocity to the determined adequate limit of the turbines. Modify the share of modifiable wind turbines to maintain grid frequency in the designated limits. This step is instrumental in determining the least necessary fraction of adaptable wind turbines η.
2. After stabilized grid operations, there is an abrupt rise in load L_1 by 300MW at t = 40s. The aim is to limit the determined load change rate ε that the grid handles while staying within the prescribed frequency limits.

Adjust the increment value to 5%, thereby facilitating a gradual rise in the grid's wind power permeability. Table 1 displays the varying proportions of frequency modulation (FM) wind turbines corresponding to different permeability levels. It is evident that as permeability ξ escalates, effectively managing the power grid's frequency fluctuations becomes feasible by augmenting the proportion of frequency adjustable wind turbines η. Consequently, the load change rate ε also rises, aligning with real world scenarios. However, it's noteworthy that an excessively high proportion of FM wind turbines might lead to a decreased utilization rate of wind power.

Table 1 Frequency regulation partaking of wind turbines at varied penetration rates

Penetration rate ξ (%)	Fraction of wind turbine η (%)	Rate of Load change ε (%)
7	5.4	7.0
12	17.6	11.00
16	27.4	14.7
22	41.1	16.3
27	57.6	23.0
30	75.8	28.89

5.2.2 Enhanced Ability of FR of a Turbine Across Varying Wind Speeds

Utilizing the framework of Figure 10, this study investigates the K_w and β of the windmills across velocities of wind ranging from a minimum of five meters/seconds to a maximum of sixteen meters/seconds. This investigation follows the methodology described in section 2.3. The findings are presented in Figure 11. For instance, in calculations in this article, to confirm the ability of the turbine's FR, the coefficients α_1=2 and α_2=1 in equation (22) are determined after thorough consideration. Figure 11 also displays comprehensive coefficient K of the windmill's FR at various velocities of wind. Additionally, the frequency and power change curves of the turbine of wind under both traditional and frequency adjustable conditions are illustrated in Figure 12 and Figure 13, with Δf_1 and Δf_2 representing frequency variations of the windmill having and not having FM, respectively.

The curve in Figure 11 reveals that as wind speed increases, the K_w also surges. Notably, when the speed reaches 13m/s, which is the assessed speed for the wind turbine, K_w attains its determined value. Further, as the velocity of wind increases beyond this point, the coefficient β decreases, hitting its lowest value at a wind speed of 13m/s. Operating above the rated wind velocity, the wind turbine maintains consistent parameters by dissipating wind energy of wind via pitch angle control. Within the velocity range of 09 to 13m/s, the adaptable wind turbine exhibits superior FR ability and a higher utilizing coefficient. Reflecting on the wind curtailment rates in recent years, from 2011-2014 and 2015, the nationwide rate of power of wind waste was approximately 20%. In certain regions, these rates were even higher: 35.2% in Jilin Province, 32% in the Xinjiang Uygur Autonomous Region, 39% in Gansu Province, and 18% in the Inner Mongolia Autonomous Region [37, 44]. Given these figures, and based on the utilization coefficient β, maintaining the rate of abandoned wind within 5% to 35% in the 10 to 12m/s wind speed range aligns with current standards for wind power waste. Consequently, wind turbine units within a wind farm that operate at wind speeds between 10 and 12m/s should be prioritized for participation in frequency modulation.

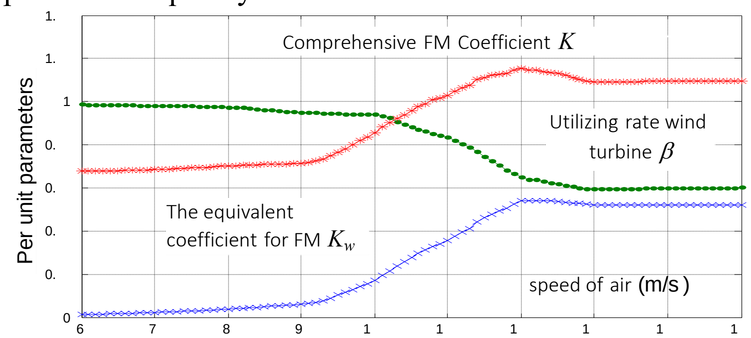

Fig. 11 Corresponding and Inclusive FM Coefficients Kw and K, along with the Wind Power Utilizing Rate

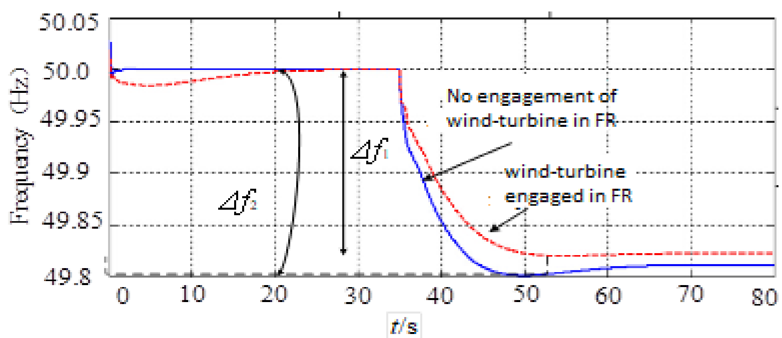

Fig. 12 Contrasting of frequency of grid less than 10 meters per second

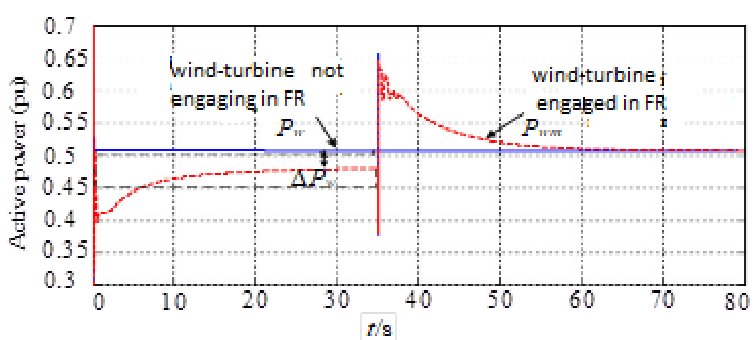

Fig. 13 Contrasting active power output at a speed of wind less than 10 meters per second.

Figure 12 shows that with a constant capability of dynamo machines involved in grid FR, the frequency difference of the electricity network is smaller when the windmill partakes in this management compared to when it does not. This indicates that an increase in atmospheric energy permeability and the windmill power utilization coefficient can lead to further reductions in the grid's frequency deviation by regulating the operative way of the turbine. On the other hand, Figure 13 demonstrates that when the turbine is not part of the modulation of grid's frequency, its generated active power remains stable due to its flexible connection with the grid. In contrast, when the turbine is engaged in the modulation of grid's frequency, the active power it generates varies in accordance with the grid's frequency changes. This variation is a result of the rigid association between the turbine and the grid during frequency modulation, giving the wind turbine similar dynamic features to an equivalent synchronous generator.

6 Conclusive remarks

This research formulates a framework for frequency control tailored to doubly-fed asynchronous wind turbines, investigating their contribution to regulating grid frequency. Key conclusions include:

1. Creation of a model enabling wind turbines to adaptively respond to deviations in the frequency of the grid. The model shows wind turbines behaving similarly to synchronous generators in grid dynamics
2. For the first time, the research identifies and quantifies the relationships among several key factors: the total adjustment coefficient, synchronous generators rate of adjustment, the coefficient of frequency modification of loads, wind turbines' modification coefficient, permeability, and the frequency modification rate within a wind farm, followed by in-depth demonstrations and analysis of these relationships.
3. The results from the simulations indicate that, given consistent wind power permeability, the adjustable wind turbine is capable of effectively reducing the frequency fluctuations within the power grid.
4. The research determines the necessary participation level of wind turbines in regulation of frequency and the parameters of dynamic load changes.
5. Additionally, in varying wind power conditions, the optimization coefficient adjusts to grid needs, allowing for strategic frequency modulation and effective windmill field integration into the electricity network grid.

7 Engagement of Interests

The authors affirm that there is no engagement of interests among them.

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