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Frequency Control Strategy for Black Starts via PMSG-Based Wind Power Generation

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Abstract: The use of wind power generation (WPG) as a source for black starts will significantly enhance the resiliency of power systems and shorten their recovery time from blackouts. Given that frequency stability is the most serious issue during the initial recovery period, virtual inertia control can enable wind turbines to provide frequency support to an external system. In this study, a general procedure of WPG participating in black starts is presented, and the key issues are discussed. The adaptability of existing virtual inertia control strategies is analyzed, and improvement work is performed. A new coordinated frequency control strategy is proposed based on the presented improvement work. A local power network with a permanent-magnet synchronous generator (PMSG)-based wind farm is modeled and used to verify the effectiveness of the strategy.

Keywords: black start; frequency control; virtual inertia; permanent-magnet synchronous generator (PMSG)

1. Introduction

Black start is the procedure of restoring an entire power system or portion of a power system without relying on the external electric power network after a blackout. A black start entails power stations with the ability to self-start being first started and then gradually reconnected to the other stations to form an interconnected system again [1,2]. Conventionally, power sources with high operation reliability (e.g., pumped-storage power stations or gas turbine generating units) are utilized as a black start power supply. Black start power supplies are still in short supply and irrationally located due to limitations in the distribution of water resources and the maintenance requirements of power stations. In the last decade, wind power generation (WPG) has gradually become one of the main sources of power in many regions of the world, with the penetration level continuing to increase. With the development of wind power prediction, operation and control technologies, the utilization of large-scale wind farms for black starts is beneficial for both theoretical research studies and practical applications [3–5].

Traditional studies regarding the black start of power networks are largely focused on the recovery strategy, optimizing the restoration paths and program evaluation. In recent years, with the maturation of micro-grid technology, several researchers have proposed using WPG in the black start procedure of a local network with auxiliary energy storage [6–11]. These schemes ensure that a micro grid undergoes a seamless transition from grid-connected mode to island mode when a blackout occurs in the external power network [12]. Due to the cost, capacity and application status of energy storage, few of these schemes can be adopted directly for the black start of bulk power systems. The key issue of black start via WPG is ensuring that the voltage and frequency remain stable during the initial period of time. Considering wind turbines, some researchers connected a battery storage system with the DC link of a back-to-back pulse-width modulation (PWM) converter in a doubly fed induction generator (DFIG) [13,14], and the improved control strategy of the grid-side converter was adopted. Considering wind power transmission, voltage source converter (VSC)-based high voltage direct current (HVDC) links were used to assist wind power stations (offshore wind farms especially) participating in the black start of large-scale power systems [15,16]. However, a HVDC transmission system will bring greater impact to the AC grid, and the DC blocking may also lead to the collapse of the AC system, so in some scenarios, a HVDC transmission system on power grid black start and recovery may also bring adverse effects. Due to the unique requirements in either equipment or network structure, the above schemes cannot be easily applied to many situations. Thus, the main objective of this work is to present a more generic procedure for the participation of WPG in black starts.

The majority of wind turbines currently in use are controlled by converters to achieve a variable speed and constant frequency (VSCF). The complete decoupling between the rotor speed and frequency of the power grid inhibits wind turbines from providing inertial support to external power systems. Because frequency stability is essential during the initial period of the black start process, WPG is restricted from participating in the procedure. Virtual inertia technology introduces the deviation of the system frequency to the control system of wind turbines, thereby releasing the hidden rotational kinetic energy for rapid power control during frequency fluctuations, which provides a threat for using WPG as a black start source. Existing virtual inertia control strategies include accessional power outer-loop control [17], optimal power tracing control [18] and accessional pitch angle control [19], among them, accessional power outer-loop control can make the rotor speed of the wind turbine no longer coupled with the grid frequency, but it can only provide a very short frequency support for the power grid, and has no contribution to reducing the frequency steady-state error; optimal power tracing control changes the power tracking curve to optimize the power tracking characteristics of the wind turbine when the grid frequency changes, thus releasing the hidden kinetic energy of the wind turbine to achieve the purpose of adjusting the frequency; however, it sacrifices the utilization rate of wind energy and reduces the economic benefits of wind power generation (WPG); accessional pitch angle control obtains the reserve capacity by adjusting the pitch angle of the wind turbine, the adjustment of the pitch angle is a mechanical process with a slower response speed, which is likely to cause the mechanical wear of the wind turbine as well, as it is not conducive to the economic operation of wind power generation (WPG). In view of the peculiarities of black start, the suitability of these strategies must be analyzed and improvement works must be performed.

This paper investigates the black start procedure with WPG and the related key problems based on the actual demand of an electric utility in China. A new virtual inertia control strategy is proposed to support the frequency stability of the system. The effectiveness of the method is verified by a local power network model built based on real data. The research achievements will be adopted in an on-site test.

2. Research Background and Key Issues of WPG Participating in Black Starts

2.1. Current Situation of the Electric Network in Jiangsu Province, China

Jiangsu Electric Power Company is the largest provincial power utility in China; the company provides the majority of the energy for one of the largest metropolitan regions in the world. There exist three black start sources: a gas turbine generating unit in the north and two pumped-storage power stations in the south, as shown in Figure 1. The north station has already been in service for a long time, and its startup characteristic is currently poor. In contrast, the two south stations are located relatively close to each other, which inhibits them from assisting in the restoration of the entire network. More black start stations and a more rapid recovery process are in urgent demand due to the rapid increase in power load. Considering the existence of a ten million-kilowatt wind power base in the coastal area of Jiangsu, the participation of wind generation in black start will be highly beneficial.

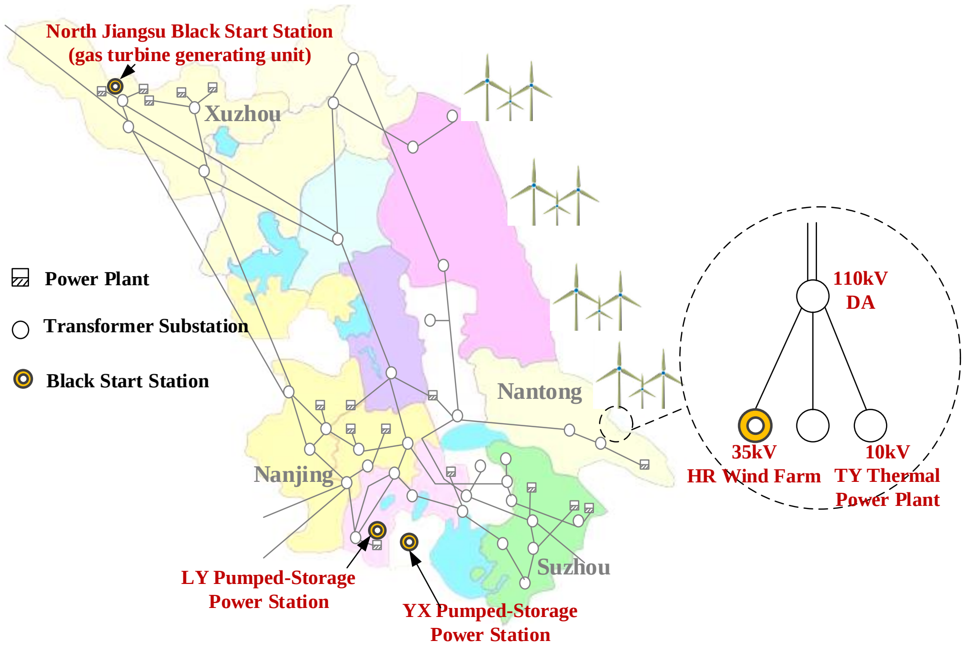

Figure 1. 500-kV power grid of Jiangsu Province, China and the three existing black start stations.

Based on an analysis of the power network structure and a field investigation, a wind farm in the eastern coastal area (i.e., the HR Wind Farm in Figure 1) is chosen as a potential black start source. The goal is to start the thermal power plant (i.e., the TY Thermal Power Plant in Figure 1) connected at the same 110-kV transformer substation (i.e., the 110-kV DA transformer substation in Figure 1) using the wind farm with 33 1.5 MW wind turbines. The wind farm (i.e., the HR Wind Farm in Figure 1) in the eastern coastal area of Jiangsu has abundant wind resources and the geographical distribution of wind turbines is extremely broad, which reduces the probability of WPG without wind resources. Besides, the wind turbine units are able to control its output flexibly. Therefore, it has unique and favorable conditions for WPG participating in black starts and the feasibility of the wind farm as a black start power source was greatly increased. The research project is divided into two parts: (1) modeling analysis to verify the scheme and control strategy and (2) field test. This paper is focused on the former.

2.2. Key Issues of WPG Participation in Black Starts

Both the volatile nature of the power output and the current control strategy of wind turbines make it difficult for WPG to establish the voltage and frequency of an isolated system. Therefore, the following key issues must be discussed to introduce WPG into the black start procedure.

2.2.1. Selection of the Wind Turbines

Currently the mainstream types of power generators used in wind farms include DFIGs and permanent-magnet synchronous generators (PMSGs), both of which can theoretically regulate the output power within the entire range through active pitch control, thereby stabilizing wind power fluctuations to a certain degree. Compared with DFIGs, PMSGs have fewer requirements for the reactive power during power system faults, and the grid-side converter is better able to participate in the voltage and reactive power regulation of power grids, that is, PMSGs are more beneficial to the system stability. Moreover, the wind turbine is connected with the PMSG directly instead of through mechanical transmission devices (e.g., gearbox), thus avoiding the decline in reliability. The lack of an additional excitation source provides PMSGs with more advantages during the black start procedure. In this paper, PMSG-based WPG is considered for further study. With the appropriate transformation, the strategy proposed in this study can also be used in DFIG-based systems.

2.2.2. Selection of the Startup Power Supply

A startup power supply with limited capacity is essential to providing the voltage and frequency references during the initial period of the black start, which typically includes diesel generators and energy storage devices. The latter option typically has better dynamic characteristics, although the high cost and relatively low support time limit its application. Thus, for a more general situation, mobile diesel power generation is adopted due to its practicality and economic efficiency.

2.2.3. Start Time of the Static Synchronous Compensator

The static synchronous compensators (STATCOMs) equipped in wind farms can be utilized to provide voltage support during the black start procedure. STATCOMs will absorb active power of a certain capacity at the startup moment, which has a considerable impact on the relative vulnerable system during a black start. Therefore, in this study, the STATCOM is started immediately after the startup of the diesel generator and before the operation of the wind turbines.

2.3. General Procedure of Black Start by PMSG-Based WPG

The general structure of the local power system with a wind farm and thermal power plant is built based on real data, as shown in Figure 2.

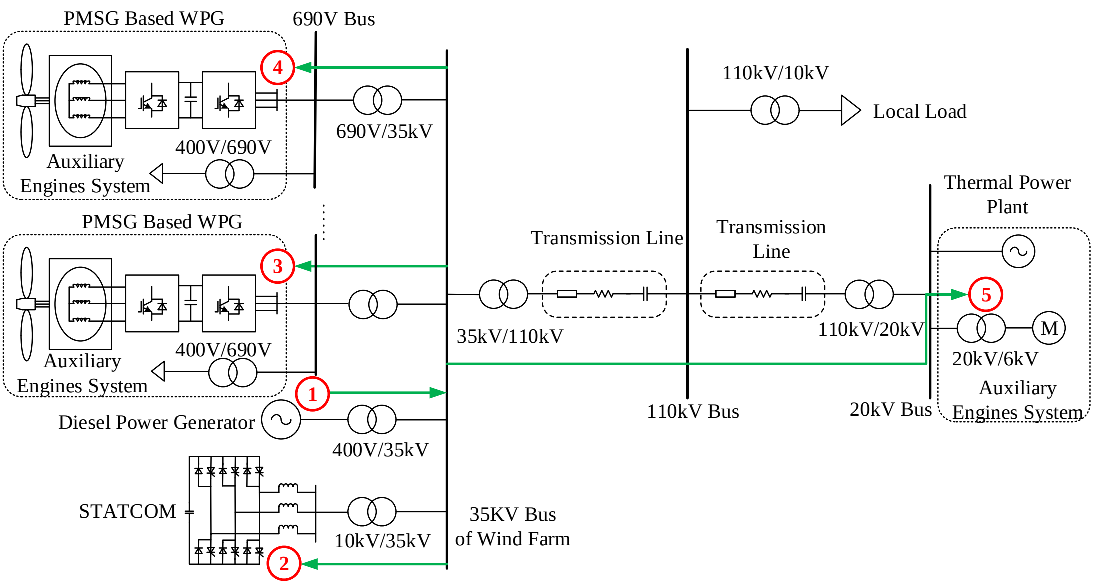

Figure 2. Structure of the local power system with a wind farm and thermal power plant (the red numbers with green lines represent the startup sequence in the black start procedure).

Based on the above discussion, the black start procedure is as follows:

(1) A mobile diesel power generation is connected to the 35-kV bus of the wind farm and starts to supply power. This mobile diesel power generation is used as the main reference source in the black start process to provide stable voltage amplitude and frequency reference for isolated systems. By adjusting the port voltage amplitude of the diesel generator, the diesel generator is able to realize the raising voltage from zero. When the diesel generator is started, the no-load charging of the box type transformer in the wind farm is completed.

(2) STATCOM is started after its capacitances and control system are charged through the 35-kV bus to provide voltage support for the isolated system.

(3) The auxiliary engine system of the PMSG-based WPG is powered; when the wind speed satisfies the starting condition, the wind turbine is started up and begins to transfer energy to the 35-kV bus through the PMSG.
(4) The active power output of the started wind generator is limited to 10%–20% of the rated capacity through pitch angle control in order to achieve the power balance for the isolated system. Then the auxiliary engines systems of other wind generators are powered one by one so as to realize the self-starting of the whole wind farm.
(5) The capacity of the isolated systems is expanded through the startup of multiple wind generators. When the capacity of the wind farm reaches a certain scale, the output transmission line and transformers are put into service to feed power to the auxiliary engine system of the adjacent thermal power plant with the ability to supply power to the base load.

In step 4, the power output of wind generation should be limited because the load (mainly includes the necessary auxiliary equipment in wind farms) is not sufficiently large to consume the additional active power.

In this study, the system model shown in Figure 2 is established using PSCAD/EMTDC simulation software. The capacity of the equivalent auxiliary engines in the wind generators is 80 + j40 kVA, whereas that of the thermal power plant is 450 kVA. The parameters of the PMSG-based WPG are shown in Table 1.

Table 1. Parameters of the PMSG-based WPG.

Parameters	Values	Parameters	Values
Blade RadiusAction (m)	50	Number of Pole-pairs	44
Air Density (kg·m^{-3})	1.225	Stator Resistance (p.u.)	0.017
Rated Capacity (MVA)	1.5	D-axis Inductance (p.u.)	0.5
Rated Voltage (kV)	0.69	Q-axis Inductance (p.u.)	0.5

3. Emergency Adaptability Analysis of Frequency Control Strategy-Based Virtual Inertia

3.1. Theory of Virtual Inertia

Ignoring the damping effect, the rotational kinetic energy stored in the rotor of a conventional synchronous generator is [20].

$$E_{\mathrm{k}} = \int (P_{\mathrm{m}} - P_{\mathrm{e}})dt = \int J\omega_{\mathrm{m}} d\omega_{\mathrm{m}} = \frac{1}{2} J\omega_{\mathrm{m}}^2 = \frac{1}{2n_{\mathrm{p}}^2} J\omega_{\mathrm{e}}^2 \tag{1}$$

where ω_{m} and ω_{e} are the mechanical and electrical angular velocities, respectively, P_{m} and P_{e} are the mechanical and electromagnetic powers, respectively, and J and n_{p} are the rotation inertia and magnetic pole pairs number of the generator, respectively.

The inertia constant is typically defined to represent the impact of the generator's inertia to the dynamic behavior of power system, which is the ratio of the stored kinetic energy to the rated capacity S_{N} of the generator:

$$H = \frac{E_{\mathrm{k}}}{S_{\mathrm{N}}} = \frac{J\omega_{\mathrm{e}}^2}{2n_{\mathrm{p}}^2 S_{\mathrm{N}}} \tag{2}$$

Thus, the inertia constant of an isolated system with wind generators and a diesel power generator can be represented as follows:

$$H_{\mathrm{S}} = \frac{\sum\limits_{i=1}^{n} E_{\mathrm{kw},i} + E_{\mathrm{kd}}}{\sum S_{\mathrm{N}}} = \frac{\sum\limits_{i=1}^{n} E_{\mathrm{kw},i} + \frac{J_{\mathrm{d}}\omega_{\mathrm{ed}}^2}{2n_{\mathrm{pd}}^2}}{\sum S_{\mathrm{N}}} \tag{3}$$

where n is the number of wind generators, E_{kd} and $E_{\mathrm{kw,\,i}}$ are the rotational kinetic energies of the diesel power generator and the ith wind generator, respectively, and J_{d}, ω_{ed} and n_{pd} are the rotational inertia, synchronous electrical angular velocity and magnetic pole pairs number of the diesel power generator, respectively.

Without a control strategy, PMSG-based WPG cannot vary its rotational kinetic energy when the frequency of the external power system changes; in other words,

$$\sum_{i=1}^{n} E_{\mathrm{kw},i} \approx 0 \tag{4}$$

During the initial period of black start, the inertia from the diesel power generator is not sufficiently high to ensure frequency stability, particularly when the load of a relatively large capacity (e.g., auxiliary engine system of the thermal power plant) is connected to the power grid. Therefore, the frequency variation of the grid side must be introduced to active power control to ensure that the PMSG-based WPG virtual inertia has a value similar to that of the synchronous generator through regulation of the rotor speed. The virtual inertia is expressed as

$$J_{\mathrm{VI}} = \frac{J_{\mathrm{eq}}\omega_{\mathrm{r}} d\omega_{\mathrm{r}}}{\omega_{\mathrm{s}} d\omega_{\mathrm{s}}} \approx \frac{\Delta\omega_{\mathrm{r}}}{\Delta\omega_{\mathrm{s}}} \cdot \frac{\omega_{\mathrm{r0}}}{\omega_{\mathrm{e}}} \cdot J_{\mathrm{eq}} = \lambda \cdot \frac{\omega_{\mathrm{r0}}}{\omega_{\mathrm{e}}} \cdot J_{\mathrm{eq}} \tag{5}$$

where λ is the regulation coefficient of the rotor speed, J_{eq} is the equivalent inherent inertia of the wind turbine, ω_{r} and ω_{s} are the rotor speed of the wind turbine and the frequency of the grid side, respectively, and ω_{r0} is the initial value of ω_{r}.

According to (5), the regulation range of the rotor speed can be considerably larger than the frequency variation of the grid side (i.e., $\Delta\omega_{\mathrm{r}} \gg \Delta\omega_{\mathrm{s}}$); thus, the wind turbine can provide an inertial response over a relatively large range through virtual inertial control.

3.2. Conventional Virtual Inertial Control Strategies

3.2.1. Accessional Power Outer-Loop Control (APOLC)

The frequency deviation of the grid side is introduced to the active power control module as an auxiliary power value (i.e., ΔP_{VI} in Figure 3) through the proportional derivative [17]. A schematic diagram of the approach is shown in Figure 3: Δf is the frequency deviation, k_{pf} is the gain of the frequency deviation, k_{df} is the gain of the frequency deviation rate, ΔP_{VI} is the change of active power, ω_{r} is the angular velocity of wind turbines, $P_{\mathrm{S\text{-}MPPT}}$ is the maximum output power of wind turbines.

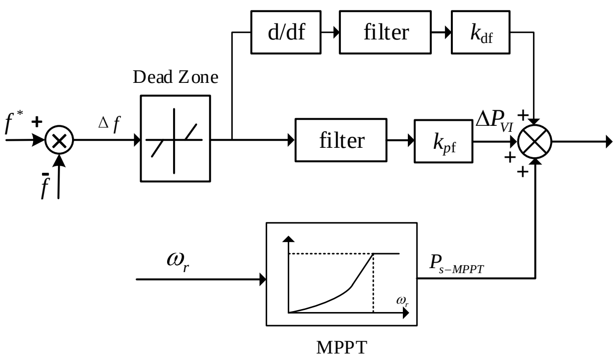

Figure 3. Schematic diagram of the accessional power outer-loop control.

3.2.2. Optimal Power Tracing Control (OPTC)

The scale coefficient (k_{opt}) of the maximum power point tracking curve used in the converter control strategy is updated in real time based on the frequency deviation (Δf) of the grid side as follows [18]:

$$k'_{\text{opt}} = \begin{cases} \frac{k_{\text{opt}}\omega_{\text{r}}^3}{(\omega_{\text{r0}}+2\pi\eta\Delta f)^3}, & \omega_0 < \omega_{\text{r}} < \omega_1 \\ \frac{\frac{(P_{\max}-k_{\text{opt}}\omega_1^3)}{(\omega_{\max}-\omega_1)}(\omega_{\text{r}}-\omega_{\max})+P_{\max}}{(\omega_{\text{r0}}+2\pi\eta\Delta f)^3}, & \omega_1 < \omega_{\text{r}} < \omega_{\max} \end{cases} \quad (6)$$

where k_{opt} is the maximum power tracking curve coefficient of wind turbine, ω_{r0} is the initial angular velocity of wind turbines, η is a factor used to regulate the control effect, Δf is frequency deviation, ω_0 is the cut angular velocity, ω_1 is the angular velocity when the speed reaches a constant area, $\Delta\omega_{\text{r}}$ is the angular velocity increment, $\Delta\omega_{\text{e}}$ is the increment of system synchronization angular velocity, $\omega_{\max}$ is the limit of rotor speed, $P_{\max}$ is the limiting amplitude of output active power.

A schematic diagram of the approach is shown in Figure 4, T_2 is a time constant.

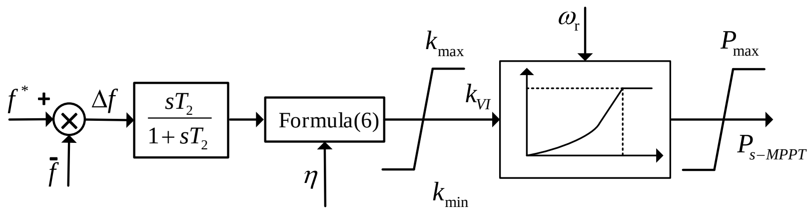

Figure 4. Schematic diagram of the accessional power outer-loop control.

3.2.3. Accessional Pitch Angle Control (APAC)

The frequency deviation of the grid side is introduced to the pitch angle control module in a manner similar to droop control through the integrating element, as shown in Figure 5 [19]: ΔP is the active power increment of the wind turbine when the frequency changes, R is a time constant, P_{m0} is the initial mechanical power of the wind turbine, P_{mref} is the reference value of the mechanical power, β is the pitch angle of the wind turbine. The control of the pitch angle is limited by the mechanical characteristics.

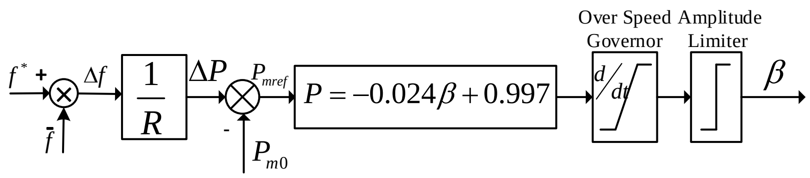

Figure 5. Schematic diagram of the accessional pitch angle control.

3.3. Adaptability Analysis of the Frequency Control Strategy-Based Virtual Inertia

To analyze the control effect of the three virtual inertia control strategies discussed above, a scenario with one wind turbine participating in black start is set: at t = 0 s, the diesel power generator and STATCOM are started; at t = 5 s, the auxiliary engine system of the wind turbine is started; at t = 10 s, the PMSG-based WPG is started; and at t = 20 s, the auxiliary engines system of the thermal power generator is started. The total simulation time is 30 s. Several key parameters are provided: in APOLC, T_{H} = 0.1 and K_{H} = 1.5; in OPTC, η = 1.0; and in APAC, the pitch variation speed is limited to [−5, +5] (°/s). The simulation results are shown in Figure 6.

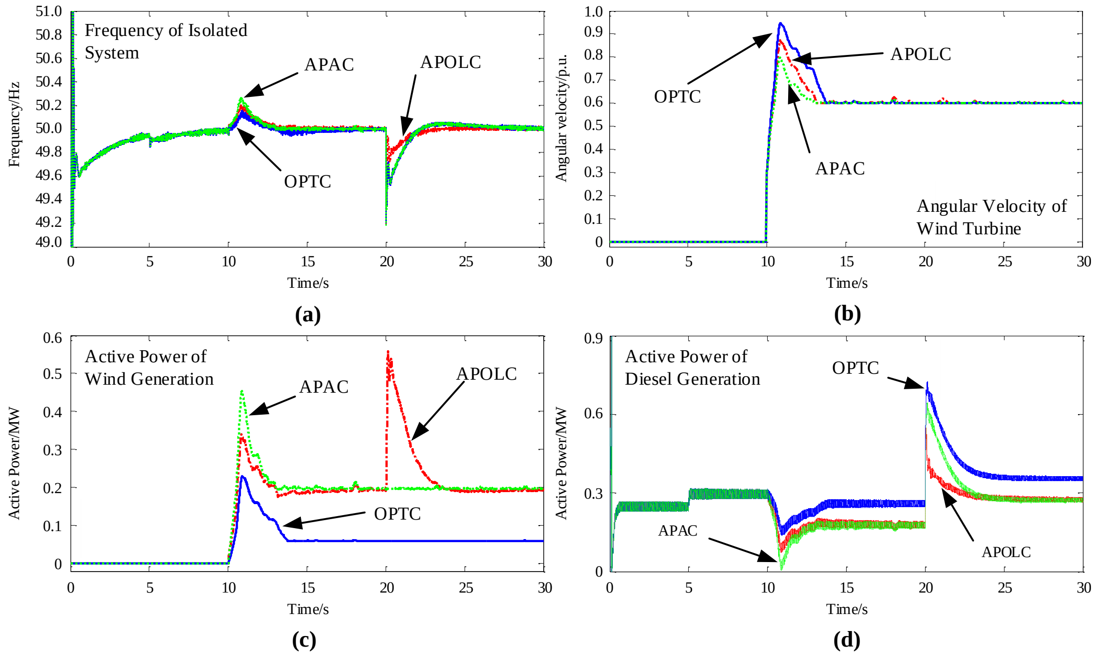

Figure 6. Simulation results of the existing virtual inertia control strategies: (**a**) frequency of the isolated system; (**b**) angular velocity of the wind turbine; (**c**) active power of wind generation; and (**d**) active power of diesel generation.

Based on the frequency variation shown in Figure 6a, the entire dynamic procedure can be separated into two main stages: the startup process of the wind generator and the connecting process of the auxiliary engine system of the thermal power plant. During the former process, the optimal power tracing control strategy has the best effect due to the direct control of the scale coefficient; however, during the latter process, the accessional power outer-loop control strategy provides the best performance. Due to mechanical limitations, the pitch angle cannot be controlled to completely follow the frequency variations.

From Figure 6c,d, adopting the optimal power tracing control strategy will cause the active power output of wind generation to be insufficiently high because the original output was restricted during the startup of the wind turbine.

4. Frequency Control Strategy for Black Start via PMSG-Based WPG

4.1. Deficiencies of Existing Control Strategies

As shown in Figure 6a, the adoption of existing control strategies will cause relatively high frequency fluctuations due to their inherent defects when either wind generation or an auxiliary engine system of large capacity is connected. The frequency fluctuations must be minimized to guarantee that the entire system recovers rapidly and safely. Thus, in this study, the switching method strategy is considered based on the following principles:

(1) Because the direct utilization of accessional pitch angle control has an unsatisfactory effect, considering that 80% of the rated rotor speed is limited by pitch control, the frequency deviation can be introduced to the rotor speed reference element. Thus, we can use an improved pitch angle control (IPAC) strategy as the auxiliary frequency control method.

(2) The conventional control strategies (APOLC and OPTC) should be switched during different stages of the black start procedure to achieve a better performance.

(3) A coordinated control strategy should be proposed considering the frequency response characteristics of both the wind turbine and diesel power generator.

4.2. Coordinated Frequency Control Strategy

Based on the above principles, we propose a new coordinated frequency control strategy for WPG participating in the black start procedure, as shown in Figure 7.

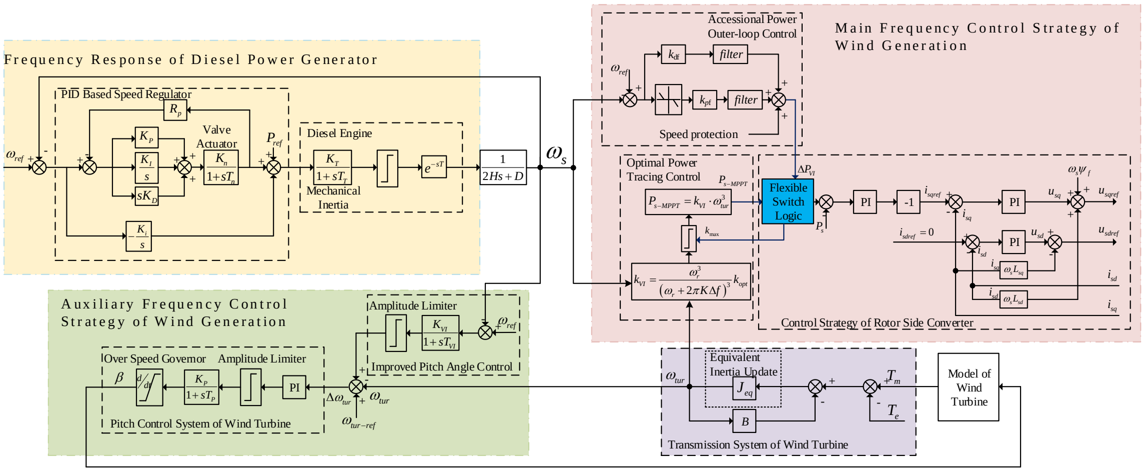

Figure 7. Coordinated frequency control strategy for WPG participating in the black start procedure.

Coordinated frequency control strategy consists of three control modules: (1) frequency response module of diesel generator, the primary frequency modulation function of the diesel generator governor is used to respond to the frequency variation of the system, and the frequency response of diesel power generation is considered as the base frequency regulation method; (2) main frequency control strategy of wind generation, APOLC and OPTC are adopted as the main frequency control strategies due to their superior control effects during different time periods, and flexible switching between APOLC and OPTC is implemented by the module of flexible switch logic; (3) auxiliary frequency control strategy of wind generation, the pitch angle control is used as the auxiliary frequency control because the frequent speed variations of the blades will cause mechanical aging problems.

4.2.1. Improved Pitch Angle Control (IPAC)

To improve the APAC, the frequency deviation of the external power grid is introduced to the pitch control system of the wind turbine through an inertial element and amplitude limiter, as shown in the green part of Figure 7. The effects of the different strategies are compared in Figure 8. In contrast to conventional APAC, the IPAC acts directly on the reference rotor speed, and thus, the angular velocity of rotor is reasonably reduced at the startup moment of the wind turbine, and part of the rotational kinetic energy is restored. The restoring energy is released to increase the rotor speed when the auxiliary power engine system of the thermal power plant is connected.

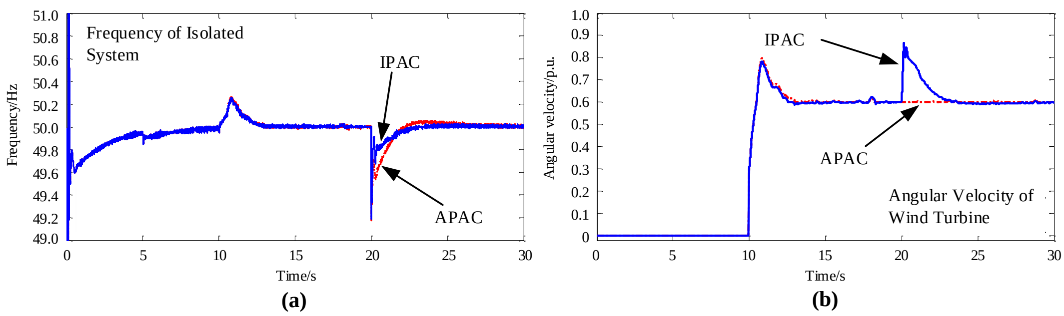

Figure 8. Effect of the improved pitch angular control strategy: (**a**) frequency of the isolated system; (**b**) angular velocity of the wind turbine.

4.2.2. Flexible Switching between APOLC and OPTC

Regarding the main frequency control strategy of wind generation, switching directly between APOLC and OPTC may affect the entire system considerably. Thus, a flexible switch method is proposed in this study, as shown in Figure 9. In OPTC logic, the new scale coefficient (k'_{opt}) of the maximum power point tracking curve is restricted by an amplitude limiter, which is the direct cause of the switching impulse. Therefore, a linear transfer function of k_{max} is applied, which makes k_{max} increase evenly. Moreover, the switching condition is determined for the switching option after connecting the wind generation and when the frequency is relatively stable.

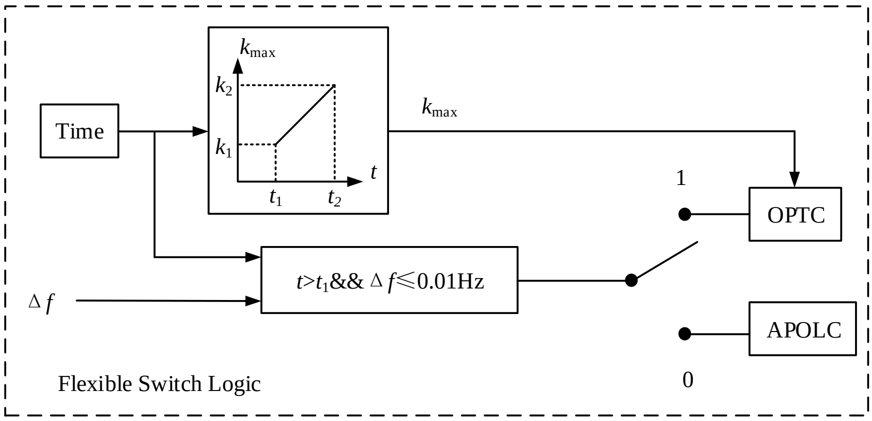

Figure 9. Flexible switch logic of OPTC and APOLC.

Thus, the detailed implementation process of flexible switch logic of OPTC and APOLC is as follows:

During the startup process of the wind turbine, the OPTC has the best effect due to the direct control of the scale coefficient, the switch is locked at 1. When the wind turbine is started, the k_{max} increases evenly to the fixed proportional coefficient (k_{opt}) with a linear transfer, and the wind turbine will operate at the maximum power tracking state without changing its original power tracking curve. Then, the frequency error of the system is detected at the same time, if the wind turbine frequency deviation is extremely small, which means that the wind turbine has reached a stable operating state, the switch position will be converted to 0, and the APOLC strategy is adopted as the main frequency control strategy to guide the wind turbine response appropriately to frequency variation of external system. Since the new scale coefficient (k'_{opt}) of the maximum power point tracking curve has been replaced by a fixed proportional coefficient (k_{opt}) of the original control strategy and the wind turbine is restored to its original state evenly without storage kinetic energy, the impact caused by switching between APOLC and OPTC is reduced greatly.

In this study, t_1 and t_2 are set as 10 s and 15 s, respectively, and k_1 and k_2 are set as 0.1 and 0.9, respectively. The effects of the different strategies are compared in Figure 10. With the direct switch strategy, the frequency fluctuates considerably at the switching point, and an overshoot phenomenon is observed. When adopting the proposed method, the frequency shock at the switching point is eliminated and the frequency curve response becomes less severe.

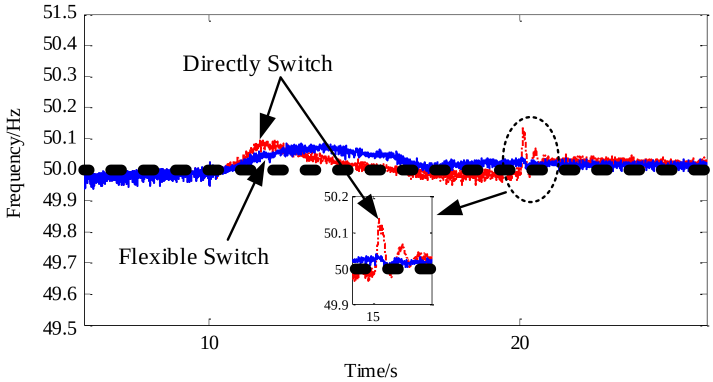

Figure 10. Effect of the flexible switch method.

4.2.3. Coordinated Frequency Control Strategy for Black Start via PMSG-Based WPG

During the whole dynamic procedure of black start via PMSG-based WPG, mobile diesel power generation is adopted as the main frequency reference of the isolated system. OPTC strategy is firstly utilized during the initial stage to introduce frequency deviation to rotor side control of PMSG; once the flexible switching condition is satisfied after the startup of PMSG, APOLC strategy is adopted as the main frequency control strategy to guide the wind turbine response appropriately to frequency variation of external system. When the requirement of pitch control is met, the improved pitch angle control strategy is involved as the auxiliary frequency control strategy.

4.3. Results of the Proposed Strategy

The simulation results of the entire procedure involving the proposed control strategy is shown in Figure 11, along with a comparison with the APOLC and OPTC strategies.

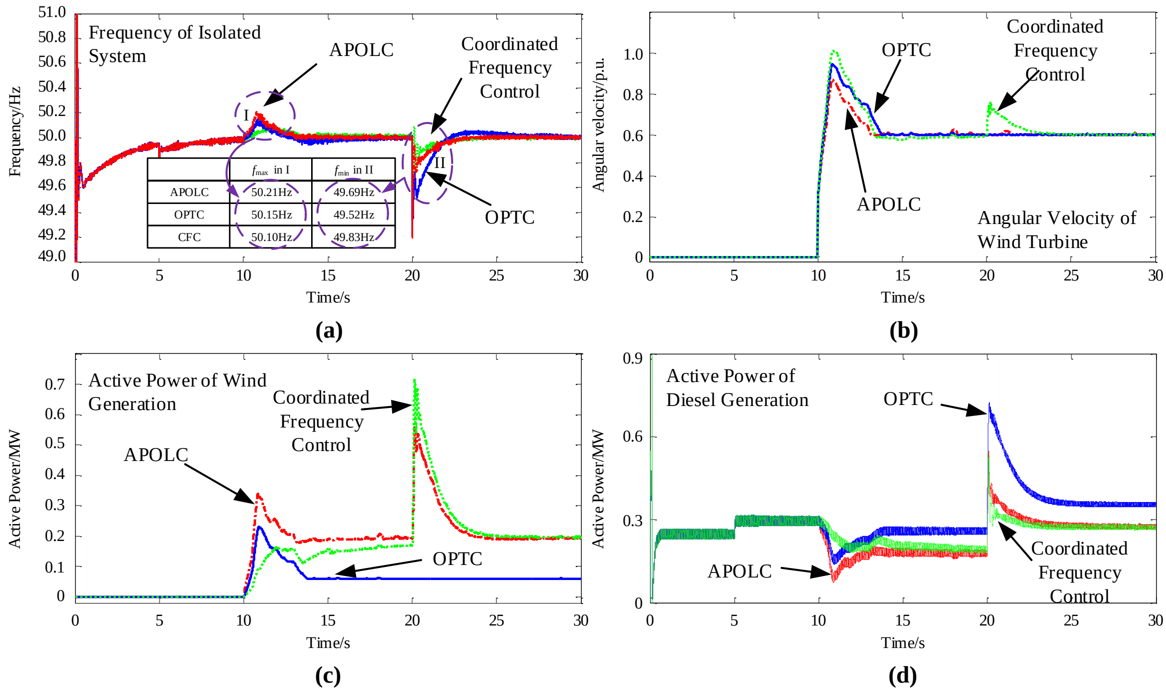

Figure 11. Simulation results of the entire control procedure of the proposed strategy: (**a**) frequency of the isolated system; (**b**) angular velocity of the wind turbine; (**c**) active power of wind generation; and (**d**) active power of diesel generation.

Considering the frequency variations of the isolated system, adopting the proposed control strategy reduces the maximum frequency of the wind turbine startup process to 50.10 Hz while increasing the minimum frequency of the auxiliary power engine system of the thermal power plant connecting process to 49.83 Hz, as shown in Figure 11a. Compared with the conventional virtual inertia-based control strategies, the proposed strategy fully utilizes the frequency response capability of wind generation, thus enhancing the stability of the system in the black start procedure.

As shown in Figure 11b, the proposed strategy utilizes the adjustment space of the remaining rotor speed via variable pitch control and provides inertia and frequency support during the black start procedure (e.g., time = 20–23 s in Figure 11b).

Figure 11c,d illustrate that the proposed strategy reduces the maximum power output of the diesel power generator (i.e., from 0.74 MW to 0.52 MW). Thus, adoption of the proposed strategy can reduce the capacity requirement of the diesel generator.

4.4. Control Effect under a Variable Wind Speed Scenario

To test the proposed control strategy under a practical circumstance, a variable wind speed module is applied in the studied system. The simulation result is shown in Figure 12.

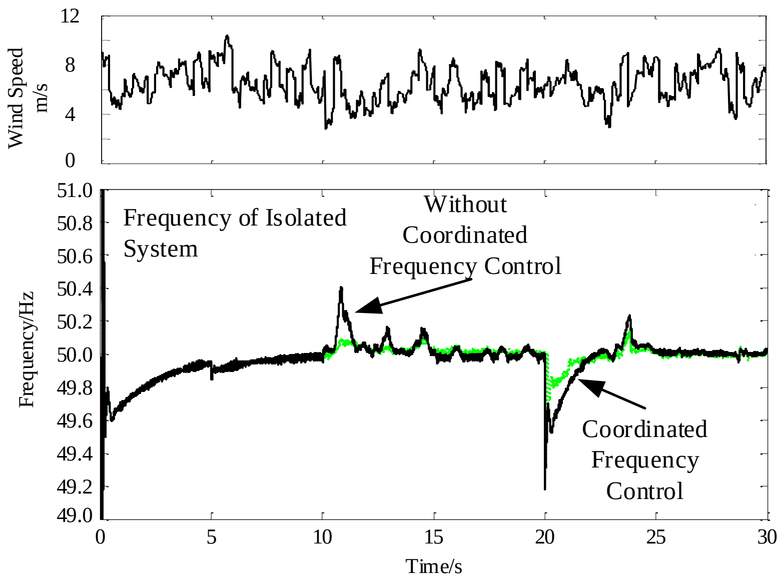

Figure 12. Simulation results under variable wind speed.

Without coordinated control, the diesel power generator cannot address the wind variability, and the frequency curve fluctuates considerably. Adopting the coordinated frequency control strategy makes the frequency gentler even under variable wind speed.

5. Conclusions

The utilization of WPG in the black start procedure will significantly enhance the resiliency of the power system. In this study, we analyzed the procedure of using WPG for black start based on actual demand data from a utility company. Considering the frequency issues occurring during the startup process, we proposed a new virtual inertia-based control strategy, which coordinated and improved upon the conventional methods, to utilize WPG to maintain the frequency of the isolated system. The following conclusions can be drawn:

(1) When a blackout occurs in a power system, wind farms can act as a black start source with mobile diesel power generation or other easily obtained power supplies, the originally equipped reactive power compensation devices and a reasonable coordinated control strategy.

(2) In this study, the proposed frequency control strategy, which adopts APOLC and OPTC as the main control pattern with improved pitch angular control as an auxiliary pattern, can effectively enhance the frequency stability of the system.

At present, this paper only analyzes and discusses the single equivalent wind turbine as the black start power supply, the start-up path and the coordination control technology of considering the black start of multiple wind turbines are the next research work we need to carry out. Besides, the proposed black start procedure and control method will be adopted in a field test in the near future.

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