Research on optimization strategy of grid frequency modulation based on doubly-fed wind turbines

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Abstract
The increasing global energy and environmental problems are encouraging to the development and utilization of renewable and clean energy in various countries. Wind power is one of the major sources in large-scale renewable energy applications. However, the frequency regulation becomes a critical issue while the technology is spreading. Research on the frequency modulation (FM) technology of wind turbines and its control strategy for future power grids become significant. The paper proposes a novel coordinated frequency control strategy with the synchronous generator to solve the unmatched state between the output power of the doubly-fed wind turbines (doubly-fed induction generators) and the grid frequency, combined with the frequency response characteristics of the synchronous generator. The FM coordination strategy is formulated by the modulation coefficient from current wind speed and operation mode of each wind turbine. By coordinating the FM output of the doubly-fed wind turbine and the synchronous generator within the allowable range of frequency deviation, it will achieve the dual goal of reducing the frequency regulation pressure of the synchronous generator and indirectly reducing the abandoned wind volume of the wind turbine. The simulation is carried out on the MATLAB/SIMULINK platform. The results show that the presenting variable coefficient frequency modulation strategy could significantly smooth the wind power fluctuation, and allow the reserve power of the doubly-fed wind turbine can fully engaged in frequency modulation which will reduce the frequency modulation pressure of the synchronous generator in the system.

Keywords: renewable energy; frequency modulation strategy; doubly-fed wind turbine; variable coefficient

1. INTRODUCTION
As a kind of clean energy, wind power occupies an important position in the proportion of energy, and all countries are increasing research on large-scale wind power. The world wide wind power industry is developing relatively fast. By 2050, the world is 100% supplied by renewable energy, of which wind power accounts for 40%. This shows the dominance of wind power in the future renewable energy market. However, the randomness and volatility of wind power become an issue with the growing wind power ratio in the network. The frequency modulation (FM) of the system becomes a problematic point to control. It is because current grid connection requires the wind turbine to have particular power grid FM capability. The operation mode of the common doubly-fed wind turbine rotor speed and the grid frequency is wholly decoupled, so that it does not have the FM capability, thus reducing the inertial response and FM capability of the grid, which also brings insufficient utilization of the grid-connected wind power and abandonment in many countries.

There are great quantity of contribution from researchers on the FM of wind turbines participating in the grid system, especially in the frequency control strategy, such as rotor inertia control, droop control and load-shedding control in the primary control aspect. The literature [1–4] introduced the load-shedding control and reserved a part of the active power as the FM standby of the system to provide frequency support for the system.
However, the load shedding control method reduces the utilization of wind energy and reduces the economy when the scale of the wind farm increases. In [5–8], the proportional frequency differential controller is used to design the primary FM controller of the rotor side converter, so that the doubly-fed wind turbine can respond quickly to the system frequency change. Further, based on the speed control, the literature [9–13] combines the pitch technology with the virtual inertial control to propose a frequency integrated control scheme for the variable speed wind turbine. In the research of combined control, the literature [14–15] for the double-fed and direct-drive wind turbines, where the control effects of inertia, over-speed and pitch are combined according to the wind speed interval to provide a more reliable FM spare capacity. The above literature covers the study of the FM in the wind power system from the perspective of wind turbine internal control or wind farm. However, from the literature [16–18], when the adjustable frequency wind power is incorporated into the grid as a new FM power supply, it has to take the doubly-fed wind turbine operation into account as well as neutral and system FM requirements. Therefore, the proper way to coordinate the FM output between the doubly-fed wind turbine and the synchronous generator according to the adjustable frequency capacity of the doubly-fed wind turbine under different wind speeds will be the direction for further improvement on the wind power FM technology.

Based on the principle of synchronous generator primary FM, this paper shows that the adjustable frequency wind turbine can effectively share the FM responsibility of the grid from the perspective of the modulation coefficient. It is also be able to simulate the primary FM principle of the traditional synchronous generator, and the maximum power tracking in the operation of the doubly-fed wind turbine. We are designing the primary FM controller on the rotor side converter, and we introduce pitch angle modulation coefficient in the constant power region. Therefore, the doubly-fed wind turbine can also realize the load-shedding standby in the constant power region and response to the system frequency change. The variable modulation coefficient of doubly-fed wind turbines under constant wind speed is set, and an FM strategy is proposed for the coordination of the doubly-fed wind turbines and the synchronous generators based on the variable coefficients. Within the allowable range, the doubly-fed wind turbines fully utilize the spare capacity to participate in the system FM and achieve reduction of the FM pressure of the synchronous generator and indirectly reduce the amount of abandoned air. Finally, the simulation fully approves the effectiveness of the proposing strategy.

2. DOUBLY-FED WIND TURBINE
COORDINATED FREQUENCY CONTROL

2.1. Doubly-fed wind turbine power control principle
Figure 1 illustrates the power control system for the doubly-fed wind turbine. The rotor-side converter and the grid-side con-
verter dynamically control the power flow of the unit and decouple the rotor speed from the grid frequency to achieve variable speed operation. The rotor-side converter realizes independent control of the stator active power \( P_s \) and reactive power \( Q_s \) by controlling the injected rotor currents \( i_{sd} \) and \( i_{dq} \), which is active and reactive power decoupling control. Through the doubly-fed induction generator electromagnetic torque control \( T_{em} = P_{ref} / \omega \) (\( \omega \) is the rotor speed, \( P_{ref} \) is the active power reference value), the rotor always operates according to the optimal speed \( \omega_{ref} \) in respect to the maximum power tracking characteristic curve. The grid frequency is supported by adding the auxiliary grid frequency support control module. Its aim is to correct the active power reference value \( P_{ref1} \) from the maximum power-tracking controller. The frequency support module input quantity is the grid frequency \( f_{grid} \), the grid and \( d \)-axis voltage \( v_{sd} \). The input quantity for maximum power tracking control is wind speed \( V_w \), wind turbine active power \( P_{grid} \) and rotor speed \( \omega \). The grid-side converter provides positive or negative active power alternatively between the rotor-side converter and the grid by adjusting the DC link voltage. In Figure 1, the generator operates in a super-synchronous state, where the rotor active power \( P_r \) and the reactive power \( Q_r \) flow from the rotor side to the grid through the converter, while the rotor absorbs the wind turbine mechanical power and outputs the stator active power \( P_s \) through the stator to the grid. The working power \( Q_s \), the wind turbine output active power \( P_{grid} \), is the sum of the stator active power \( P_s \) and the active power \( P_{dc} \) delivered by the DC link to the grid.

2.2. FM characteristics of doubly-fed wind turbines
and synchronous generators running in parallel
Based on the principle of coordinating the modulation frequency for the doubly-fed wind turbine and the synchronous generator, the modulation coefficient \( R_w \) of the doubly-fed wind turbine is defined as follows:

\[
R_w = \frac{\Delta f}{\Delta P_w}
\]

where:

\( \Delta P_w \) = the frequency response of the doubly-fed wind turbine,

\( \Delta f \) = the system frequency change.

When the synchronous generator is operated in parallel with a doubly-fed wind turbine, the relationship between the FM characteristics and the active power distribution between the units can be illustrated in Figure 2. In Figure 2, the straight line ABD represents the regulation characteristic curve of the synchronous generator, and the straight line ACE represents the double of the regulation characteristic curve of the feed wind turbine. Assume that the total load of the system is \( P_{tot} \), that is line segment CB. When the system frequency is at the rated frequency \( f_N \), the load of the synchronous generator is \( P_{G1} \), and the load of the wind turbine is \( P_{w1} \), so the total load of the system will be

\[
P_{G1} - P_{w1} = P_{tot}.
\]
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When the system load increases by $\Delta P_L$, the system frequency will be stable at $f_1$, the synchronous generator could get additional power $\Delta P_G$ and the total power is $P_{G2}$; according to Figure 2 and formula (1) we could obtain the relationship for the wind turbine's additional power $\Delta P_w$, and the total power $P_{w2}$:

$$\frac{\Delta P_G^w}{\Delta P_w} = \frac{R_w^*}{R_G^*},$$

In equation (3) $\Delta P_G^w$ and $\Delta P_w^*$ are the standard output values from synchronous generators and doubly-fed wind turbines respectively; $R_G^*$ and $R_w^*$ are the standard values of the differential coefficients of synchronous generators and doubly-fed wind turbines. In case of parallel connection, the power distribution between the synchronous generator and the doubly-fed wind turbine will be inversely proportional to the individual modulation coefficients, which means the unit with a small coefficient has a large load increment, and the unit with a large coefficient of modulation has a small load increment. Therefore, equation (3) tells the following: (1) When the synchronous generator and the doubly-fed wind turbine are operated in parallel, the doubly-fed wind turbine will participate in the FM to effectively reduce the frequency regulation pressure of the synchronous generator; (2) Adjusting the ratio of $R_G^*$ and $R_w^*$ could coordinate the distribution of the output from the synchronous generator and the doubly-fed wind turbine.

### 2.3. Coordinated control of doubly-fed wind turbines after integration into the grid
The standard value of the modulation coefficient in the primary FM theory of synchronous generators is defined as follows:

$$R^* = -\frac{\Delta f^*}{\Delta P^*} = -\frac{\Delta f}{\Delta P N}.$$

In equation (4), $\Delta f^*$ is the standard value of the system frequency change; $\Delta P^*$ is the standard value of the generator's frequency output; $P_N$ is the rated capacity of the generator; $\Delta P$ is the frequency output of the generator, which can be exported from equation (4):

$$\Delta P = -\frac{1}{R^*} \frac{\Delta f}{f_N} P_N.$$

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When there is a doubly-fed wind turbine in the system running in parallel with the \( n \) synchronous generators, the following modulation equation can be obtained according to equation (5):

\[
\Delta P_{Gi} = -\frac{1}{R_i^*} \frac{\Delta f}{f_N} P_{GiN}, \quad i = 1, 2, \cdots, n.
\] (6)

\[
\Delta P_w = -\frac{1}{R_w^*} \frac{\Delta f}{f_N} P_{WN}.
\] (7)

In equations (6) and (7), \( \Delta P_{Gi} \) and \( R_i^* \) are the standard values of the frequency-modulated output and the modulation coefficient of the \( i \)th synchronous generator; \( P_{GiN} \) and \( P_{WN} \) are the rated capacities of the \( i \)th synchronous generator and the doubly-fed wind turbine, respectively. If the frequency changes, then it should not be in the steady state; the \( \Delta P_{\Sigma} \) output of all units in the studied wind power system is the following:

\[
\Delta P_{\Sigma} = \sum_{i=1}^{n} \Delta P_{Gi} + \Delta P_w.
\] (8)

By simultaneous analysis of formula (6), formula (7) and formula (8), it can obtain the following:

\[
\Delta P_{\Sigma} = -\frac{\Delta f}{f_N} \left( \sum_{i=1}^{n} \frac{P_{GiN}}{R_i^*} + \frac{P_{WN}}{R_w^*} \right).
\] (9)

With all of the generators in the system replace by an equivalent unit, the whole system’s FM output will be as follows:

\[
\Delta P_{\Sigma} = -\frac{1}{R_{\Sigma}^*} \frac{\Delta f}{f_N} P_{\Sigma N}.
\] (10)

In equation (10), \( R_{\Sigma}^* \) is the coefficient of system equivalent modulation; \( P_{\Sigma N} \) is the total system capacity. Combining equations (6) and (7) and equation (6) we could get the following:

\[
-\Delta f^* = \frac{R_i^* \Delta P_{Gi}}{P_{GiN}} = \frac{R_w^* \Delta P_w}{P_{WN}} = \frac{R_{\Sigma}^* \Delta P_{\Sigma}}{P_{\Sigma N}}.
\] (11)

Combining equations (9) and (10), we will get the following:

\[
R_{\Sigma}^* = \frac{P_{\Sigma N}}{\sum_{i=1}^{n} \frac{P_{GiN}}{R_i^*} + \frac{P_{WN}}{R_w^*}}.
\] (12)

It can be seen that in the power system from equation (9) and equation (12), when the capacity in the access system is constant, the equivalent modulation coefficient \( R_{\Sigma}^* \) of the system is proportional to the coefficient of variation of each unit operating in parallel; the smaller equivalent modulation coefficient makes more power can be adjusted, and lead to a stronger the frequency modulation capability. The larger the coefficient of modulation of each unit operating in parallel in the system, the larger the system \( R_{\Sigma}^* \) could be get, and gives a small unit modulation power, and a weaker the primary frequency modulation capability. According to equation (11), when there is a load changing in the system, the power assumed by each generator can be determined as follows:

\[
\Delta P_i = \frac{R_i^* \Delta P_{\Sigma} P_{GiN}}{P_{\Sigma N}}.
\] (13)

When the wind turbine with no FM capability is connected to the grid, \( \frac{P_{WN}}{R_w^*} \approx 0 \), which means \( R_w^* \) is infinite, and the remaining synchronous generators are differentially adjusted. When more FM-free wind turbines replace traditional synchronous generators in the grid, the denominator of equation (12) \( \frac{P_{WN}}{R_w^*} = 0 \), and the system \( R_{\Sigma}^* \), will be larger with connected large-scale FM-free wind turbines. Entering the grid with such condition will significantly reduce the ability of the system to adjust the frequency.

3. DOUBLY-FED WIND TURBINES PARTICIPATE IN COORDINATED FM STRATEGY

The primary FM control structure of the doubly-fed wind turbine associated with the synchronous generator is shown in Figure 3, which involve three control modules.

In Figure 3, \( \beta \) is the pitch angle inertia time constant, \( \beta \) is the pitch angle of the final output of the wind turbine and \( \beta_{\text{ref}} \) and \( P_{\text{ref}} \) are the pitch angle and power reference, respectively. In area A: control module in the constant power zone adjusts the active output of the doubly-fed wind turbine by the pitch angle action system in response to system frequency changes. Area B: The maximum power tracking control module realizes the power reserve by switching the running curve of the doubly-fed wind turbine and adjusts the active participation FM of the doubly-fed wind turbine according to the set variable modulation coefficient. Area C: The coordinated control module of the synchronous generator changes the modulation coefficient of the synchronous generator according to the magnitude of the system frequency deviation and coordinates the frequency-modulated output of the synchronous generator and the doubly-fed wind turbine. For this aspect, the proposed coordinated FM strategy can reasonably coordinate the FM output of the doubly-fed wind turbine and the synchronous generator according to the frequency deviation and the current wind speed.

3.1. Doubly-fed wind turbines participate in the control strategy of primary FM

Although the doubly-fed wind turbine can participate in the FM of the system like a conventional synchronous generator theoreti-
ically, the precondition is that the doubly-fed wind turbine must be reloaded to have an active reserve because the power output of a doubly-fed wind turbine is related to wind speed, as well as the active reserve. In this paper, the doubly-fed wind turbine will control the load-shedding operation through the rotor speed by improving the traditional doubly-fed wind turbine operation mode in the maximum power tracking area; while in the constant power zone, the load reduction operation will be controlled by the pitch angle, and the active power will be reserved.

(1) Control strategy of the maximum power tracking area.

In the maximum power tracking area, the traditional operation mode of the doubly-fed wind turbine is to implement maximum power tracking control in this area to ensure that the wind turbine can obtain the maximum wind energy utilization coefficient.
In equation (14), $\Delta f_0$ is the critical value of frequency change, taking $\Delta f_0 = 0.2$ Hz; $P_0$ is the power reserve of the doubly-fed wind turbine during load-shedding operation. It takes 20% of the maximum power at the current wind speed, and so when the wind speed is larger, the reserve power $P_0$ gets larger.

$R_{\omega}$ is a variable value and can be dynamically changed in real-time depending on the current wind speed. According to the principle of primary FM of synchronous generators, the FM power of wind turbines in response to system frequency changes can be expressed as equation (15):

$$
\Delta P_{\omega} = - \frac{\Delta f}{R_{\omega}} = \frac{\Delta f}{\Delta f_0} P_0.
$$

The variable modulation coefficient is adjusted in the maximum power tracking area, so that the doubly-fed wind turbine can participate in FM like the traditional synchronous generator. Additionally, the modulation coefficient can be automatically adjusted with wind speed, thereby determining the FM power of the doubly-fed.

(2) Control strategy of constant power zone.

When the wind speed is higher than the rated wind speed, the pitch angle control system can control the active power generated by the doubly-fed wind turbine and control the active output of the doubly-fed wind turbine by reducing the pitch angle to achieve a designed system with load shedding of 20%. Compared with the traditional synchronous generator governor, the intake valve is adjusted according to the system frequency variation. In the constant power region, the doubly-fed wind turbine can control the mechanical power by adjusting the pitch angle to improve the power frequency static characteristics of the doubly-fed wind turbine. The pitch angle modulation coefficient is introduced here to improve the traditional pitch angle control system, so that the doubly-fed wind turbine can also realize the load-shedding standby in the constant power zone in response to the system frequency change. In the power constant zone, the doubly-fed wind turbine load-shedding operation can be realized by the pitch angle control system to reserve the pitch angle $\beta_0$. The size of $\beta_0$ can be obtained according to the following equation (16):

$$
0.44 \left(1 - d \right) \sin \frac{\pi \left(\lambda_c - 3\right)}{15} = \left(0.44 - 0.0167 \beta_0 \right) \sin \frac{\pi \left(\lambda_c - 3\right)}{15 - 0.3 \beta_0} - 0.00184 \left(\lambda_c - 3\right) \beta_0.
$$

In equation (16), $\lambda_c$ is the tip speed ratio of the doubly-fed wind turbine; $d$ is the percentage of load shedding. In Figure 3 zone $A$, $\Delta \omega$ is the difference between the maximum rotational speed of the rotor and the actual rotational speed. The improved pitch angle control system enables the doubly-fed wind turbine to respond to changes in system frequency by adjusting the pitch angle in the constant power zone with variable wind speed. Introducing a variable modulation coefficient of the pitch angle-frequency characteristic in the power constant zone will allow the doubly-fed wind turbine to change the mechanical power captured by the doubly-fed wind turbine in respect to the pitch angle changing to respond to the system frequency change, thereby making the doubly-fed turbine participate in the FM process.

### 3.2. FM coordination strategy

The generators with FM capability in the whole system coordinate and share the frequency of modulation. When the adjustable-frequency doubly-fed wind turbine is connected to the system, the conventional generator set needs to be aware of the existence of the wind turbine. When the system frequency changes, a part of the FM power should be allocated to the wind turbine according to the current wind speed and frequency deviation. Therefore, it is necessary to divide the FM region of the system according to the magnitude of the system frequency deviation.

According to the modulation of the relevant power system, the frequency control of the power system is within the range of
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(50 ± 0.2)Hz. In the research, it takes the frequency deviation index $\Delta f_0 = 0.2$Hz as critical value of the frequency division region. When the frequency deviation is <0.2Hz, the system is in the frequency normal regulation area; When the frequency deviation is >0.2Hz, the system is in the emergency control area. According to the C area in Figure 3, the analysis is as follows:

1. The system is in the normal control area, and the frequency deviation is within the allowable range 0.2Hz. The doubly-fed wind turbine participates in the FM load-shedding operation, which generates a certain amount of wind, thus reducing the costs of wind power. In order to reduce the abandonment of the doubly-fed wind turbine during the operation, the synchronous generator can give more responsibility for the FM to the wind turbine. Usually, the synchronous generator has a modulation coefficient between 0.03 and 0.05. Setting the synchronous generator’s modulation coefficient $R_G$ to 0.05, it can reduce the synchronous
generator's frequency-modulated output, where the power from
the doubly-fed wind turbine reserve can be used for FM, and
make full use of the reserve power of the doubly-fed wind turbine
during the load-shedding process. In the constant power zone, the
power of the doubly-fed wind turbine is large, so that adjustable
frequency output is large.

When the system is in the emergency control area, the
frequency deviation is large. In order to stabilize the system and
recover the acceleration frequency, the synchronous generator
and the doubly-fed wind turbine should participate in the system
FM as much as possible. Then, the modulation coefficient of the
synchronous generator can be set to 0.03, and the modulation
coefficient of the synchronous generator is reduced, the output of
the synchronous generator will increase and the doubly-fed wind
turbine can participate in the system FM according to the current
wind speed.

Based on the above analysis of the principle of coordinating the
primary FM of the doubly-fed wind turbine and the synchronous
generator, the detailed process of the coordination strategy of the
primary FM of the doubly-fed wind turbine and the synchronous
generator is summarized as follows:

Step 1: Measure the frequency of the system and calculate the
frequency deviation.

Step 2: If the system frequency deviation is > 0.2Hz, set the syn-
chronous generator's modulation coefficient to 0.03; if the system
frequency deviation is < 0.2Hz, set the synchronous generator's
modulation coefficient to 0.05.

Step 3: Measure the rotor speed \( \omega_r \) of the doubly-fed wind
turbine at the current wind speed.

Step 4: If \( \omega_r > \omega_{\text{max}} \), adjust the constant zone pitch angle
modulation coefficient \( R_\beta \) and send \( R_\beta \) to the pitch angle action
system.

Step 5: If \( \omega_r \leq \omega_{\text{max}} \), calculate the modulation coefficient \( R_\omega \) of
the doubly-fed wind turbine of the maximum power tracking area
according to equation (14) and send \( R_\omega \) to the frequency response
control link.

Step 6: According to step 2, the primary frequency power \( \Delta P_G \)
of the synchronous generator can be obtained, and according to
step 4 or 5, the primary frequency power \( \Delta P_w \) of the doubly-fed
wind turbine can be obtained to further obtain the total power
\( \Delta P_{\Sigma} = \Delta P_G + \Delta P_w \) of the system once FM.

4. SIMULATION ANALYSIS OF
FM STRATEGY

According to the control strategy designed in Figure 4, it car-
rries out a simulation to prove the effectiveness in the MAT-
LAB/Simulink platform. The simulation model is built to establish
a four-machine two-area power grid model. As shown in Figure 5,
it consists of four traditional synchronous generators with a rated
power of 700 MW, where the inertia time constant is 6.5 s. Con-
necting a 800 × 1.5 MW doubly-fed wind turbine to the bus-bar
2, the upper limit of the output of the power standard is 1 and
the sizes of the loads \( L_1 \) and \( L_2 \) are 2200 MW and 1800 MW,
respectively. In the simulation study, the pitch constant of the
doubly-fed wind turbine is set to 3 s, the rated wind speed at
12 m/s, the unit performs 20% load reduction operation and there
is a load step when the load \( L_1 \) is set for 40s.

4.1. Simulation analysis of load change in maximum
power tracking area

(1) The maximum power tracking area frequency change is
< 0.2 Hz.
Set the wind speed at 9 m/s, the load suddenly increases by 300 MW at the 40s, the frequency change is <0.2 Hz and the synchronous generator’s modulation coefficient $R_G$ is 0.03, 0.04 and 0.05, respectively. The simulation results are shown in Figure 6.

In Figure 6, when the synchronous generator’s modulation coefficient increases, the synchronous generator’s frequency-modulated output will gradually decrease, and the frequency-adjusted output of the doubly-fed wind turbine will gradually increase. From the perspective of the system’s frequency recovery, the best result is by taking $R_G = 0.03$. However, according to Figure 6c, when the modulation coefficient of the synchronous generator is small, the frequency output of the doubly-fed wind turbine will be limited, and the frequency variation at this time is within the allowable range. When the $R_G = 0.05$ is taken, the frequency has recovered to within 0.2 Hz, and the system frequency can be relatively stable. At this time, in order to maximize the frequency-adjusting output of the doubly-fed wind turbine, the reserve power of the doubly-fed wind turbine is fully used for FM, and the modulation coefficient of the synchronous generator is taken as $R_G = 0.05$.

(2) The maximum power tracking area frequency change is >0.2 Hz.

Set the wind speed to 9 m/s, the load suddenly increases by 600 MW at 40s, the frequency change is >0.2 Hz and the synchronous generator’s modulation coefficient $R_G$ is 0.03, 0.04 and 0.05, respectively. Those simulation results are shown in Figure 7.

In Figure 7, it can be seen from (a) that the frequency recovery of the system is best when $R_G = 0.03$ is used. When the frequency changes by >0.2 Hz, the system is in the emergency FM stage, and the system frequency recovery effect is better as the ultimate goal. The wind turbine motor synchronous machine should output as much power as possible. From the simulation results in Figure 6, the coordination coefficient of the synchronous generator set should be taken as $R_G = 0.03$.

4.2. Simulation analysis of system load change in power constant zone
(1) Frequency variation is <0.2 Hz in constant power zone.

In the constant power zone, the pitch angle of the doubly-fed wind turbine is adjusted mainly by the pitch mechanism of the doubly-fed wind turbine to adjust the wind energy captured by the doubly-fed wind turbine. Set the wind speed to 15 m/s, the load suddenly increases by 300 MW at 40s, the frequency change is <0.2 Hz and the synchronous generator’s modulation coefficient $R_G$ is 0.03, 0.04 0.05, respectively. The simulation results are shown in Figure 8.

As the load increases, it can be seen from Figure 8 that when the system frequency is reduced within 0.2 Hz. The frequency variation of the synchronous generator’s modulation coefficient $R_G$ is 0.03, 0.04 and 0.05, and the frequency can be very well restored. It can be seen from Figure 8d that when the $R_G$ value is 0.05, the action amplitude of the pitch angle reaches 2.8 degrees at the maximum, and the reserve power of the released doubly-fed wind turbine reaches 0.07, which reduces the steady-state frequency deviation of the system by 0.15 Hz. Not only the power change rate of the synchronous generator is effectively reduced in the initial stage of the frequency change, but also the active support
for the power grid is continuously provided during the frequency change process. In the FM process, increasing the FM output of the doubly-fed wind turbine can fully use the reserve power of the doubly-fed wind turbine for FM, which indirectly reduces the wind. Comprehensive analysis of the simulation results of Figure 8 shows that when the frequency variation is within the allowable range, the larger the value of \( R_G \) will lead the smaller the value of the pitch angle static modulation coefficient \( R_\beta \), and the pitch angle action amplitude will become larger. The FM capability of the wind turbine is also enhanced, which enables it to take on more FM output and reduce the steady-state frequency deviation of the power grid.

(2) Frequency change is \( >0.2 \) Hz in constant power zone.

Set the wind speed at \( 15m/s \), the load suddenly increases 600 MW at 40s, the frequency change is \( >0.2 \) Hz and the synchronous generator’s modulation coefficient \( R_\beta \) is 0.03, 0.04 and 0.05, respectively. The simulation results are shown in Figure 9.

It can be seen from Figure 9 that when \( R_\beta \) is taken as 0.03, the frequency recovery effect is the best, and it is restored to within 0.2 Hz. At this time, the frequency deviation is \( >0.2 \) Hz, the frequency changes greatly and the system is in the emergency regulation phase so that the system frequency recovery effect is better. At this time, the constant power zone is high, and the wind speed is higher, and the doubly-fed wind power unit has more standby power. The doubly-fed wind turbine can fully use the reserve power for FM. From the frequency recovery effect of the amount (a) in Figure 9, the \( R_\beta \) is taken as 0.03, and the doubly-fed wind turbine and the synchronous generator can participate in the FM as much as possible, and in Figure 9c, the doubly-fed wind turbine is full and the 20% active power in reserve is put into the FM process; the lowest frequency drop and steady-state deviation have been significantly improved.

5. CONCLUSION

This paper first analyses the power control principle and frequency characteristics of the doubly-fed wind turbine generator. Based on that, the coordinated control with the synchronous generator is proposed. According to the current wind speed and operation mode of each wind turbine in the wind power generation system, the modulation coefficient is continuously optimized. The difference coefficient is formulated to participate in the grid frequency control strategy of the wind turbine so that the doubly-fed wind turbine can provide inertial power support to the grid, and participate in FM with the synchronous generator. In the process of research and analysis, the variable modulation coefficient of the doubly-fed wind turbine in different wind speed segments is defined and tuned. When the current wind speed changes dynamically in real-time, the intensity of the FM output can be determined according to the current spare capacity. By coordinating the FM output between the doubly-fed wind turbine and the synchronous generator, the frequency deviation is within the allowable range. Additionally, the reserve power of the doubly-fed wind turbine is used for FM as much as possible, which not only meets the requirements of the power grid FM but also reduces the wind generated by the doubly-fed wind turbine due to load shedding. Finally, the simulation experiment of coordinating primary FM between the wind turbine and the synchronous generator is designed. The results show that the proposed control strategy can control the frequency output deviation of the doubly-fed wind turbine and synchronous generator to ensure the frequency deviation within the allowable range. The doubly-fed wind turbine is used for FM, which reduces the frequency regulation of the synchronous generator and reduces the wind generated by the wind turbine due to load shedding.

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