Frequency regulation characteristics optimization and analysis of DFIG-VSG based on rotor inertia control

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***Abstract*—DFIG-VSG (doubly-fed induction generator-virtual synchronous generator) based on rotor inertia control has gained popularity in engineering application. This approach can guarantee the economical operation of wind turbine and provide effective frequency support to the grid meanwhile. The adaptation of frequency regulation by DFIG-VSG is analyzed and speed restoration methods which are suitable for engineering application are studied. First, influencing factors on support time of DFIG-VSG utilizing rotor inertia control is analyzed. Thus general range of support time of wind turbines are given. Second, constant-value and comprehensive speed restoration methods are proposed, followed by comparing them with conventional MPPT curve restoration. Comprehensive speed restoration can inhibit second frequency drop significantly. Frequency regulation characteristics of DFIG-VSG is simulated in Simulink where wind turbines are connected with synchronous generator. Comprehensive restoration method is then testified.**

***Index Terms*—DFIG-VSG, rotor inertia control, frequency regulation**

I. INTRODUCTION

In recent years, installed capacity of wind power in China rises tremendously and the penetration ratio of renewable energy in several provincial grid has exceeded 40%. However, the equivalent inertia and frequency regulation ability of power system decreases as the penetration ratio of wind power rises. DFIG-VSG has been one novel solution to this problem.

DFIG-VSG can cause severe second frequency drop during speed restoration, leading to even worse frequency stability of the grid. Some papers have proposed methods to mitigate second frequency drop. Inertia control methods based on switching of power tracking curves are proposed in [1-4]. By rectifying tracking coefficient and switching tracking curves, deep drop of DFIG-VSG output power is weakened to avoid second frequency drop. Some reserve capacity is ensured by pitch control or overspeed in [5-6]. When grid frequency drops, reserve capacity is released to provide continuous support. These approaches could solve the problem of second frequency drop at the cost of considerable energy production loss. Some works deploy energy storage equipment for each wind turbine or at the PCC of wind farm to provide extra power support for the grid [7-9]. Obviously, these approaches would increase total cost of the system substantially. Modified rotor inertia control could keep the rotor speed at low value for a while, postponing the time of second drop until grid frequency recovers [10]. Delayed speed restoration method calculates active power reference in real time to improve frequency regulation effect. But it requires current wind speed as input for the algorithm [11]. Extended state observer is used to estimate input mechanical power of wind turbine, with which specialized power reference curve is designed to improve second frequency drop [12]. The approach requires complicated mathematical calculation and the code for curve design is not given. Reference [13-14] considers cooperative control of wind turbines in a wind farm.

In this paper, a review on rotor inertia control is introduced first. Wind turbine support ability is studied focusing on influencing factors of inertia support time. Based on that, speed restoration methods are researched. Constant-value and comprehensive speed restoration methods are proposed and compared with conventional MPPT curve restoration. Then

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proposed restoration methods are testified by simulation. The results show that comprehensive restoration method could improve second frequency drop significantly.

II. ROTOR INERTIA CONTROL OF DFIG-VSG

Control diagram of rotor inertia control is showed in Fig. 1. The wind turbine releases part of its rotation energy to enhance output active power when grid frequency drops. Active power reference P_{ref} is composed of two parts, namely P_{mppt} and ΔP P_{mppt} is a function of current rotor speed ω and is calculated from MPPT tracking curve. ΔP is calculated from equation (1) which shows how active power reference is related to the grid frequency.

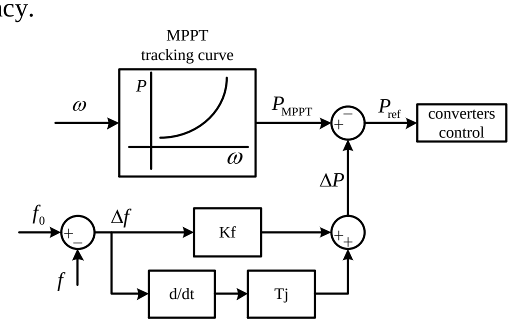


Fig. 1. Control diagram of wind turbine rotor inertia control.

$$\Delta P = K_{\mathrm{f}}(f_0 - f) + T_{\mathrm{j}}\frac{\Delta f}{\Delta t} \quad (1)$$

Fig. 2 shows typical waveforms of wind turbine with rotor inertia control. During support stage, more active power is injected into the grid at the cost of speed decline. When lower limit of speed is reached, output power of wind turbine drops sharply in a sudden, which would result in second frequency drop.

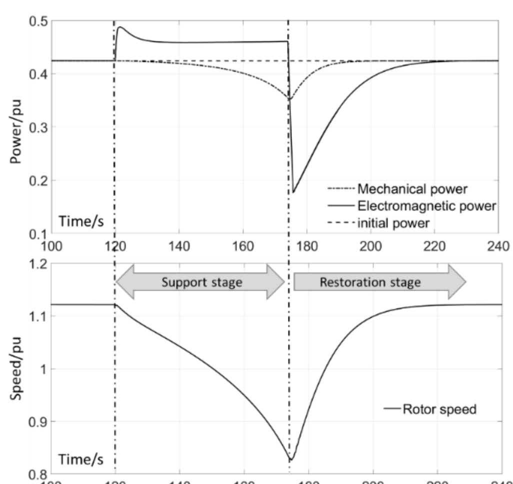


Fig. 2. Power and speed waveforms in frequency regulation with rotor inertia control.

III. ANALYSIS ON INFLUENCING FACTORS OF SUPPORT TIME

First, we need to describe mechanical movement with proper formula. One-mass and two-mass model is usually used to write motion equation of rotating part of wind turbine. In terms of support time analysis, one-mass model is enough. Motion equation can be written as (2) with damping factor omitted.

$$2H_{\mathrm{W}}\omega\frac{d\omega}{dt} = P_{\mathrm{m}} - P_{\mathrm{e}} \quad (2)$$

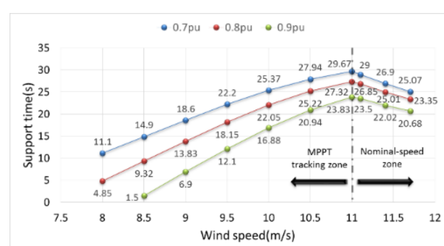
Moreover, nominal capacity of converter is generally 30%~40% of that of wind turbine. Slip power might exceed the limit of converter capacity if rotor speed is too low. Because of that, speed limit of frequency regulation, which is commonly set higher than conventional hardware and software protection, is very necessary.

In the following, speed limit and inertia constant are studied as main influencing factors of support time. To simplify the calculation, ΔPe is set as 10% of nominal power and keep constant during support stage. Nominal rotor speed is defined as 1500rpm.

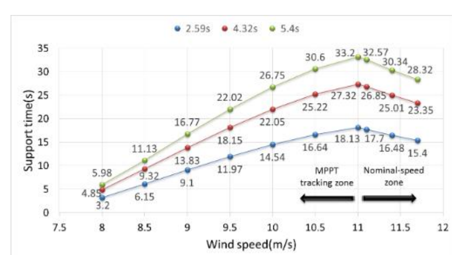
A. *Speed Limit's Influence on Support Time*

Fig. 3(a) shows the relationship between support time and speed limit for a typical 2MW DFIG-VSG. In the figure, inertia constant is set as H_W=4.32s.

In MPPT tracking zone, support time of wind turbine increases monotonically as wind speed rises. It turns out just the opposite in nominal-speed zone. Speed limit is set to 0.7pu, 0.8pu and 0.9pu respectively. Obviously, support time increases as speed limit decreases at a certain wind speed. Moreover, it can be concluded that speed limit has bigger influence on support time at lower wind speed.



(a) Support time vs. speed limit



(b) Support time vs. inertia constant

Fig. 3. Relationship between support time and influencing factors under

different wind speed.

B. *Inertia Constant's Influence on Support Time*

Fig. 3(b) shows the relationship between support time and inertia constant. In this figure, speed limit is set as 0.8pu. Inertia constant is set as 2.59s, 4.32s and 5.4s respectively in this figure. It can been seen that support time increases as inertia constant increases. Actually, larger inertia constant means the wind turbine preserves more kinetic energy for a certain rotor speed, which coincide with the calculation results in this figure.

IV. OPTIMIZATION ON SPEED RESTORATION METHOD

Some modified speed restoration methods have been proposed to mitigate second frequency drop. However, these methods involves complicated calculation and are not fit for engineering application. In this section, constant-value restoration and comprehensive restoration methods are proposed.

A. *Constant-value Restoration*

At the beginning of restoration stage, active power reference is set as a certain constant value. When rotor speed recovers to original value, active power reference would switch to MPPT tracking curve. Fig. 4 shows waveforms of a certain type DFIG-VSG with constant-value restoration. The defect of this method is that a power disturbance might occur when power reference switch to MPPT tracking curve. It is disadvantageous for both grid and wind turbine itself.

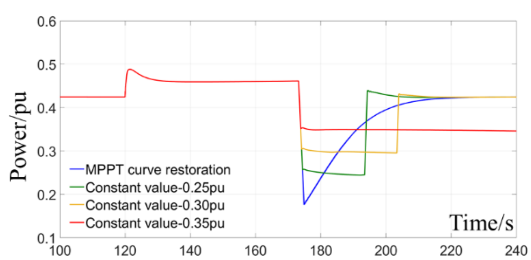


Fig. 4 Power waveforms of DFIG-VSG with constant-value restoration.

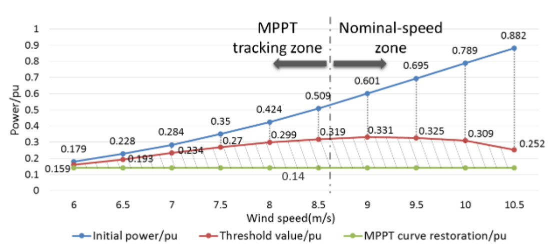


Fig. 5 Threshold value of constant power (Speed limit is set as 0.8pu).

It should be noted that constant value must be set lower than mechanical power at the beginning of restoration stage. Otherwise rotor speed would decrease continuously until shut-down. For the certain DFIG-VSG, the threshold value of constant power is given in Fig. 5, which should not be surpassed in application.

B. *Comprehensive Restoration*

To solve the problem of smooth switching of active power reference, comprehensive restoration method is proposed. The principle of comprehensive restoration is shown in Fig. 6.

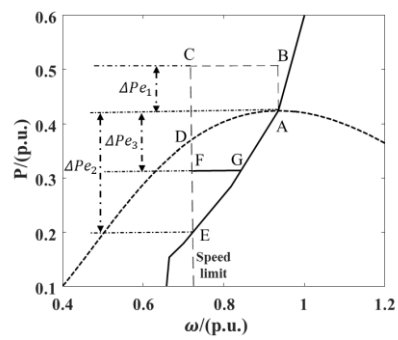


Fig. 6 Principle diagram of comprehensive restoration.

During support stage, active power rises up to point B and moves to C. In the beginning of restoration stage, active power drops to point F in Fig. 6 instead of point E as MPPT curve restoration. Active power reference keeps constant like constant-value restoration until it moves to point G, where the constant value intersect MPPT curve. Then, active power reference moves along MPPT curve until point A. Compared with constant-value restoration, the proposed comprehensive restoration ensures smooth switch from constant-value to MPPT curve tracking reference. Fig. 7 shows waveforms of DFIG-VSG with comprehensive restoration.

As can be seen, comprehensive restoration is the combination of MPPT curve restoration and constant-value restoration. With this method, second frequency drop can be significantly mitigated and smooth switch is ensured.

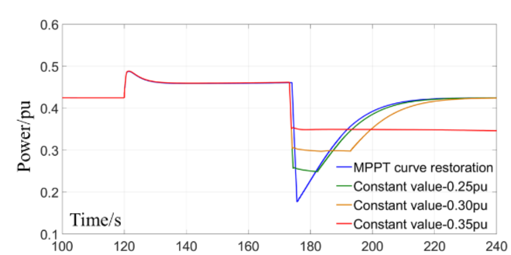


Fig. 7 Power waveforms of DFIG-VSG with comprehensive restoration

V. SIMULATION VERIFICATION

A. *Simulation System*

Simulation system consisting of typical synchronous generator is shown in Fig. 8. Penetration ratio of wind turbines and power shortage ratio are set as 20% and 4% in simulation. Main simulation parameters are listed in Table I and II. In the following simulation, wind speed is set as 8m/s and DFIG operates in MPPT tracking zone.

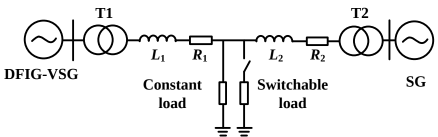


Fig. 8 Topology diagram of simulation system.

TABLE I
MAIN PARAMETERS OF SYNCHRONOUS GENERATOR

Parameters	Value
Inertia constant	5s
Frequency coefficient	15
Frequency factor of load	2
Primary frequency control limitation	3.5%
Main gas pressure pipeline flow coefficient	3
Time constant of drum heat storage	300s
Time constant of the superheater	10
Boiler fuel release time constant	10
Combustion release delay	20s

TABLE II
MAIN PARAMETERS OF DFIG-VSG

Parameters	Value
Inertia constant	5s
Primary frequency regulation coefficient	20
Inertia frequency regulation coefficient	5
Speed limit	0.83pu

B. *MPPT Curve Restoration*

MPPT curve restoration method is simulated. A switchable load of 4% capacity of the system is applied to the grid at 120s.

It can be seen that DFIG-VSG could effectively reduce first frequency drop compared with conventional DFIG. However, severe second frequency drop is witnessed. Minimum value of active power is only decided by speed limit with MPPT curve restoration. Thus, deeper active power drop would occur with higher initial active power (namely higher wind speed), leading to more severe second frequency drop. Grid frequency drops to 49.08Hz in Fig. 9.

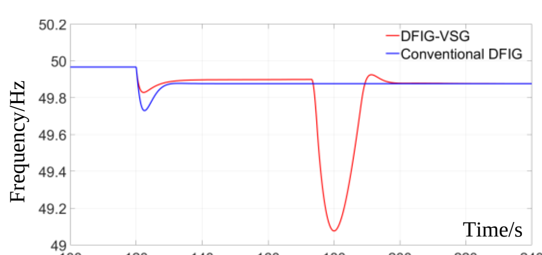


Fig. 9 Simulation results of wind turbine VSG with MPPT curve restoration

C. *Constant-value Restoration*

Constant-value restoration can mitigate second frequency drop. In Fig. 10, if constant-value is set as 0.35pu, the depth of second frequency drop could decrease by 78% compared with MPPT curve restoration. However, the switch of active power reference leads to frequency disturbance, whose peak value reaches 50.14Hz in Fig. 10.

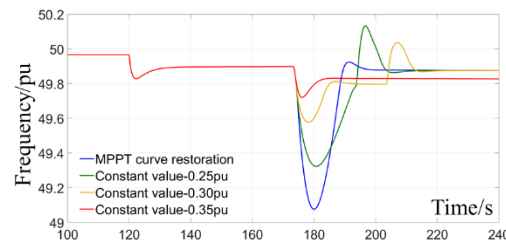


Fig. 10 Simulation results of wind turbine VSG with constant-value restoration.

D. *Comprehensive Restoration*

Results in Fig. 11 shows that comprehensive restoration method could mitigate second frequency drop dramatically and ensure smooth switch at the same time. It is noteworthy that minimum value of grid frequency in Fig.11 is exactly the same as that in Fig. 10. Thus, is can also be concluded that depth of second frequency drop is only determined by the power drop amplitude while DFIG-VSG exits speed restoration.

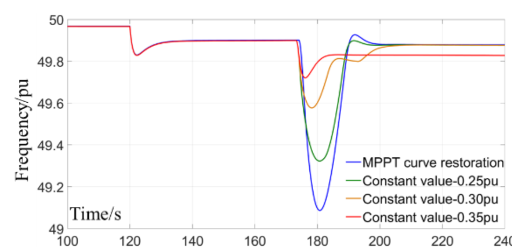


Fig. 11 Simulation results of wind turbine VSG with comprehensive restoration.

VI. CONCLUSION

As wind turbines play a more important role in the grid, VSG technology has become one of the most feasible solutions to decrease of power system inertia and lack of frequency and voltage regulation capability. However, second frequency drop is one critical constraint on large-scale usage of rotor inertia control in terms of DFIG-VSG. Influencing factors on inertia support time of DFIG-VSG is studied, followed by optimization of rotor recovery methods in this paper. Constant-value restoration and comprehensive restoration are proposed respectively to improve performance of DFIG-VSG.

Results show that inertia support time would increase and then decrease as wind speed increases. Besides, support time is mainly decided by speed limit and rotor inertia constant. Theoretical analysis and simulation results reveal that constant-value restoration and comprehensive restoration methods could mitigate second frequency drop sharply.

However, constant-value restoration might lead to power and frequency disturbance, which is harmful to both grid and DFIG itself. Comprehensive restoration method, by contrast, could ensure smooth switch of active power reference as well as mitigate second frequency drop..

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