Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

# Virtual Synchronization Control Strategy of Direct Drive Permanent Magnet Wind Turbine under Load Shedding Operation Mode*

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***Abstract* -In terms of the problems of insufficient interia supporting capacity of the system and loss of stable performance of grid frequency caused by increased wind power grid-connected capacity, virtual synchronous generator technology to simulate the operation characteristics of synchronous generator has become an effective solution. In this paper, the direct-drive permanent magnet wind turbine, one of the mainstream wind farm models, is taken as the research object, and a virtual synchronous control strategy is introduced into the grid-connected control to improve the equivalent inertia of the direct-drive permanent magnet wind turbine and make it deliver smooth power to the grid. The spare capacity is provided by the coordinated control of overspeed and pitch change of the unit itself, and the active power output is increased through the inertia response control link of the virtual synchronous generator, thus improving the primary frequency modulation capability of the system. The simulation results show that the coordinated control strategy proposed in this paper can make full use of the load shedding operation of wind turbines and the virtual synchronous generator technology andeffectively improve the frequency stability and intertia support effect of the grid-connected system, contributing to the safe and stable operation of the power system.**

***Index Terms - Direct drive permanent magnet wind turbine，Virtual synchronization control，Spare capacity，Inertia，Primary frequency modulation***

## I. INTRODUCTION

In order to cope with the increasingly severe energy crisis and environmental pollution, renewable energy power, such as wind power and photovoltaic power, has developed rapidly. Especially for Gansu power grid, by the end of 2018, the total installed capacity of Gansu power grid was 54.425 million kilowatts, and the installed capacity of new energy was 21.2148 million kilowatts, accounting for 41.50% of the totalinstalled capacity. Among them, the installed capacity of wind power reached 128.13 million kilowatts, accounting for 25.08% of the installed capacity of wind power. However, for the variable speed constant frequency wind turbine widely used in wind farms, maximum power power point tracking (MPPT) control mode is mainly used to decouple the output of wind turbine from the system frequency, which does not have the interia support capacity of traditional synchronous generators. With the increase of wind power Grid-connected capacity, the inertia of power system will be greatly reduced, and the frequency instability will become more prominent.

In order to improve the inertia support capability of wind turbines and solve the problem of large-scale new energy absorption[1], reference [2] simulates the inertia and damping characteristics of traditional synchronous generators, and proposes the concept of grid-connected control based on virtual synchronous machines. Because the traditional synchronous generator has the functions of maintaining power balance and frequency and voltage regulation in the power system, virtual synchronous generator technology has the same indispensable role in wind power system[3]. In reference [4-5], the model of traditional synchronous generator is introduced into the grid-connected control of three-phase inverters to realize the electromagnetic characteristics, moment of inertia, frequency modulation and voltage regulation characteristics similar to the traditional synchronous machine. The control strategy of virtual synchronous generator has been successfully applied.

Due to the randomness and volatility of wind energy, the speed regulation capability of wind turbine generator is limited, thus affecting the stability of high permeability wind power grid-connected system. At the same time, traditional wind power grid connection adopts MPPT control based on frequency decoupling and phase-locked loop technology, which makes its grid connection interface lack of independent frequency modulation and voltage regulation capability [6].In order to solve these problems, the document [7] realizes the

* This work is partially supported by National Natural Science Foundation of China #51967012 and Gansu Province Major Science and Technology Special Fund Project #17ZD2GA010 and Scientific Research and Innovation Team Project of Gansu Education Department #2018C-09 and State Grid Gansu Power Company Science and Technology Project #522722170018

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cooperative action between the wind turbine and the energy storage equipment at the junction point and realizes the interface characteristics of the virtual synchronous generator by configuring controllable energy storage on the AC side of the wind turbine, but the additional energy storage device increases the equipment cost of the wind farm. Literature [8] proposes a virtual synchronous fan control scheme based on limited power by utilizing the kinetic energy stored in the fan rotor, but the storage capacity of the fan rotor is limited. However, due to the limited storage capacity of the fan rotor the system cannot get long-term power support. Document [9-10] reserves reserve capacity for wind turbine frequency modulation by modifying MPPT curve and pitch control, thus enabling the wind turbine to simulate the frequency modulation and voltage regulation characteristics of traditional synchronous machines.The scheme enables the fan to have similar characteristics of frequency and voltage regulation to the traditional synchronizer without additional energy storage device, and provides power support for the system for a long time. However, due to reserve of active power for standby, the utilization rate of wind energy in the steady state of the fan is reduced, and the maximum wind energy is not fully utilized. Literature [11] proposes the application ofvirtual synchronization technology in full-power fans. Although its virtual inertia and frequency control do not depend on power grid frequency detection, how to use fan's own characteristics to provide frequency support for the system has broad prospects for further mining.

In this paper, a virtual synchronous control strategy for wind turbines under load-shedding operation mode is proposed, taking one of the main wind farm models, the direct-driven permanent magnet synchronous generator (D-PMSG), as the research object. Firstly, according to the calculation of pitch angle and the analysis of system power, pitch control is carried out to realize the coarse adjustment of system frequency. Secondly, the unit enters the load shedding mode through overspeed control, thus realizing fine frequency adjustment. On this basis, the virtual synchronization control strategy is introduced into the D-PMSG grid-connected control, and active power output is increased through to enhance the inertial support and primary frequency modulation. Finally, a system simulation model is built through MATLAB/Simulink platform to verify the correctness and effectiveness of the proposed control strategy, thus providing theoretical and experimental basis for large-scale wind power consumption.

## II. ANALYSIS OF TRADITIONAL CONTROL MODE OF D-PMSG

The typical structure of D-PMSG grid-connected system is shown in Figure1. The active and reactive power decoupling control of wind turbines is realized by vector control, and themaximum wind energy is captured by stator-side converter, improving the power generation efficiency.

Fig. 2 shows the wind turbine power characteristic curve. Each curve corresponds to different wind speeds. When the speed is constant, different wind speeds cause the wind turbine to output different powers.

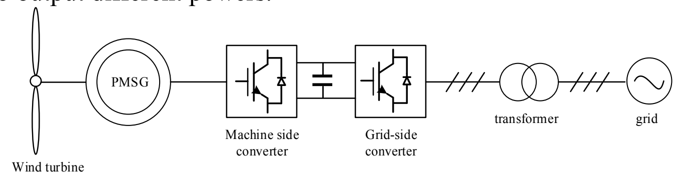



Fig.1 D-PMSG structure diagram

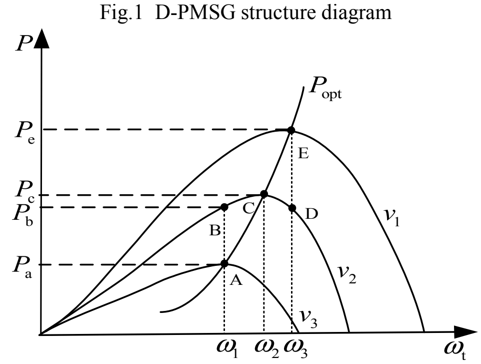



Fig2 Wind turbine power characteristics

## III. FREQUENCY INTEGRATED CONTROL OF D-PMSG

### A. Virtual Synchronous Control Strategy

The VSG mathematical model is established with reference to the classical second-order model of the synchronous generator. It consists of two parts: mechanical and electromagnetic. The mechanical characteristics are represented by the equation of motion of the rotor (1).

$$\begin{cases} 2H\dfrac{d\Delta\omega}{dt} = P_{\mathrm{m}} - P_{\mathrm{e}} - D(\omega - \omega_{\mathrm{N}}) \\ \dfrac{d\delta}{dt} = \omega - \omega_{\mathrm{N}} \end{cases} \tag{1}$$

Where $H$ is the inertia time constant; $D$ is damping coefficient, $P_{\mathrm{m}}$ and $P_{\mathrm{e}}$ are the mechanical and electromagnetic power of the grid-side converter, respectively, $\omega$ is the rotor angular velocity, $\omega_{\mathrm{N}}$ is the rated angular velocity, $\delta$ is the rotor power angle.

When modeling the electromagnetic part, the stator electrical equation is used as the reference object, as shown in equation (2):

$$\dot{E}_{0\mathrm{i}} = E_0 \sin\theta = \dot{U}_{\mathrm{i}} + \dot{I}_{\mathrm{i}}(r_{\mathrm{s}} + jx_{\mathrm{s}}) \tag{2}$$

Where $\dot{E}_{0\mathrm{i}}$ , $\dot{U}_{\mathrm{i}}$ and $\dot{I}_{\mathrm{i}}$ are three-phase induced electromotive force, stator terminal voltage and stator current, respectively, $\theta$ is the phase angle, $r_{\mathrm{s}}$ is the stator armature resistance, $x_{\mathrm{s}}$ is the equivalent impedance of the line.

In the control algorithm, power control is the main control part of VSG. The instantaneous electromagnetic power output by the change of rotor kinetic energy can be expressed as [12]:

$$P_{\mathrm{e}}(\mathrm{t}) = -\frac{P_{\mathrm{N}}H}{f_{\mathrm{N}}^2} f(\mathrm{t})\frac{df(\mathrm{t})}{dt} \tag{3}$$

Where $P_e(t)$ is instantaneous electromagnetic power, $P_N$ is the rated power of the synchronous machine, $f_N$ is the rated frequency , $f(t)$ is the instantaneous frequency.

It can be assumed that $f(t) \approx f_N$ , so Equation (3) can be simplified as [12] :

$$P_e(t) \approx -\frac{H}{f_N}\frac{df(t)}{dt}P_N \tag{4}$$

The output of instantaneous inertia support power will cause torque imbalance and exert severe torque impact on D-PMSG equipment. Therefore, in the design of D-PMSG inertia support, an additional first-order inertia part with adjustable time constant $K$ is introduced to slow down the sudden change of torque[13] , as shown in Fig. 3.

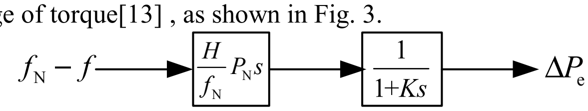



Fig.3 Diagram of fan VSG inertia support control

## B. Load Shedding Control

Overspeeding techniques are carried out applying the so-called deloaded optimum torque (or power) – omega curves $T-\omega$ [14-15], as shown in Fig.4, these curves impose operating points out of the optimum $T-\omega$ curve that allows extracting the maximum available power from the wind.

However, operating conditions below the rated wind speed are only applicable to overspeed control. Therefore, overspeed control needs to distinguish between low wind speed and medium-high wind speed modes [16], and $\omega_r$ is the specific load reduction level $r$ that can be obtained only by overspeed control, and $\omega_{t_N}$ is the fan rated speed .When $\omega_r \le \omega_{t_N}$ , D-PMSG load shedding can be completed only by overspeed control, which can be determined as low wind speed condition, and vice versa.

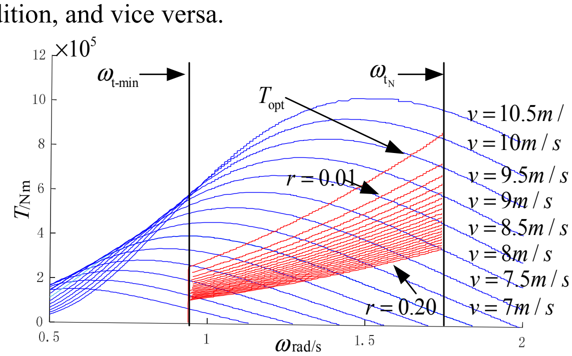



Fig 4. D-PMSG load shedding curve

Among them, $\omega_r$ can be calculated by looking up a graph, $r$ load shedding curve is drawn by spline interpolation, and the corresponding rotor speed $\omega_r$ is obtained from the torque $T_{del}$ after load shedding. $T_{del}$ can be calculated by the following formula:

$$T_{del} = (1-r)T_{opt} \tag{5}$$

The load shedding level $r$ is defined as the ratio of the generated power $P_{opt_{del}}$ to the maximum power $P_{opt}$ extracted from the wind, which can be expressed as:

$$r = \begin{cases} \dfrac{P_{opt_{del}}}{P_{opt}}, & v \le v_N \\ \dfrac{P_{opt_{del}}}{P_{rated}}, & v > v_N \end{cases} \tag{6}$$

When the pitch angle and torque are combined to achieve the required spare capacity, the load reduction level $r$ can be further supplemented as follows:

$$\begin{aligned} \frac{P_{opt_{del}}}{P_{opt}} &= \frac{0.5\rho A v^3 C_{Pdel}(v,\omega_{t_N},\beta)}{0.5\rho A v^3 C_{Popt}(v,\omega_{t_{opt}},0)} \\ &= \frac{C_{Pdel}(v,\omega_{t_N},\beta)}{C_{Popt}(v,\omega_{t_{opt}},0)} = r \end{aligned} \tag{7}$$

Where $v \in (v_{min}, v_N)$ , $v_{min}$ is the minimum wind speed corresponding to each load reduction level. the required pitch angle under different conditions can be solved through different wind speeds and load reduction levels, and the optimal torque $T$ required for load reduction can be found at the same time, as shown in equation (8):

$$T_{opt_{del}} = \frac{P_{opt_{del}}}{\omega_{t_N}} \tag{8}$$

For simplicity of calculation, it is defined that the electromagnetic torque required for load reduction will remain unchanged under the pitch angle $\beta_{max}$ corresponding to different load reduction levels. Its calculation is formula (9)：

$$T_{opt_{del|\beta\ge\beta_{max}}} = \frac{rP_{rated}}{\omega_{t_N}} \tag{9}$$

The relationship between pitch angle and torque is shown in Fig.5:

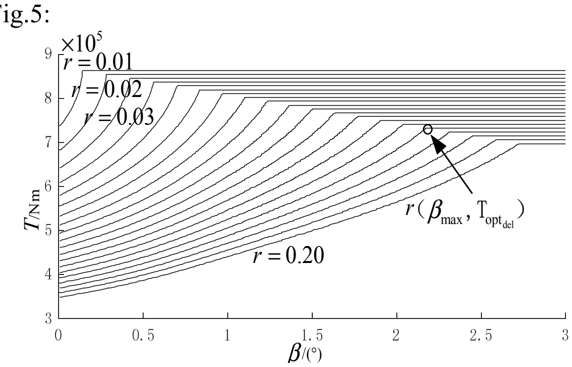



Fig.5 The curve between pitch angle and torque

Considering that the rotational speed of the wind turbine is lower than the rated, the electrical torque reference is obtained accessing to the $T-\omega$ curve (Fig. 4). This torque reference is sent to the low level control algorithm of the rotor-side power converter of the wind turbine, i.e. the inner current control loop for the converter. Once the rated speed of the wind turbine is reached, the regulation of the pitch angle comes into play. A conventional speed controller drives the pitch actuator. This way the speed of the turbine is not exceeded. In this operating range, the torque reference for the generator is obtained accessing to the $T-\beta$ curves of Fig.5. It is worth noting that the electrical torque reference varies according to the slow dynamics of the pitch controller in this operating range. In the process of load shedding, pitch control is used as a rough adjustment scheme because it operates on mechanical components, and overspeed control with fast frequency response is used as an accurate adjustment scheme. The combined action of the two provides frequency support for the system and makesthe power system more stable.The control flow is shown in Fig.6, and the operation steps are as follows:

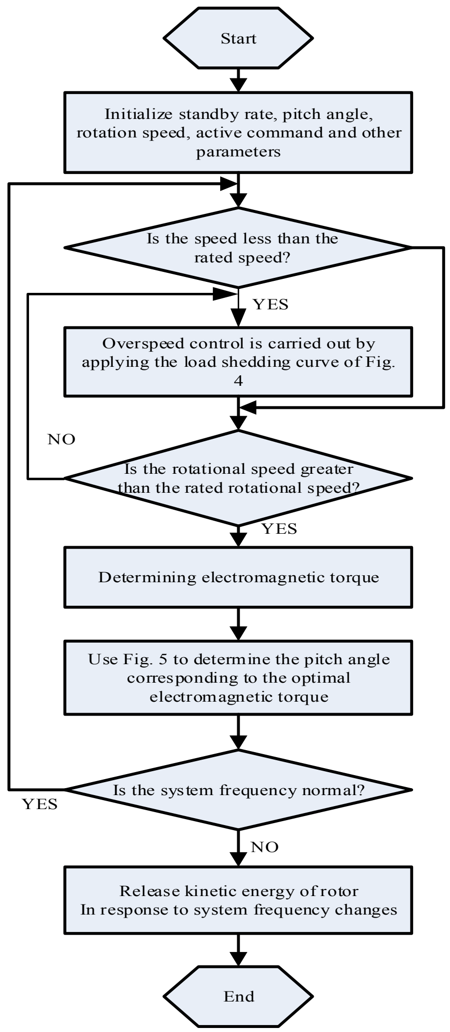



Fig.6 Flow chart of coordinated control of overspeed and pitch frequency

### C. *Integrated Frequency Control*

The virtual synchronous control strategy for wind turbines based on load shedding operation proposed in this paper mainly designs the primary frequency modulation and inertia response functions of the power system. As shown in Fig. 7.

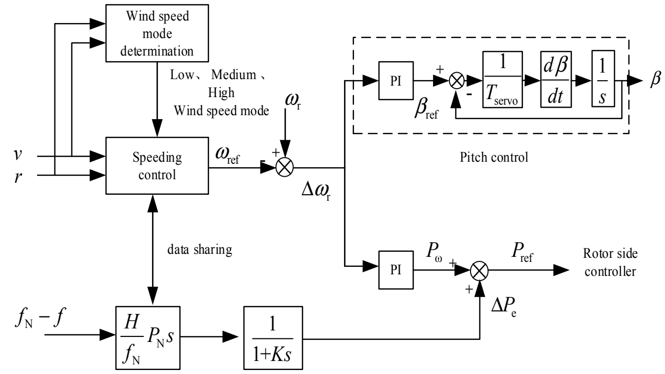



Fig.7 Structural diagram of fan VSG inertial support and primary frequency modulation control

## IV. SIMULATION ANALYSIS

In order to verify the effectiveness of the virtual synchronous control strategy of direct-drive permanent magnet wind turbine under load shedding operation mode, a simulation system as shown in Fig. 8 is built in MATLAB/Simulink simulation platform. The system consists of two synchronous generators ( $G_1$ , $G_2$ ) with capacity of 150MW and 300MW respectively and 20 2MW direct-drive permanent magnet wind turbines (using single machine equivalent model). Loads $L_1$ , $L_2$ and $L_3$ are active loads with capacities of 110MW, 100MW and 50MW respectively.

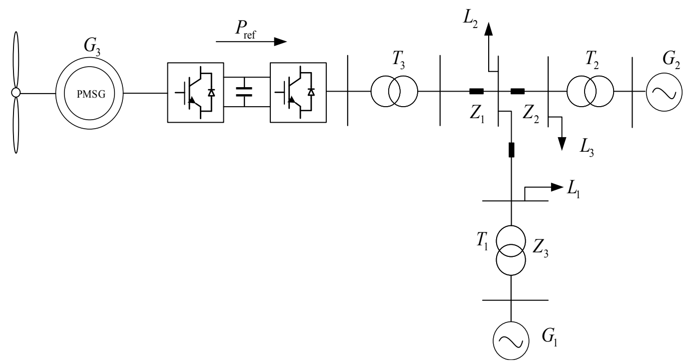



Fig.8 Schematic diagram of power system simulation structure

System simulation parameters:

TABLE I
PARAMETERS OF 2MW DIRECT DRIVE PERMANENT MAGNET SYNCHRONOUS GENERATOR

| Parameter | Numerical value |
|---|---|
| $R_s/\Omega$ | 0.0067 |
| $L_d$ / mH | 1.4 |
| $L_q$ / mH | 1.4 |
| $\psi_f$ / Wb | 9.25 |
| $H$ / s | 5.8 |
| $P$ | 32 |

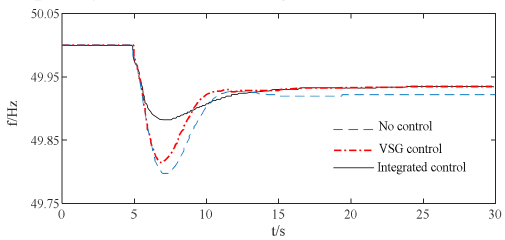
TABLE II
Parameters of Traditional Synchronous Generator $G_1$ 、$G_2$

| Parameter | Numerical value $G_1$ | Numerical value $G_2$ |
|---|---|---|
| $X_d/\Omega$ | 2.13 | 2.00 |

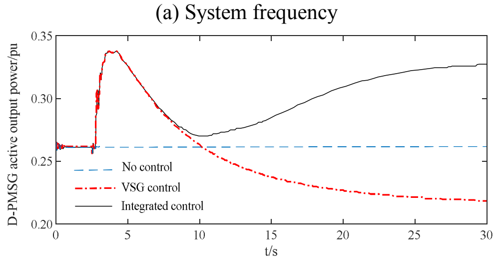
| | | |
|---|---|---|
| $X_d^{'}/\Omega$ | 0.308 | 0.35 |
| $X_d^{''}/\Omega$ | 0.234 | 0.252 |
| $X_q/\Omega$ | 2.07 | 1.9 |
| $X_q^{'}/\Omega$ | 0.906 | 2.19 |
| $X_q^{''}/\Omega$ | 0.234 | 0.243 |
| $R_s/\Omega$ | 0.004 | 0.004 |
| $X_1/\Omega$ | 0.17 | 0.17 |
| $T_{d0}^{'}/s$ | 6.0857 | 8.00 |
| $T_{d0}^{''}/s$ | 0.0526 | 0.0681 |
| $T_{q0}^{'}/s$ | 1.653 | 0.9 |
| $H$ / s | 3.84 | 5.2 |

## *A. Simulation Analysis of Sudden Load Increase*

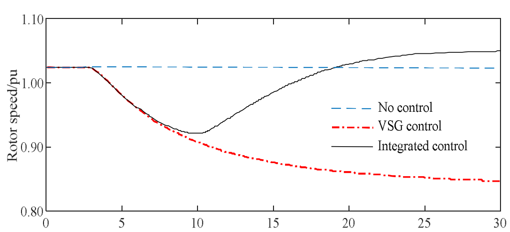
Assuming that the wind speed is a fixed value of 10m/s, the wind turbine will initially maintain a 10% load shedding operation state, and the load $L_1$ will suddenly increase from 110MW to 150MW at 10s, which leads to a decrease in the system frequency. As shown in Fig. 9.



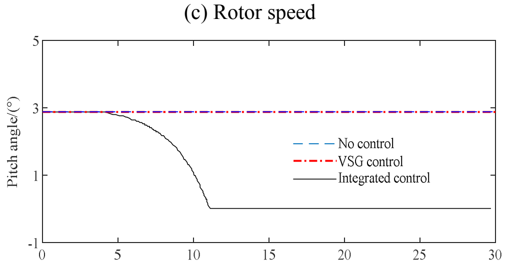

(a) System frequency




(b) D-PMSG active output power




(c) Rotor speed



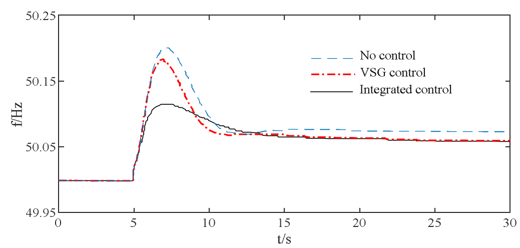

(d) Pitch angle

Fig.9 Comparison of system dynamic response after sudden increase of load $L_1$

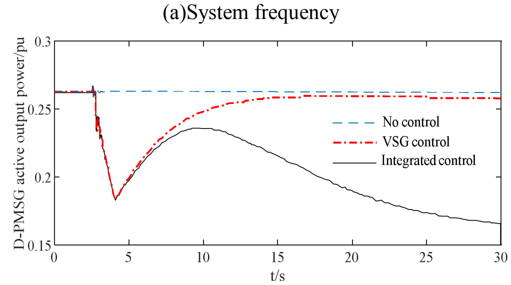
We comparethe dynamic response of system frequency, active output of wind turbine and rotor speed when D-PMSG has no control, VSG control and frequency integrated control, as is shown Fig.9. When the D-PMSG has no other control, the decreasing rate and amplitude are the largest. Through VSG control, the wind turbine can prevent the maximum deviation of frequency to a certain extent, and the lowest frequency can be increased from 49.48Hz to 49.67Hz. However, under the integrated control frequency of D-PMSG load shedding and VSG technology, D-PMSG can not only maintain the inertia supporting function of the system, but also participate in a frequency adjustment of the system. Compared with PMSG without control, the maximum frequency offset is reduced from 0.52 to 0.31, reduced by 40.4%, which has obviously improved the frequency characteristics of the system. Among them, the active support of the system can be continuously provided by the active reserve capacity pre-left by the D-PMSG load shedding operation.When the system frequency drops at the initial stage, it is beneficial to reduce the power change rate for the recovery of the system frequency.

## *B. Simulation Analysis of Sudden Load Reduction*

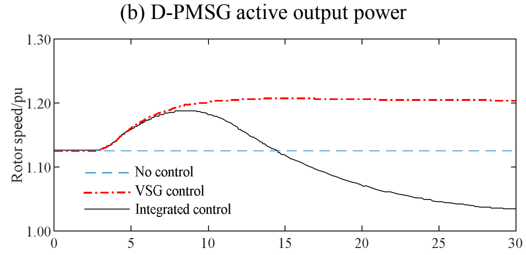
At 10.0s, the load $L_1$ suddenly decreases from 110MW to 70MW, which leads to a decrease in the system frequency. The simulation results are shown in Fig. 10.



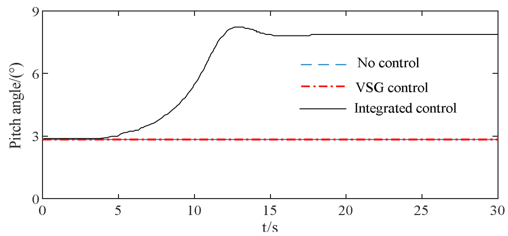

(a)System frequency




(b) D-PMSG active output power




(c) Rotor speed




(d) Pitch angle

Fig.10 Comparison of system dynamic response after load $L_1$ sudden reduction

As shown in Fig.10,when the D-PMSG has no control, it can hardly respond to the system frequency change. Under the control of VSG, D-PMSG rapidly reduces the power output and increases the rotational speed of the wind turbine, as a result of which storing kinetic energy reduces the system frequency from 50.54 Hz to 50.32Hz. Compared with D-PMSG without control, the frequency of the system is reduced to 50.28 under the combined action of D-PMSG load shedding operation and VSG, and the maximum frequency offset of the system is reduced from 0.54 to 0.28, accounting for 48.1%. From the comparison of power dynamic response, it can be concluded that the unbalanced power in the system is obviously improved after the system frequency changes.

## V CONCLUSION

Based on the load shedding control strategy of direct-drive permanent magnet wind turbine, this paper further proposes a virtual synchronous control method of wind turbine based on load shedding operation mode. In order to fully reduce the load of wind turbine, coordinated control of overspeed and pitch change are adopted to generate a certain reserve capacity for primary frequency adjustment of the system, supporting the combination with virtual synchronous generator technology for system frequency. The simulation results show that the control strategy proposed in this paper can prevent the system frequency fluctuation caused by wind speed change and sudden change of power grid load, and can effectively improve the inertia response and primary frequency modulation capability of the system compared with the traditional virtual inertia control method.


## ACKNOWLEDGMENT

This paper is supported by National Natural Science Foundation of China (No.51967012), Gansu Province Major Science and Technology Special Fund Project (No. 17ZD2GA010),Scientific Research and Innovation Team Project of Gansu Education Department (No.2018C-09) and State Grid Gansu Power Company Science and Technology Project (No.522722170018).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