Emergency Active Power Control Considering Power Reserve for Direct Driven Wind Power System Under Overspeed Power Shedding Operation

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2021 IEEE Sustainable Power and Energy Conference (iSPEC) | 978-1-6654-1439-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/iSPEC53008.2021.9736000

***Abstract*—In order to meet the requirements of high reliability and stable operation of wind farms in the future, the wind turbines (WTs) not only need to be able to achieve a sudden power drop but also have the ability to increase emergency active power in emergency power control (EPC). Generally, WTs operate at the maximum power point to gain the optimal benefit. However, at this time, the generator unit lacks the ability to further increase the active power. Therefore, the energy storage system is usually equipped traditionally. Moreover, with the establishment of the wind farm panoramic monitoring system (PMS), a rapid control network has been built to meet the EPC response requirements to satisfy the fine level control for each generator unit. In this paper, the overspeed power shedding operation mode is adopted for the direct-drive wind power system (DDWPS) to reserve the active power. After the wind farm receives the emergency active power increase command, the method is realized by controlling the machine-side converter to reduce the rotor speed to release the kinetic energy. Based on Matlab/Simulink, a rated 1.5MW DDWG system simulation model is established to compare the response time and duration time under different emergency active power increases, which provides a theoretical basis for the future EPC multi-objective optimization of wind farms.**

***Keywords*—emergency power control, overspeed power shedding operation, panoramic monitoring system, rotor kinetic energy, direct driven wind power system**

I. Introduction

With the development of renewable energy utilization, wind power as a mature renewable energy is widely applied all over the world [1]. According to China's renewable energy plan, it is estimated that China's installed wind power capacity will reach 1.2 billion kilowatts by 2030 to achieve the "Carbon Neutrality" goal [2]. Furthermore, increasing the active power output of wind farms and reducing the amount of wind curtailment have become important means to improve the efficiency of wind farms and reduce investment costs [3, 4]. In order to realize the above target, the maximum power point tracking (MPPT) control is adopted for wind power system [5-7].

At present, in order to ensure the safe and stable operation of the power grid, when an emergency in the power grid occurs, some methods such as cutting machines or cutting farms are usually used to decrease the output power of wind turbines. In [8], authors compared the advantages and disadvantages of the different methods of cutting farms, cutting machines and the combination of the two methods based on the comprehensive index evaluation for the wind farm emergency power control (EPC). In [9], authors put forward the technical requirements, architecture and scenarios of renewable energy EPC for northwest grid in China, and proposes a control strategy with the goal of minimizing the control cost. It can be obtained that during EPC of wind turbines, there will be scenarios where active power increases. The traditional MPPT control makes it impossible to gain additional output active power. Therefore, in order to meet the emergency power increase, energy storage devices are usually placed, which increases the installation and operation and maintenance costs.

Regardless of the installation of energy storage devices, in order to achieve primary frequency control, the power shedding operation is adopted for wind turbines to reserve active power [10]. The mode of power shedding operation for wind power generator is generally realized by using overspeed control and pitch control to deviate from the MPPT curve [11, 12]. Usually the response time of EPC is within hundreds of milliseconds. The time scale of pitch control is too large to be suitable for EPC. The traditional communication system has many levels and the response time need several seconds, which cannot meet the needs of EPC. Fortunately, the constructed PMS can solve the above problems. The overall EPC action time does not exceed 300ms [9].

According to PMS, the overspeed power shedding operation mode is applied to reserve the active power for EPC in the direct-

This paper is fund by On-site Implementation Technology Research for Gansu Northwest Grid System Protection Construction (SGTYHY/19-JS-218).

drive wind power system (DDWPS). When the wind farm receives the emergency active power increase command, the machine-side converter is controlled to reduce the rotor speed to release the kinetic energy to support the emergency active power. A rated 1.5MW DDWPS simulation model is built and analyzed by using Matlab/Simulink to compare the response time and effective action time of different emergency active power increases, which provides a theoretical basis for the future EPC multi-objective optimization of wind farms.

II. Principle of Overspeed Power Shedding Operation

A. Traditional MPPT Control

The wind power generation system with DDWPS is shown in Fig. 1. The back-to-back full capacity converter is applied in machine-side and grid-side respectively to limit the current harmonics and improve the output power performance. Moreover, MPPT control method is adopted in machine-side converter to enhance the wind energy utilization. Besides, the information such as control commands and signal detections can be interacted rapidly between the DDWPS controller and PMS.

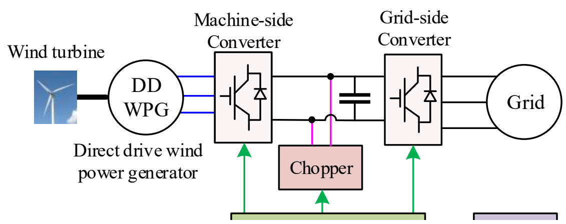


Fig. 1. Diagram of DDWPS.

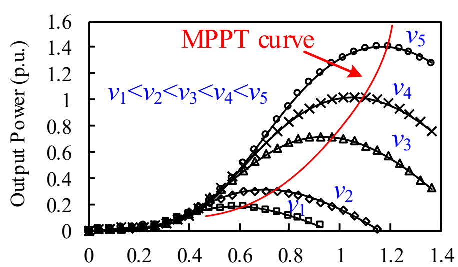


Fig. 2. MPPT curve of DDWPS.

According to wind turbine operation characteristics, the wind energy utilization coefficient C_p can be determined by the pitch angle β and tip speed ratio (TSR) λ. Therefore, the output power of wind turbine can be controlled by adjusting the pitch angle and rotor speed of permanent magnet synchronous generator (PMSG) in DDWPS. From Fig. 2, the maximum output powers can be realized by controlling the generator rotor under different wind speeds with constant pitch angle to extract the maximum wind energy. However, the MPPT control method makes DDWPS work at the maximum power point and cannot further provide active power support to participate in grid regulation. Especially when the power grid is under an emergency situation, DDWPS is prone to large-scale disconnection, which expands the scope of the accident. Generally, it is realized by cutting off to satisfy the emergency power decrease requirement. When the grid requires DDWPS to increase the active power urgently, the existing methods are generally implemented through energy storage.

B. Overspeed Power Shedding Operation

Without considering the energy storage device, in order to achieve DDWPS participating in EPC, the active power needs to be reserved for backup. According to Betz theory and wind turbine characteristic curve, it can be concluded that both overspeed control and pitch control can achieve the power shedding operation. At this time, DDWPS no longer runs on the MPPT curve to capture the maximum wind energy, so that the wind turbine maintains a certain reserve capacity. For EPC, the required response time is very short, usually in the hundreds of milliseconds, so the pitch control cannot meet the requirements. The overspeed control can store capacity in the PMSG rotor. When an EPC command is given, the PMSG rotor can release energy instantly which is likely to a flywheel energy storage device. With the PMS establishment for wind farms, the communication time can limit within 100ms, which is able to realize the wind turbines to participate in EPC. Therefore, the overspeed control with zero pitch angle is used to achieve reduced power operation., as illustrated in Fig. 3.

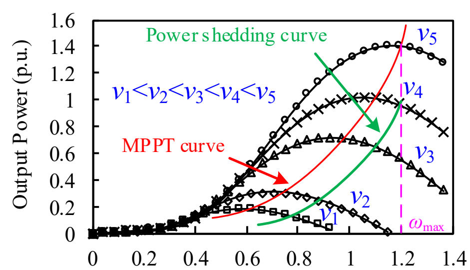


Fig. 3. Overspeed power shedding operation curve.

In order to ensure the safe operation of wind turbine, the rotor speed of PMSG in DDWPS need to be limited below the maximum speed ω_{max}. Therefore, the overspeed power shedding operation is suitable for the low/middle wind speed ranges without adjusting the pitch angle. Seen from Fig. 3, assuming v_5 is the maximum wind speed, the rotor speed reaches the maximum simultaneously when MPPT is realized. At this time, the overspeed power shedding can not be implemented without adjusting pitch angle due to the rotor speed limit. When the wind speed is below maximum value, the power shedding rate is defined as d, which can be expressed as,

$$d = \frac{P_{opt} - P_d}{P_{opt}} \tag{1}$$

where, P_d is the shedding power considering the maximum rotor speed limit, and P_{opt} is the optimal power with MPPT control.

The required electromagnetic torque for PMSG under different wind speeds with power shedding operation can be obtained as,

$$T_{em\_d} = \frac{P_d}{\omega_d} = \frac{(1-d)P_{opt}}{\omega_d} \tag{2}$$

where, ω_d is the rotor angular speed with power shedding operation under different power shedding rate d. And the maximum ω_d is $\omega_{\max}$. From Fig. 3, the electromagnetic torque decreases compared with the one under MPPT control.

According to (2), the reference torque can be calculated to control the machine-side converter to realize the overspeed power shedding operation. The detailed control chart is given in Fig. 4. Especially, for each generator unit in wind farm, the actual allowable maximum power shedding rate $d_{\max}$ under overspeed condition is not only restricted by the wind power system parameters such as wind speed, PMSG speed and pitch angle, etc., but also limited to the required active power output by the grid.

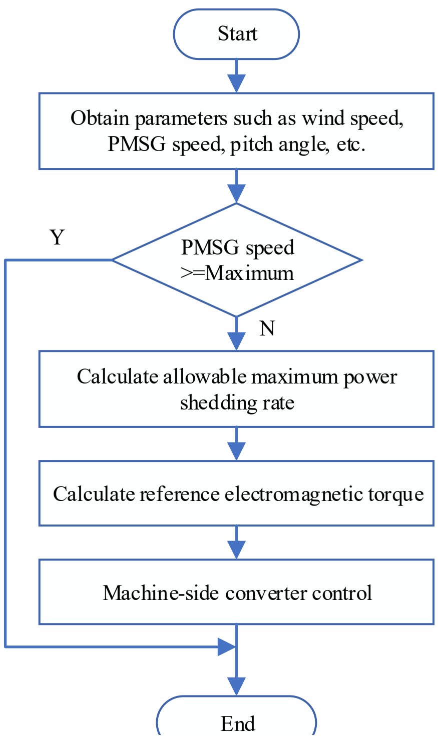


Fig. 4. Overspeed power shedding control chart.

III. Control of Emergency Active Power Increase

A. *Principle of emergency active power increase control*

The PMSG speed is higher under overspeed power shedding operation condition than that under MPPT condition. And it has continuous active power reserve and large rotational kinetic energy for EPC application. According to its active power characteristics, the kinetic energy of the PMSG rotor can be quickly released in the initial stage of emergency power response by controlling the machine-side converter to increase the output active power. At this time, due to the increase of PMSG electromagnetic power P_{em}, the output power of the wind turbine generator P_o is greater than the captured mechanical power P_{mec}, resulting in a rapid decrease in the speed of the PMSG, and the operating point of the PMSG will move from the overspeed power shedding curve to the MPPT curve. The power curve for EPC under overspeed power shedding operation is depicted as Fig. 5. The maximum output active power $P_{\max}$ is determined by the control strategy.

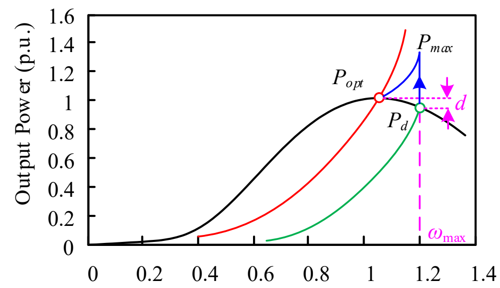
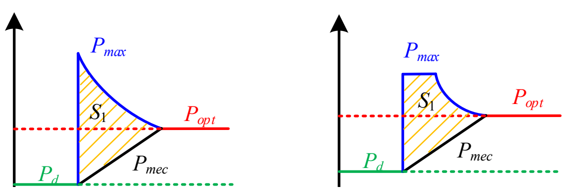


Fig. 5. DDWPS power curve for EPC under overspeed power shedding operation.

When the DDWPS receives the EPC command, the reference active P_{ref} for controlling the machine-side converter can be obtained as,

$$P_{ref} = P_{mec} + \alpha\left(\frac{\omega - \omega_{opt}}{\omega_0 - \omega_{opt}}\right) \tag{3}$$

where, ω is the rotor angular speed of PMSG; ω_0 is the initial rotor angular speed of PMSG before EPC; and α is the coefficient related with the maximum output active power at the beginning of EPC, which is determined by the rotor inertia of PMSG and wind turbine. The output active power with different coefficients under EPC can be indicated as Fig. 6.



(a) (b)

Fig. 6. Output active power with different coefficients under EPC. (a) maximum coefficients. (b) middle coefficients.

It can be indicated from Fig. 6 that the output energy from the rotor of PMSG and wind turbine at the same initial speed and wind speed is definite, marked as S_1. When the required emergency power is high, the duration time is short. Therefore, when multiple units exist in a wind farm under overspeed power shedding operation, if the EPC command send, the emergency output active power combination of these units can be optimized. The relationship between the reserved rotor kinetic energy and output power can be analyzed as the flywheel energy storage device. The output energy at entire EPC process can be expressed as,

$$S_1 = \frac{1}{2} J_r \left(\omega_0^2 - \omega_{opt}^2\right) \tag{4}$$

where, ω_{opt} is the optimal rotation speed. J_r is the inertia of rotor, which can be calculated by the rotor mass and diameter as,

$$J_r = \int r^2 \mathrm{d}m \tag{5}$$

where, r is the distance between the infinitesimal mass dm and the rotation axis.

Besides, the maximum output power P_{max} also is limited by the allowable IGBT current to avoid damaging the machine-side converter due to high junction temperature. The control chart during EPC is given in Fig. 7.

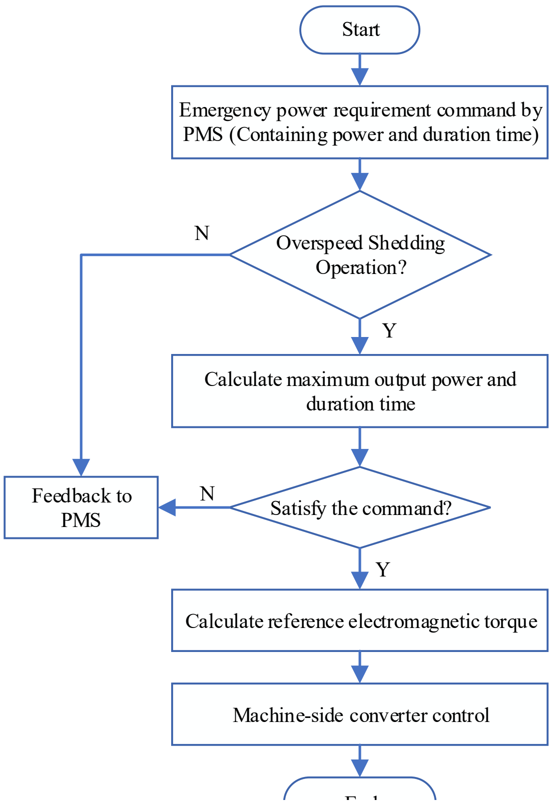


Fig. 7. Control chart during EPC

B. Control of machine-side converter

In order to realize the overspeed power shedding operation and EPC for DDWPS, the machine-side converter need to be controlled. The typical converter topology is back-to-back type. And the machine-side one and its control loop are shown in Fig. 8, which includes the outer speed control loop and inner current control loop. The traditional PI controller is adopted for the current inner control loop and the speed outer control loop respectively. Moreover, the entire controller interacts with the PMS.

Generally, the PMSG in DDWPS is surface-mounted. The dq axial inductances are the same, namely L_d=L_q. The i_d=0 control method is adopted to improve the DDWPS efficiency. The voltage equation and the mechanical equation are expressed under the rotating frame as,

$$\begin{cases} u_d = R_s i_d + L_s \dfrac{\mathrm{d}i_d}{\mathrm{d}t} + \omega L_s i_q \\ u_q = R_s i_q + L_s \dfrac{\mathrm{d}i_q}{\mathrm{d}t} - \omega L_s i_d - \omega \psi_f \end{cases} \tag{6}$$

$$T_{em} = 1.5 p \psi_f i_q \tag{7}$$

where, R_s is the stator resistance of PMSG; L_s is the stator inductance of PMSG; i_d and i_q are the dq axial currents; ω is the electrical angular speed; p is the pole pairs; and ψ_f is the flux linkage of permanent magnet.

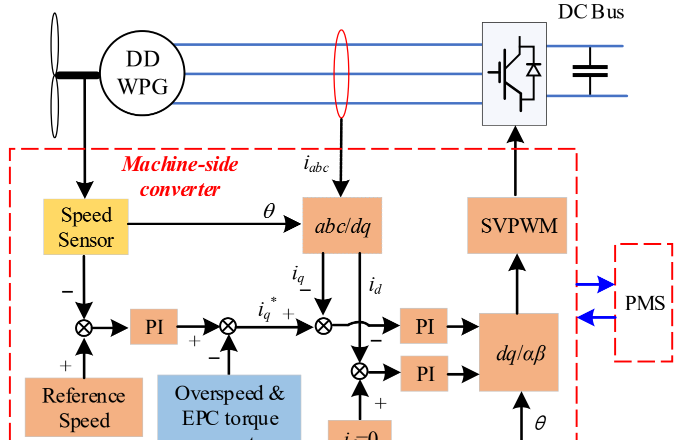


Fig. 8. Machine-side converter and its control diagram.

Because the dq axial current controllers have the same structure, The diagram of the q axial current inner control loop is given in Fig. 9. k_{PWM} is the gain of converter; e_q is the induced electromotive force disturbance; and T_i is the sample time of PMSG currents.

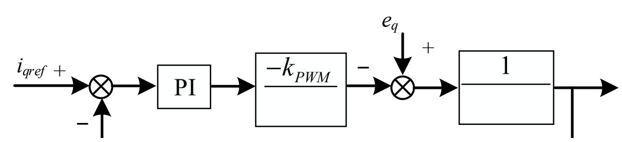


Fig. 9. q axial current inner control loop diagram.

For outer speed control loop, the output of this control loop is the q axial reference current. However, when the overspeed control or the emergency control implements, the electromagnetic torque reference current need to be changed, which can be superimposed on the initial q axial reference current as a disturbance. The diagram of the speed outer control loop is given in Fig. 10.

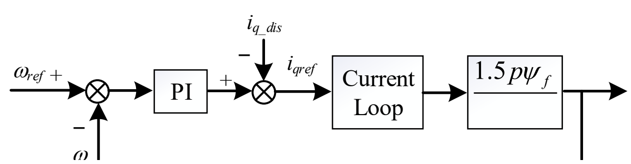


Fig. 10. Speed outer control loop diagram.

IV. Simulation and Comparisons

To verify the overspeed power shedding control and EPC for DDWPS, a simulation model with 1.5MW DDWPS based on Matlab/Simulink is built. And the key parameters of wind turbine and PMSG are listed in Table 1.

Fig. 11 plots the output power of wind turbine with different wind speed inputs under the zero pitch angle below the maximum allowable rotor speed 27r/min. The rated power is 1.5MW at 10m/s when the rotor speed reaches 23r/min. The maximum power is set to 2.3MW considering the IGBT performance when wind speed is 11.5m/s.

TABLE I. KEY PARAMETERS OF WIND TURBINE AND PMSG

Parameter	Value	Unit
Rated power	1.5	MW
Rated wind speed	10	m/s
Optimal TSR	7.8	
Radius of wind turbine	35	m
Maximum rotation speed	27	r/min
Phase of PMSG	3	
Stator resistance	6	mΩ
d axial inductance	0.3	mH
q axial inductance	0.3	mH
Flux linkage of permanent magnet	1.48	Wb
Rotor inertia	35000	kgm^2
Pole pairs	160	
DC Voltage	1200	V
PWM frequency	10	kHz

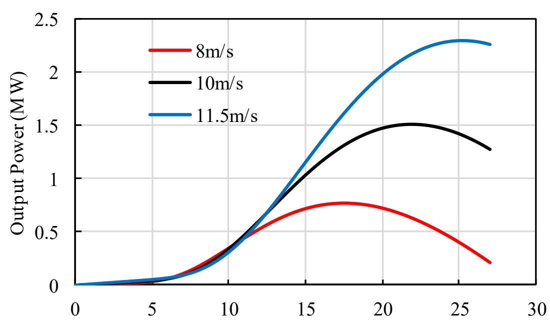
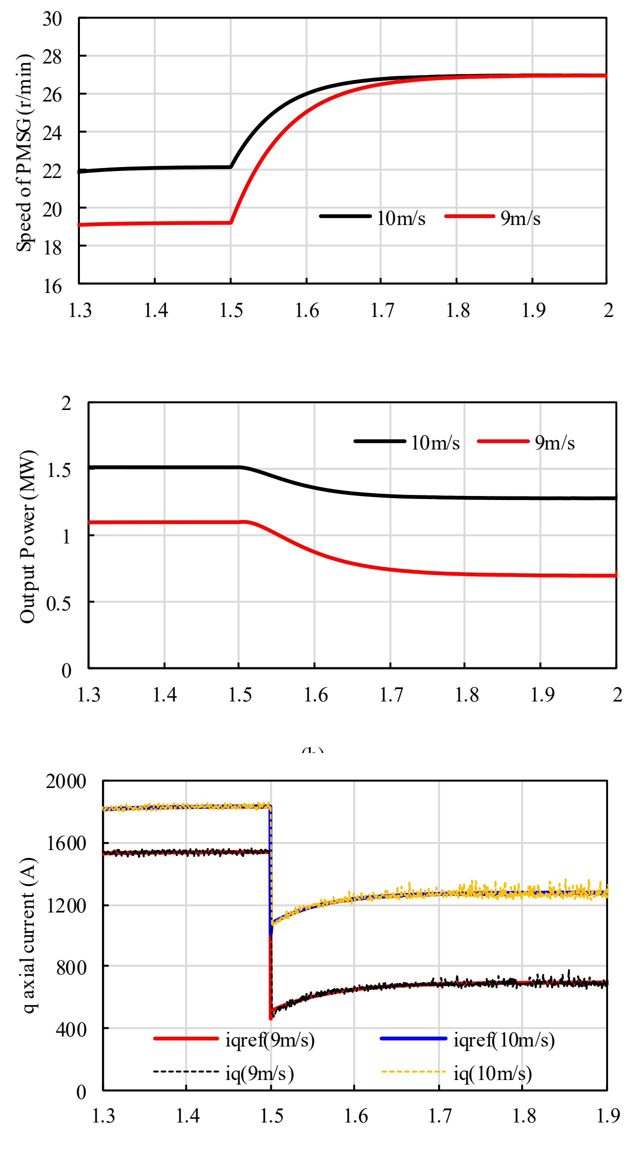


Fig. 11. Output power of simulated wind turbine.

Considering the unbalanced wind speed imposing to multiple units in the same wind farm, the overspeed power shedding operation simulations at rated wind speeds of 10m/s and 9m/s for DDWPS are carried out respectively, as shown in Fig. 12. Before 1.5s, the DDWPS operates along the MPPT curve. And then enters the overspeed power shedding situation until the rotor speed reaches the allowable maximum.

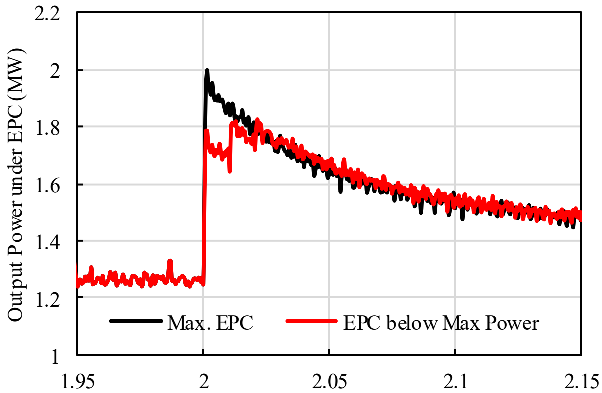
It can be illustrated from Fig. 12 that the overspeed power shedding rates are 85% and 63% when wind speeds are 10m/s and 9m/s respectively by controlling the electromagnetic torque current i_q. From the simulated DDWPS, when wind speed is at rated 10m/s, the output power can be reduced from 1.5MW to 1.28MW. The decreased power is about 0.22MW. And when wind speed is at 9m/s, the output power can be reduced from 1.1MW to 0.7MW. The decreased power is about 0.4MW. Besides, according (4), the rotor kinetic energies stored in these processes can be calculated as 46.5kJ at 10m/s and 69.8kJ at 9m/s respectively. It is concluded that the more power shedding can be realized and more kinetic energy can be stored when the DDWPS operate below the rated wind speed. Therefore, for a wind farm with multiple units under different wind speed conditions, the optimal overspeed power shedding operation combinations exist to satisfy the grid power requirement as well as the maximum rotor kinetic energy storage.



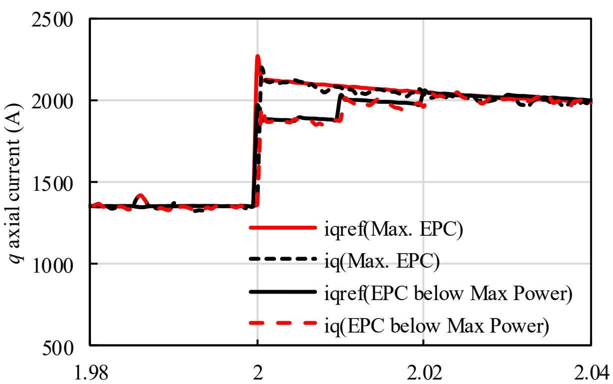
(c)

Fig. 12. Overspeed power shedding operation simulation with wind speed at 10m/s and 9m/s respectively. (a) rotation speeds of PMSG. (b) output powers of wind turbine. (c) q axial currents of PMSG.

The emergency active power increase control strategies are simulated under wind speed 10m/s. The simulation results are shown Fig. 13(a) and (b), which illustrate that the response time of EPC by releasing rotor kinetic energy under overspeed condition are within 1ms to satisfy the EPC requirement. From Fig. 13(a), the output active powers by releasing the rotor kinetic energy are plotted. The maximum output power under EPC when DDWPS operates at maximum overspeed power shedding condition is about 2MW, which is limited by the IGBT performance. However, the duration time of the maximum output active power is too short, which is about 5ms. Moreover, if the output active power is limited to 1.8MW under EPC, the duration time can be largened to 30ms. Fig. 13(b) shows the electromagnetic torque current in both control strategies. Therefore, when multiple units of a wind farm are under EPC, there is also an optimal combination of active power output and duration time.



(a)



(b)

Fig. 13. Output active power and q axial current under EPC. (a) output power. (b) q axial current.

V. Conclusion

The emergency power increase operation mode for DDWPS is studied in this paper. Combining with the PMS, the information interaction time for EPC can be shorten. In order to reverse the active power for DDWPS with the constraint of EPC requirement, the overspeed power shedding operation is adopted. And then the corresponding control strategy for machine-side converter is analyzed. Based on it, a 1.5MW DDWPS simulation model with PMSG is built by Matlab/Simulink. Moreover, the overspeed power shedding operations under different wind speeds are analyzed. The results indicate that the generator unit runs below rated wind speed can gained more power shedding rate and rotor kinetic energy. Besides, the EPC modes are compared considering the different output power increase requirements. The simulation results show that the emergency active power surges within 1ms to the EPC requirement by releasing the rotor kinetic energy. The maximum output power during EPC is determined by the limits of IGBT and duration time. Therefore, when multiple units of a wind farm are controlled for EPC, the combinations can be optimized among the overspeed power shedding rate, the active power output and the duration time of EPC, which provides a theoretical basis for the future EPC multi-objective optimization of wind farms.

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