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Improved Grid Voltage Control Strategy for Wind Farms with DFIGs Connected to Distribution Networks

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Abstract

This paper presents an improved grid voltage control strategy for wind farms with doubly-fed induction generators (DFIGs) connected to distribution networks based on an analysis of the operation limits of DFIG systems. A modified reactive power limit calculation method in different operation states is proposed and a reactive power control strategy during grid voltage dips/rises is further discussed. A control strategy for compensating unbalanced grid voltage, based on DFIG systems, by injecting negative sequence current into the grid through the grid side converter (GSC) is proposed. In addition, the negative current limit of the GSC is discussed. The distribution principle of the negative sequence current among the different DFIG systems in a wind farm is also introduced. The validity of the proposed voltage control strategy is demonstrated by Matlab/Simulink simulations. It is shown that the stability of a wind farm and the power grid can be improved with the proposed strategy.

Key words: Distribution networks, Doubly fed induction generator wind farm, Grid voltage control, Negative sequence voltage compensation

I. INTRODUCTION

Today most wind farms are located in remote areas that are far from the main network. As a result, they usually require long-distance transmission lines to connect to it. Wind farms connected to distributed networks are prone to grid faults such as voltage dips/rises or unbalanced faults [1],[2]. The presence of wind farms in such weak systems raises serious concerns about system stability, voltage regulation, and post-fault power swings.[3] With the increasing penetration of wind farms, new wind turbine installations should be capable of regulating voltage or reactive power to maintain a smooth voltage profile at the point of interconnection under normal conditions to protect against voltage flickers caused by wind gusts. In addition, they should also be capable of tolerating system disturbances like voltage rises/dips and unbalanced faults caused by different phase impedances, asymmetric faults and loads, etc [4].

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The AC excited Doubly Fed Induction Generator (DFIG) power scheme is one of the most widely used schemes. This scheme can keep a constant frequency under variable wind speed by using converters of low power capacity. This kind of system can be used as either an active resource or as a reactive resource when needed because of the decoupled control of the active and reactive power [4]. As a reactive resource, the DFIG system can adjust the voltage within a threshold at the connection point by changing the reactive power delivered to the grid [5],[6].

In [7]-[9], some reactive power strategies are proposed to improve the LVRT ability of DFIG systems. However, those strategies can not compensate the negative sequence voltage in a network when unbalanced faults occur. This can cause over-current, overheating, and extra mechanical stresses due to voltage, current, power and torque fluctuations. Therefore, compensation control for the unbalanced faults is necessary to improve wind generation system stability. In [10]-[12], rebalancing strategies are proposed to eliminate torque and power fluctuations. However, they fail to consider how to contribute to network support, which means they can not eliminate the negative voltage sequence in the grid.

In this paper, a new voltage control strategy for DFIG systems is presented based on the conventional DFIG control

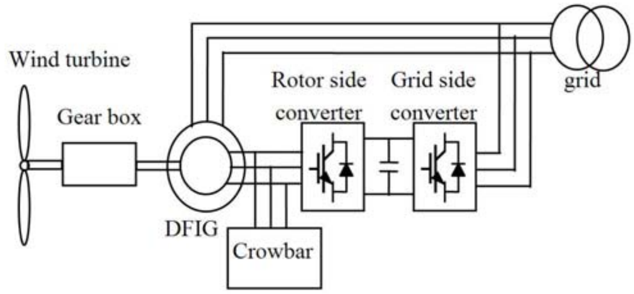


Fig. 1. Schematic diagram of a DFIG-based generation system.

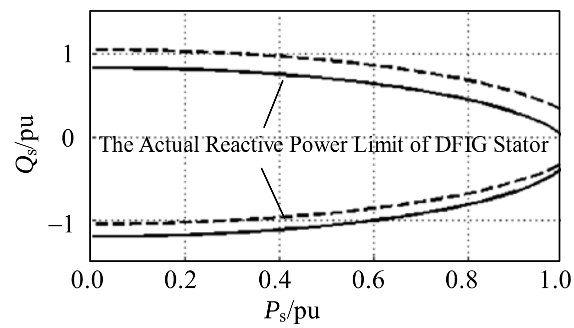


Fig. 2. Reactive power generation capability of DFIG stator.

strategy, which can compensate the negative sequence voltage by injecting negative sequence current into the grid. The reactive power capacity of DFIG systems is analyzed according to imposed power limitations and the distribution algorithm of the reactive power among DFIG systems is also presented. Furthermore, both the negative compensation limit and the distribution algorithms of the negative sequence current are analyzed for an unbalanced grid situation. The simulation results show that the voltage control strategy presented in this paper can improve the stability of the voltage and the performance of wind farms.

II. REACTIVE POWER LIMITS OF A DFIG

Control strategies of reactive power have been proposed in [7]-[9] for DFIG-based wind farms. According to the DFIG system configuration shown in Fig. 1, a DFIG system can transmit reactive power into the power grid through the stator and the grid side converter (GSC). Therefore, both the stator and the GSC reactive power limits should be considered when calculating a generator's reactive power limit.

When calculating a DFIG's stator reactive power limit, the power capacity of the stator should be considered first. If the stator active power P_s is given, the stator reactive power limit can be calculated according to both the stator power limitation and the rotor current limitation. When considering the stator's power limitation, the maximum reactive power Q_{smax} generated/absorbed by the stator can be expressed in its absolute value:

$$Q_{smax} = \sqrt{S_{smax}^2 - P_s^2} \tag{1}$$

where S_{smax} is the maximum apparent power of the DFIG, which is usually calculated by $S_{smax} = 1.05P_{smax}$, and P_{smax} is the maximum active power generated by the stator.

According to the power relationship between the stator and the rotor of a DFIG, a percentage of the stator reactive power, which can be considered as the slip reactive power, is delivered through the rotor side converter (RSC) [14]. The relationship between rotor current and the stator power can be written as follows:

$$\begin{cases} i_{rd} = \dfrac{L_s}{L_m}\dfrac{2P_s}{3U_s} \\ i_{rq} = -\dfrac{L_s}{L_m}\dfrac{2Q_s}{3U_s} - \dfrac{U_s}{\omega_s L_m} \end{cases} \tag{2}$$

where U_s is the stator peak voltage which equals the grid peak voltage when the stator is connected to the grid, i_{rd} and i_{rq} are the d and q axis components of the rotor current under the synchronous reference frame.

When considering the RSC current limit, inequality (3) can be obtained based on (2):

$$\left(\frac{L_s}{L_m}\frac{2}{3U_s}P_s\right)^2 + \left(\frac{L_s}{L_m}\frac{2}{3U_s}Q_s + \frac{U_s}{\omega_s L_m}\right)^2 = i_r^2 \le I_{r\max}^2 \tag{3}$$

where $i_r^2 = i_{rd}^2 + i_{rq}^2$ and I_{rmax} is the current limit of the RSC.

When the stator active power P_s is given, the maximum reactive power generated and absorbed by the stator can be derived based on (3) respectively as:

$$\begin{cases} Q_{smax\_out\_r} = -\dfrac{3U_s^2}{2\omega_s L_s} + \sqrt{(\dfrac{3}{2}\dfrac{L_m}{L_s}U_s I_{rmax})^2 - P_s^2} \\ Q_{smax\_in\_r} = -\dfrac{3U_s^2}{2\omega_s L_s} - \sqrt{(\dfrac{3}{2}\dfrac{L_m}{L_s}U_s I_{rmax})^2 - P_s^2} \end{cases} \tag{4}$$

where $Q_{smax\_out\_r}$ is the maximum reactive power generated by the stator, and $Q_{smax\_in\_r}$ is the maximum reactive power absorbed by the stator, both of which are calculated according to the RSC current limit I_{rmax}.

After both the stator power capacity and the RSC current limit are considered, the stator reactive power limit is obtained as follows:

$$\begin{cases} Q_{smax\_out} = \min(Q_{smax}, Q_{smax\_out\_r}) \\ Q_{smax\_in} = \max(-Q_{smax}, Q_{smax\_in\_r}) \end{cases} \tag{5}$$

where Q_{smax_out} and Q_{smax_in} are the reactive power limit generated and absorbed by the stator of the DFIG respectively.

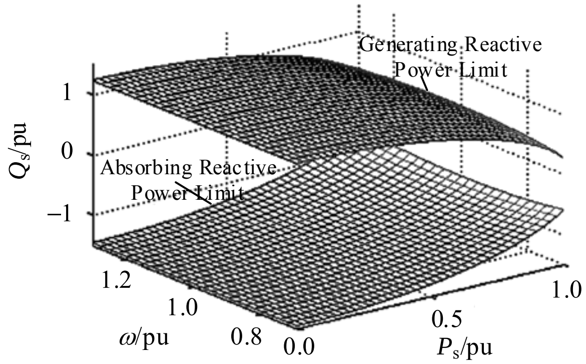


Fig. 3. Reactive power generation capability of the DFIG system under different operation state.

Plots of the stator generating/absorbing reactive power limit versus the stator active power are drawn in Fig. 2. The solid curve in the picture shows this relation when the RSC current limit is considered, while the dotted line describes the relationship when the stator reactive power limit is considered. Fig. 2 shows that the maximum reactive power generated by the stator is decided by the limit of the rotor current, while the maximum reactive power absorbed is decided by the limit of the stator power. Therefore, the actual reactive power limit of the DFIG stator is obtained as marked in the picture.

The reactive power limit of the GSC is only dependent on its power capacity. In the DFIG system, the grid converter only delivers the slip active power under the unity power factor condition, which can be calculated by multiplying the slip ratio *s* and the active power generated by the stator. If the maximum apparent power of the GSC is expressed by S_{cmax}, the generating/absorbing reactive power limit of the GSC Q_{cmax} can be obtained in its absolute value as follows:

$$Q_{\mathrm{cmax}} = \sqrt{S_{\mathrm{cmax}}^2 - s^2 P_{\mathrm{s}}^2} \tag{6}$$

As mentioned above, *s* is the slip ratio.

Taking the stator and the GSC reactive power limit together, the reactive power limit of the DFIG system can be expressed as:

$$\begin{cases} Q_{\mathrm{max\_out}} = Q_{\mathrm{smax\_out}} + Q_{\mathrm{cmax}} \\ Q_{\mathrm{max\_in}} = Q_{\mathrm{smin\_in}} - Q_{\mathrm{cmax}} \end{cases} \tag{7}$$

where $Q_{\mathrm{max\_out}}$ and $Q_{\mathrm{max\_in}}$ are the reactive power limit generated and absorbed by the DFIG system respectively.

Based on (7), the reactive power generation capability of the DFIG system under different operation states, which is determined by the stator active power and the rotating speed of the DFIG, is depicted in Fig. 3.

According to Fig. 3, the absorbing reactive power limit of the DFIG system is higher than the generating limit due to the exciting power of the motor, which is absorbed through the RSC. In addition, the reactive power limit becomes smaller and smaller as the stator active power P_{s} increases. When the stator active power P_{s} is given, the reactive power limit of the DFIG system maximizes when the rotating speed equals the synchronous speed.

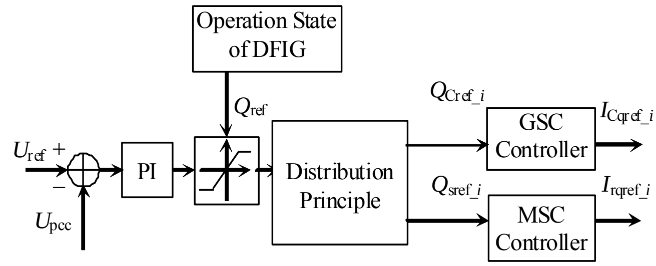


Fig. 4. Voltage control diagram of DFIG wind farms.

III. Voltage Control Strategy of DFIG Wind Farm

The voltage control diagram of a DFIG wind farm is depicted in Fig. 4. As can be seen, a proportional-integral controller is introduced in the voltage control scheme. According to the reference voltage value set by the upper controller and the sampling voltage value of the connected point to the grid, the PI controller generates the reactive power reference value as its output, which is limited by the reactive power limit decided by the operation state of the DFIG system. The specific design process of the PI controller, such as how to design the coefficients of the proportion and the integrator, is given in [9],[10]. In this paper, the reference voltage value is set to the normal grid voltage.

The distribution principle of the reactive power has been proposed in [13]. In this paper, the reactive power is distributed among the different DFIG systems in a wind farm by the proportion principle referring to the power limit of each system. In this way, the reactive power capability of each DFIG system can be fully exerted without exceeding the power limit. The specific expression can be obtained as follows:

$$Q_{giref} = \frac{Q_{gi\,\mathrm{max}}}{Q_{total\,\mathrm{max}}} Q_{gref} \tag{8}$$

where Q_{giref} is the reactive power reference value for DFIG system No. *i*, Q_{gimax} is the reactive power limit of DFIG system No. *i*, $Q_{\mathrm{total\ max}}$ is the sum of Q_{gimax}, and Q_{gref} is the reference value calculated by the PI controller mentioned above.

The distribution principle of the reactive power in one DFIG system should also be discussed. Between the DFIG stator and the GSC, the DFIG stator should be given priority when distributing the reactive power in one DFIG system. This is because the stator reactive power is actually regulated by the RSC, which only needs to deliver the slip reactive power. To transmit the same reactive power in the stator and in the GSC, the reactive power regulation is smaller in the RSC than in the GSC. As a result, all of the reactive power needed in the DFIG system should be distributed to the stator as long as the stator power limit admits. Under this condition, the grid converter will deliver the slip active power and achieve unity power factor. If the reference reactive power of the DFIG system exceeds the stator limit, the rest of the reactive power will be delivered by the GSC until it reaches the GSC reactive power limit mentioned above.

In the control system, all of the controllers use the PI structure, and the voltage and current are calculated under the positive synchronous reference frame (SFR), which is oriented to the grid voltage vector to realize the decoupled control of the active power and the reactive power. The stator reactive power can be regulated by changing the reactive current of the RSC and the GSC's reactive power can be regulated by changing the reactive power current of the GSC [14].

IV. Negative Sequence Voltage Control of Wind Farms

A. The Negative Sequence Compensation Principle

When unbalanced faults occur in the power grid, there will be negative sequence voltage in the grid voltage, which will heavily impact the performance of a DFIG system. A small negative sequence voltage can produce a high current both in the stator and the rotor of the DFIG, which will probably exceed the current limit or cause high temperatures if ignored [2]. Also, it will cause fluctuations of the electromagnetic torque and can even result in mechanical damage to the system. In addition, an over current can be produced in the GSC and the DC bus voltage will fluctuate due to the negative sequence voltage.

If an unbalanced faults occur, it is usually necessary to introduce vector control under the dual synchronous dq reference frame. This will control the positive and negative current under the respective frame, to ensure stability of the DFIG system. Different principles for setting the negative current reference value have been developed in [15-16]. As a result, the specific design process for the control system is not discussed in this paper.

There are many benefits to compensating the negative sequence voltage. The performance of the DFIG system would be improved by eliminating the impacts caused by the negative sequence voltage mentioned above. In addition, the negative sequence voltage at the connected point can be compensated by injecting the corresponding negative sequence current produced by the control system. Furthermore, the controllable operation range can be expanded after the negative sequence voltage is compensated.

Theoretically, the negative sequence current can be injected into the grid through either the stator or the GSC. However, the machinery oscillation of the DFIG system will be amplified by electromagnetic torque fluctuations if the negative sequence current in the stator increases. The GSC can produce the negative current without causing any oscillations in the DFIG due to the existence of the DC bus. Therefore, the negative current can only be produced by the GSC for compensation.

The DC bus voltage will fluctuate due to the negative sequence current injected through the GSC. However, if it is controlled within a certain scope, the bus voltage fluctuation has little impact on the performance of the DFIG system.

B. The negative sequence current capacity of the grid converter

There are two main factors which limit the negative sequence current control capability: the current limit of the GSC and the bus voltage limit.

Under unity power factor conditions, the GSC handles the slip active power, corresponding the active positive sequence current i_{Cd}^{+}. Meanwhile the reactive positive sequence current i_{Cq}^{+} should also be considered if the reactive power is distributed to the GSC. The positive current can be expressed as :

$$i_{\mathrm{C}}^{+} = \sqrt{(i_{\mathrm{Cd}}^{+})^2 + (i_{\mathrm{Cq}}^{+})^2} \tag{9}$$

Based on (9), the negative current limit is provided by:

$$-(i_{\mathrm{Cmax}} - i_{\mathrm{C}}^{+}) \le i_{\mathrm{Cdq\text{-}}}^{-} \le (i_{\mathrm{Cmax}} - i_{\mathrm{C}}^{+}) \tag{10}$$

Where i_{Cmax} is the current limit of the GSC; $i_{\mathrm{Cdq\text{-}}}^{-}$ is the limit of the negative sequence voltage for the GSC.

It is necessary to leave some margin for the bus voltage when the control system is designed. The bus voltage fluctuates when negative current is injected into the grid through the grid converter or when the active power transmitted in the DC bus fluctuates. The maximum fluctuation value of the bus voltage expressed by $U_{\mathrm{dc\_max}}$ should be set due to the voltage limit [17]. The active power fluctuation in the DC bus is provided by $p_{\mathrm{dc\_f}}$ p_{c} p_{r}, where p_{c} and p_{r} are the active power fluctuation in the GSC and the RSC respectively. The corresponding DC bus voltage is:

$$\Delta u_{\mathrm{dc\_f}} = \frac{\Delta p_{\mathrm{dc\_f}}}{C_{\mathrm{dc}} U_{\mathrm{dc}}} \tag{11}$$

To ensure the DC bus voltage limit and system stability, the following inequality should hold all the time:

$$\Delta u_{\mathrm{dc\_f}} \le \Delta u_{\mathrm{dc\_max}} \tag{12}$$

C. The compensation control for the negative sequence voltage

A negative voltage control diagram of a DFIG wind farm is depicted in Fig. 5. Because the negative sequence value is not in phase with the positive sequence, the calculation of the negative value should be conducted under the negative SFR. The negative sequence voltage is measured by a delayed signal cancellation (DSC) controller in the negative SFR. The negative sequence current in the negative SFR is measured by

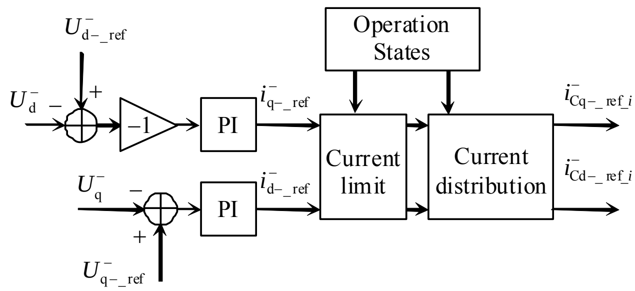


Fig. 5. Negative voltage control diagram of DFIG wind farm.

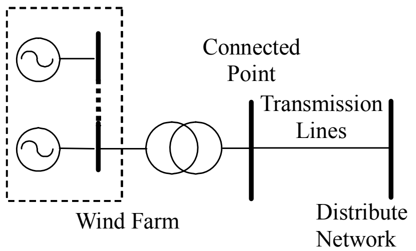


Fig. 6. Circuit diagram of DFIG wind farm and network.

eliminating the negative sequence with a 120-Hz notch filter. [18] The same methods are used to detect the positive sequence.

The distribution principle of the negative current among the different DFIG systems is similar to that of the reactive power. The concrete expression is:

$$i^-_{\mathrm{ref}\_i} = \frac{i^-_{\max\_i}}{i^-_{\max}} i^-_{\mathrm{ref}} \tag{13}$$

where $i^-_{\mathrm{ref}\_i}$ is the negative current distributed to system No. i, i^-_{ref} is the negative current of all the DFIG systems, $i^-_{\max\_i}$ is the negative current limit of system No. i, and $i^-_{\max}$ is the sum of $i^-_{\max\_i}$.

V. SIMULATION STUDIES

In order to verify the proposed voltage control strategy, simulations were carried out using Matlab/Simulink. The wind farm is simulated as a lumped 9MW model containing 6 DFIGs rated at 1.5MW. A connection diagram is depicted in Fig. 6, in which the wind farm is connected to the distribution network.

The simulation parameters for each of the DFIGs are given in TABLE I. The power capacity of both converters is 600 kW, 40% of the generator's rated power. The switching frequency for both converters is 2 kHz. The effect of the geographic position of the wind power units on wind speed is neglected and the wind power absorbed by each of the DFIG systems is only related to the machine type. The initial rotating speed of each of the DFIGs is set at 1.25pu, which means that the system operates under the super-synchronous condition. The other limit values in the controller are calculated according to the expressions above. In the simulation results, the DFIG base value is the rated value shown in table I. The DC voltage of the converter base value is 1100V. The actual limits of the active power and the negative sequence current are 90% of the calculated values for the dynamic safety margin of DFIG systems. As mentioned above, all of the vectors are oriented to the grid voltage in the control system.

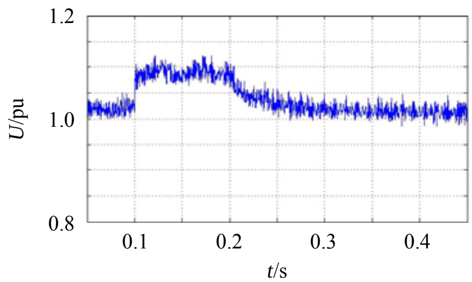
TABLE I

MOTOR SPECIFICATIONS

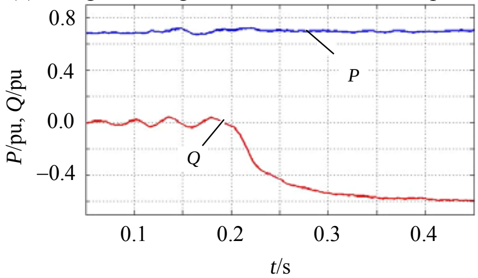
Rated Power	1.5MW
Rated stator voltage	690V
Rated frequency	50 Hz
Stator/Rotor turns ratio	1:3
Stator resistance	0.00835pu
Rotor resistance	0.00828pu
Stator leakage inductance	0.171pu
Rotor leakage inductance	0.156pu
Magnetizing inductance	5.42pu
Rated rotating speed	1500rpm
Lumped inertia constant	6s
Number of pole pairs	2
Transformer(V_1:V_2/Z_T)	110kV:690V/10%
Network (V_N/SCL)	110kV/400MVA

Fig. 7 shows the voltage recovering waveforms of the voltage control under voltage rise conditions. The DFIG voltage at the grid connected point rises by 8 percents at 0.1s and the voltage control system is started at 0.2s. Fig. 7(a) shows the voltage value (pu) at the connected point and Fig 7(b) shows the active and reactive power (pu) of each of the DFIG systems. The output Q_{giref} of the voltage control system shown in Fig. 4 is -0.7pu and the adsorbing reactive power limit of the stator decided by the operation state is -0.8pu. According to the reactive power distribution principle in the DFIG system, all of the reactive power needed can be adsorbed through the DFIG stator and the GSC is not influenced. As shown in Fig. 7(a), the grid voltage recovered to its normal value in around 0.3s.

Fig. 8 shows the voltage recovering waveforms of the voltage control under voltage sag conditions. The grid voltage at the connected point drops by 0.15pu and the voltage control system is started at 0.2s. The calculated value of the reactive power needed is 1.32pu. However, the reactive power limit of the stator is only 0.56pu at this time, and the reactive power limit of the GSC is only 0.3pu. Therefore, the maximum reactive power generated by the DFIG system is only 0.86pu, which is smaller than the demand. As a result, the reactive power generated by the DFIG system is 0.86pu and the grid voltage is recovered to 0.95pu at about 0.25s.

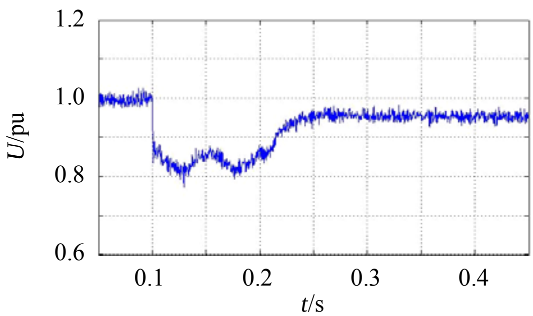


(a) The grid voltage at the DFIG connected point.

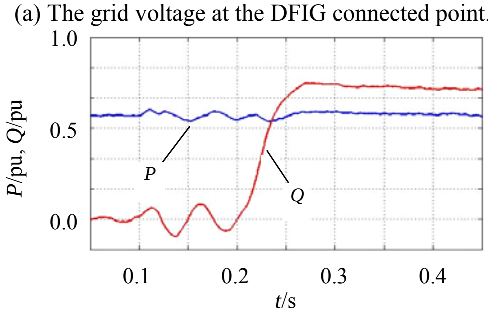


(b) The active and reactive powers of each DFIG system.

Fig. 7. Waveforms of voltage control under voltage rise conditions.

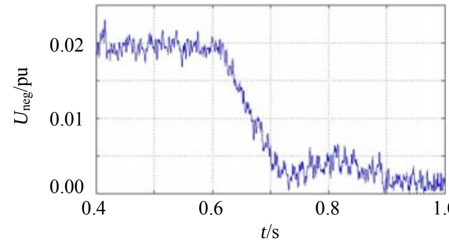


(a) The grid voltage at the DFIG connected point.

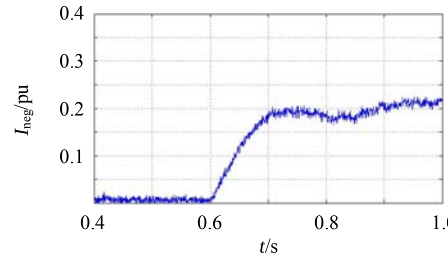


(b) The active and reactive powers of each DFIG system.

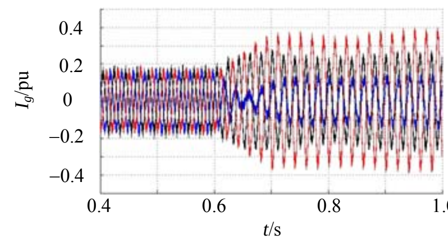
Fig. 8. Waveforms of voltage control under voltage sag conditions.



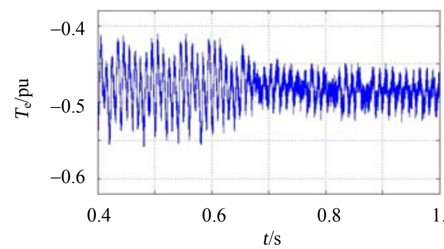
(a) The negative voltage value at the DFIG connected point.



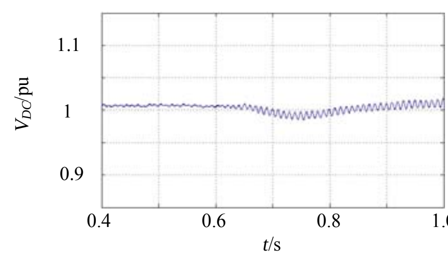
(b) The negative current value injected into the grid.



(c) The actual current waveform in the grid converter.



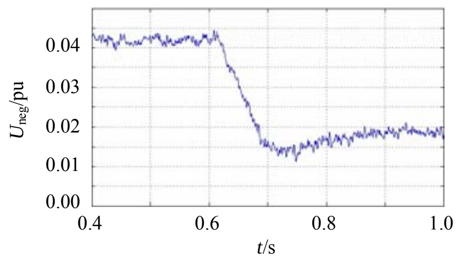
(d) The electromagnetic toque of the DFIG.



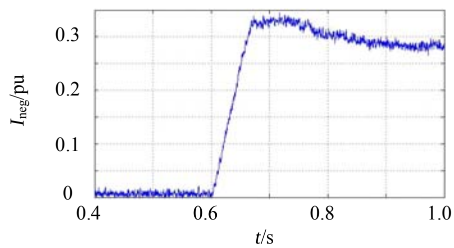
(e) The DC Voltage of converter

Fig. 9. Waveforms of voltage control under voltage unbalanced conditions(0.02pu).

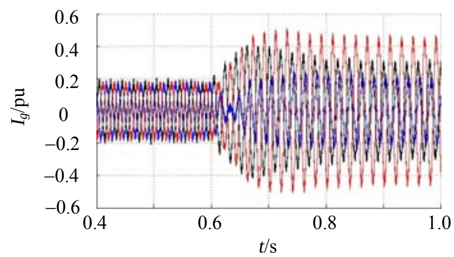
Fig. 9 shows the waveforms of the voltage control under voltage unbalanced conditions. The negative sequence voltage (pu) is 0.02pu before 0.6s according to Fig. 9(a). The compensation control system is started at 0.6s and the negative current value injected into the grid through the GSC is depicted in Fig. 9(b). Fig. 9(c) shows the actual current waveform in the grid converter. Fig. 9(d) shows that the electromagnetic torque fluctuation of the DFIG is nearly eliminated after the compensating control is applied. In this rebalancing control process, no compensation control is implemented in the RSC to avoid machinery oscillations. Fig. 9(e) shows the DC voltage of the converter. According to Fig.



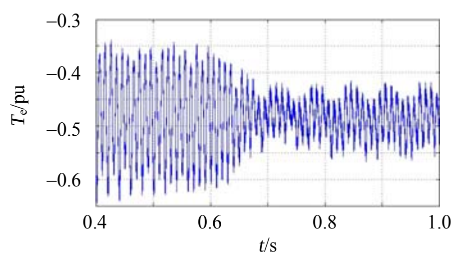
(a) The negative voltage value at the connected point.



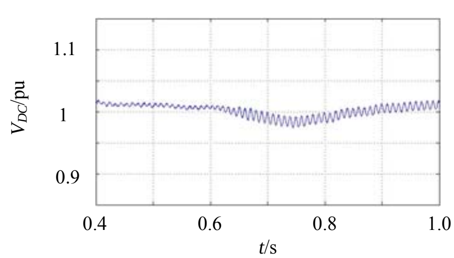
(b) The negative current value injected into the grid.



(c) The actual current waveform in the grid converter.



(d) The electromagnetic toque of the DFIG.



(e) The DC Voltage of converter.

Fig. 10. Waveforms of voltage control under voltage unbalanced conditions (0.042pu).

9, the negative sequence voltage is eliminated nearly to zero after the compensation current is injected into the grid, which verifies the effectiveness of the compensation control strategy.

Fig. 10 shows the compensation control process when the negative sequence voltage (pu) is 0.042pu. Because the negative current demand exceeds the limit of the converter current, a 0.02pu negative sequence voltage still exists. Fig. 10(c) shows the actual current waveform in the grid converter. To verify the stability of the negative voltage controller, the controller parameter is adjusted so that the negative current is regulated more quickly when compared to Fig.9. Fig. 10(d) shows that the electromagnetic torque fluctuation of the DFIG is eliminated to a great extent after the compensating control is applied. Fig. 10(e) shows the DC Voltage of the converter, and the voltage fluctuation is larger than that depicted in Fig. 9(e). According to Fig. 10, the negative sequence voltage is reduced after the compensation current is injected into the grid.

VI. CONCLUSION

A new voltage control strategy is proposed for the wind farms connected to distribution networks according to the characteristics of the DFIG system. A voltage control strategy by changing the system reactive power and the negative sequence voltage compensation strategy are included in this new method. According to the theory analysis and simulation results, the following conclusions can be made:

a) The voltage control capability of DFIG wind farms is closely related to the operation state of the DFIG. The control limit of the reactive power and the negative sequence current are analyzed and the distribution principle is also discussed in this paper.

b) By controlling the reactive power, the grid voltage can recover to its normal value when the grid voltage fluctuates within its rated limit.

c) The negative sequence voltage at the connected point in an unbalanced situation can be compensated to eliminate or reduce the negative impacts on the DFIG system.

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