Influence of SDR Resistance Value on Low Voltage Ride Through Capability of Doubly Fed Induction Generator

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Abstract: For the increasing rate of wind generation capacity, the grid codes for grid connected wind turbines evolve continuously and demand that the wind power generator has to ride through the grid faults. In this paper, the new LVRT scheme which based on SDR is presented. Analyzing the new LVRT topological structures of DFIG with SDR circuit topology and the effect of the DBR circuit during grid voltage dip, The mathematical models of the equivalent circuit of DFIG power system during normal voltage and grid voltage dip are established. Through analyzing the mathematical models of DFIG power system during normal voltage and grid voltage dip, the feasibility of the new LVRT scheme is verified. The DFIG power system mode is built with Matlab/Simulink to validate its effectiveness. Simulation results show that DFIG can operate in connection with grid to stabilize the grid voltage during fault and SDR resistance selection could guarantee to limit the rotor current and consider rotor overvoltage.

1. Introduction
Because of its cleanliness, wind energy is getting more and more attention. By the end of 2017, the installed capacity of wind power in China had reached 188 million kilowatts. With the rapid development of wind power generation technology, wind power will account for more and more of the power grid capacity. However, since 2011, there have been more than 10 breakaway failures of wind power above 500MW, which has seriously affected the safe operation of power system. Based on the analysis of previous large-scale fan delamination accidents, it is shown that the main reason for large-scale cascading decoupling of wind turbines is that wind turbines do not have the low voltage ride through capability or the low voltage ride through ability is unreliable[1]. Especially, since the doubly-fed asynchronous wind turbine is connected to the power grid by the stator side converter, and the capacity of the converter is relatively small comparing with the permanent magnet synchronous wind turbine with full power converter, the realization of LVRT is more complicated[2-4].

At present, there are two main types of LVRT solutions for doubly-fed asynchronous wind turbines. One is to improve the control strategy of wind turbine converter or propeller system without adding hardware[5]; another method is to add hardware circuits, such as grid-side dynamic reactive power compensator, FACTSs, auxiliary resistance of flexible AC transmission system[6-10]. In the first
low-voltage ride through solution, the converter needs to increase the converter capacity to achieve the control goal. But in normal operation, most of the capacity will be idle. For the control variable propeller system, because of the long pitch adjustment time, sometimes the pitch angle can not respond quickly according to the need. In the second kind of low-voltage ride through solution, crowbar circuit protection scheme is the most common. However, after the operation of crowbar, the rotor converter stops working, which increases the reactive power burden of the power network that is not conducive to the restoration of the grid voltage[11]. At the same time, it needs complicated control logic to switch between different operation states of double-fed machine before and after failure[12].

This paper introduces a new LVRT method for doubly-fed asynchronous wind turbine based on SDR: the dynamic resistance connected in series between DC capacitor and rotor inverter. The dynamic resistance is composed of a bi-directional thyristor switch and a resistor in parallel. First, the topology and working principle of the new LVRT method are described, then the mathematical model of the new inverter is established. Finally, the DFIG simulation model of 1.5MW is established based on Matlab/Simulink. The fault characteristics of doubly-fed asynchronous wind turbine with or without SDR are analyzed, and the influence of SDR with different resistance on the operation of doubly-fed asynchronous generator under voltage drop is analyzed to prove the correctness and effectiveness of the new method.

2. New Topology structure and theoretical Analysis of LVRT based on SDR

2.1. DFIG topological Mechanism with SDR

After the voltage drop of the power network, the rotor winding of the DFIG induces the very big fault current, the rotor fault current flows through the DC capacitor of the converter, causing the DC bus voltage to fluctuate. At the same time, the reduction of the grid voltage leads to the weakening of the ability of the grid side converter to control the DC bus voltage, so the excess energy of the rotor side can not be transferred to the power network in time, which results in the DC bus voltage rising rapidly and endangers the safety of the DC bus capacitance. Therefore, measures must be taken to consume the excess energy of the rotor side and prevent the DC bus voltage from being too high. In this paper, a low voltage ride through topology of DFIG based on SDR is adopted, which is different from that of crowbar protection, as shown in figure 1. Its topological structure is composed of SDR circuit connected in series between the rotor converter and DC bus of wind turbine, And the SDR circuit is composed of SDR resistor and bidirectional thyristor switch. The bi-directional thyristor switch in the SDR loop is on or off through the software instruction control. When the wind turbine is in normal operation, the bidirectional thyristor is closed and the current does not flow through the SDR resistor. And the DC bus of the converter fluctuates greatly when the power network fails. Using hysteresis principle (hysteresis threshold voltage) disconnect the bi-directional thyristor switch. The current flows through the SDR resistor and the SDR resistor continuously consumes the ability to transfer from the generator side to the DC busbar and maintains the DC bus voltage stability until the grid voltage returns to normal.

![Figure 1. Topology structure Diagram of low Voltage traversing Scheme based on SDR](image)

2.2. Mathematical Model and Analysis of New DFIG Converter

Figure 2 shows a new converter structure containing SDR.
Figure 2. New rotor converter structure

Assuming that the power devices in figure 2 are ideal switching devices, the voltage equation can be obtained from Kirchhoff's law when the bi-directional thyristor switch in the SDR loop is turned on:

\[
\begin{align*}
S_{U_a} &= U_{on} + i_{wa} R_{sd} + R_{ia} j_{ra} + d\psi_a / dt \\
S_{U_b} &= U_{on} + i_{wb} R_{sd} + R_{ib} j_{rb} + d\psi_b / dt \\
S_{U_c} &= U_{on} + i_{wc} R_{sd} + R_{ic} j_{rc} + d\psi_c / dt \\
\end{align*}
\]

(1)

\[
i_{SDR} = s_{ia} j_{ra} + s_{ib} j_{rb} + s_{ic} j_{rc}
\]

(2)

In the form: \(U_o\) is DC bus voltage of converter; \(U_{on}\) is the voltage between the neutral point O of rotor winding and the negative pole N of DC bus. \(R_{sd}, i_{sd}\) is SDR circuit resistance and current respectively; \(R_{ia}, R_{ib}, R_{ic}, i_{ia}, i_{ib}, i_{ic}\) is the rotor winding three-phase resistance and current, respectively; \(\psi_a, \psi_b, \psi_c\) is rotor winding three-phase flux chain. \(S_k (k = a, b, c)\) is the switching function of the ideal power device. When the upper arm of the rotor side converter is switched on, the lower arm is disconnected, \(S_k (k = a, b, c) = 1\). Upper arm disconnected, \(S_k (k = a, b, c) = 0\). Under normal and symmetric fault conditions, the generator is in a symmetric state and the combined (1), (2) can be obtained:

\[
U_{on} + i_{sd} R_{sd} = \frac{1}{3} (S_a U_{ac} + S_b U_{bc} + S_c U_{bc})
\]

(3)

If formula (3) is substituted separately with formula (1), then:

\[
AU_{ac} = R_{ai} j_{ia} + d\psi_{ia} / dt
\]

(4)

\[
A = \begin{bmatrix}
2 & 1 & 1 \\
3 & 3 & 3 \\
\end{bmatrix} ; \quad U'_{ac} = \begin{bmatrix} S_a U_{ac} & S_b U_{bc} & S_c U_{bc} \end{bmatrix} ; \quad R_{ai} = \begin{bmatrix} R_e & 0 & 0 \\
0 & R_e & 0 \\
0 & 0 & R_e \end{bmatrix} ; \quad \psi_{ia} = [\psi_a \ \psi_b \ \psi_c] ;
\]

The expression (4) of rotor converter in stationary coordinate system is transformed into synchronous rotation. Expressions under the coordinate system:

\[
\begin{align*}
U_\varphi &= R_\varphi j_\varphi + \omega_\varphi \psi_\varphi + d\psi_\varphi / dt \\
U_\psi &= R_\psi j_\psi + \omega_\psi \psi_\varphi + d\psi_\varphi / dt \\
0 &= R_\psi j_\varphi + d\psi_\varphi / dt
\end{align*}
\]

(5)

The mathematical model of the new rotor converter (5) and the rotor converter do not include SDR.
loop \( (R_{tor} = 0) \) mathematical model of rotor converter by contrast. After the series SDR loop between the rotor converter and the DC bus, the mathematical model of the rotor converter has not changed, that is, the control goal of the rotor converter is not changed. Therefore, the control strategy of the rotor converter including the SDR loop can make the DFIG control rotor current without changing the controller algorithm in the fault condition.

2.3. LVRT Control Strategy based on SDR
The effect of voltage drop on DC capacitance of converter and the working principle of new LVRT topology are analyzed in detail. The LVRT control strategy based on this topology is as follows: when a voltage drop occurs in the power network, the rotor energy flows through the rotor converter, and part of it is transferred to the power network by the power grid side converter. The other is DC busbar capacitor charging, which causes the bus voltage to rise too high quickly. When \( U_{dc} \geq U_{lim} \), SDR circuit bidirectional thyristor switch disconnected, SDR circuit resistor connected to DC bus circuit to release energy; when \( U_{dc} \) return to normal, SDR circuit bidirectional thyristor switch on, isolation of SDR circuit resistance, rotor converter return to original state.

3. Simulation Analysis
In order to verify the validity of the proposed scheme, a simulation model based on Matlab/Simulink is built. The model parameters are shown in Table 1.

| parameter                        | numerical value |
|----------------------------------|-----------------|
| rated capacity \( P_c \)         | 1500kW          |
| rated voltage \( U_N \)          | 690V            |
| Stator angular velocity \( \omega_s \) | 100 \pi rad/s |
| Rotor angular velocity \( \omega_r \) | 80 \pi rad/s  |
| stator resistance \( R_s \)      | 5e-2Ω           |
| rotor resistance \( R_r \)       | 5e-2Ω           |
| Stator leakage inductance \( L_{as} \) | 2e-5H         |
| Rotor leakage inductance \( L_{ar} \) | 1e-5H         |
| Stator and rotor mutual inductance \( L_m \) | 5e-3H         |
| number of pole-pairs             | 1               |
| Converter DC voltage             | 400V            |
| Rotor maximum current            | 1000A           |

3.1. Mathematical model simulation analysis
Assuming that the stator voltage drops to 20% rated voltage in 0.4s, the motor speed (40Hz) remains unchanged during the failure period. The straight and cross axis currents of the rotor are respectively \( i_s = 295A \) and \( i_q = 75A \). SDR circuit two-way thyristor switch 0.4021s off, SDR circuit resistance \( (R_{as} = 1\Omega) \) put in the circuit and stopped at 0.5s. Figure 3 shows the action of the SDR loop, figure 4 shows the rotor axis current \( i_s \) Alternating axis current \( i_q \).
As can be seen from figure 3, the rotor current is almost unchanged after the SDR circuit is switched on and off. This is because the control algorithm of the converter does not change when the SDR circuit is on and off. Therefore, the new mathematical model of converter proposed in this paper is feasible.

3.2. LVRT scheme simulation
To verify the effectiveness of the proposed low-voltage ride through control strategy, it is assumed that the fault conditions are: the stator voltage fell to 0 at 0.4 s and returned to normal. The fault lasted 200 ms, and the motor speed (40Hz) remained unchanged during the fault. The initial currents of the straight and cross axes of the rotor are respectively $i_{sr}=295A$ and $i_{qr}=75A$. The following two cases are compared and analyzed by simulation: ① when the voltage drops, no protective measures are made until the simulation is finished; ② SDR circuit resistance $R_{sd} = \Omega$ when the voltage drop is detected, the SDR bi-directional thyristor switch is on at 0.402 s and on 0.5 s, and the SDR bi-directional thyristor switch is on at 0.602 s and 0.8 s when the voltage returns to normal. During the fault period, the capacitor voltage of the converter is basically kept at 400 V.

There is no low voltage ride through protection under voltage drop. The rotor current of doubly-fed asynchronous wind turbine is shown in Figure 5. It can be seen from Figure 5 that the peak value of rotor current of wind turbine can reach 3~4 times of normal value without taking any protective measures in the case of voltage drop in power grid. What is more serious is that at the time of voltage recovery the rotor current will produce dozens or even twenty times the shock value of the normal current which will cause great harm to the rotor winding and the rotor converter of the wind turbine unit.

As can be seen from Figure 6, the peak value of rotor current is in the safe range when the converter adopts SDR circuit during the voltage drop. When the SDR circuit resistor is put in, the rotor current will decrease to the normal value quickly. When the voltage is restored, the maximum peak voltage of rotor current is only about 2 times of the normal value, and return to the normal state at about 0.1 s after the fault is eliminated. At the same time, because of the constant DC bus voltage, the reactive power of the wind turbine is basically unchanged and very stable during the fault period. The grid side converter can be controlled to provide reactive power to the power network to maintain the...
voltage stability of the network [8].

As shown in Figure 6, when the SDR resistance circuit is put into operation, the DC circuit voltage of the converter is increased. This means that the short-time overvoltage capacity of the converter should be improved properly by adopting the LVRT control strategy of the series SDR loop. This method is more economical than other methods which need to increase capacitor voltage to control rotor current. Moreover, the controller parameters of the rotor converter do not need to change before and after the operation of the bi-directional thyristor switch in the SDR loop, which reduces the complexity of the control logic of the converter. At the same time, the operation state of the doubly-fed asynchronous wind turbine is not changed under the condition of fault to avoid the negative effect of motor oscillation and reactive power consumption.

3.3. Analysis of the effect of different SDR resistors on the effect of LVRT

The effect of using SDR loop to realize LVRTR of wind turbine is closely related to the drop degree of voltage and the resistance of the circuit. The phase rotor currents are shown in Figure 7 and the line rotor voltages in Figure 8 when voltage drop to 15%.

![Figure 7. The rotor phase currents for 15% fault: the value of SDR is 0.5 Ω; 1 Ω; 3 Ω; 5 Ω.](image)

![Figure 8. The rotor line voltages for 15% fault: the value of SDR is 0.5 Ω; 1 Ω; 3 Ω; 5 Ω.](image)

From Figure 7, we could get: (a) during voltage dips, a larger value of SDR resulted in a smaller peak value of rotor currents. When SDRs were 0.5 Ω, 1Ω, 3Ω, 5Ω respectively, the maximum rotor fault currents were about 560A, 480A, 435A and 420A respectively. This also means that the larger SDR was, the less the rotor currents would increase after the activation of SDR; (b) during voltage recovery, a larger value of SDR also resulted in a smaller peak value of rotor currents. Also, a large value of SDR, such as 3Ω and 5Ω in this case, would make the maximum rotor currents during voltage recovery smaller than the maximum rotor currents during voltage dips; (c) a larger value of SDR would result in more harmonic components during SDR activation.

From Figure 8, we could get: (a) during voltage dips, a larger value of SDR resulted in a bigger peak value of rotor voltages. When SDR were 0.5 Ω, 1Ω, 3Ω, 5Ω respectively, the maximum rotor fault voltages were about 685V, 890V, 1590V and 2100V respectively; (b) during voltage recovery, a larger value of SDR also resulted in a bigger peak value of rotor voltages. However, a large value of SDR, such as 3Ω and 5Ω in this case, would make the maximum rotor voltages during voltage recovery smaller than the maximum rotor voltages during voltage dips; (c) a larger value of SDR would result in more harmonic components during SDR activation.

4. CONCLUSION

Based on the analysis of new LVRT topology and mathematical model of doubly-fed wind turbine
based on SDR, the simulation analysis of wind turbine operation under power network fault is carried out in this paper, and the following conclusions are drawn:

1. In the case of power grid voltage depth drop, the converter with SDR circuit can achieve the wind turbine low voltage traversing very well;
2. The resistance of SDR loop can not be too large or too small, so the optimal resistance should be chosen by taking into account the rotor current, rotor voltage and the stability of DFIG;
3. In order to improve the low voltage traversing ability of doubly-fed asynchronous wind turbine based on SDR, the short-time overvoltage capacity of converter should be improved.

References

[1] Monitoring of Wind Power Industry in 2014 (2014) [R].
[2] Shien He, Xinzhou Dong. Cause Analysis and Countermeasures of Large-scale Wind Turbine decoupling [J]. Power system Protection and Control, 2012N 40 (1): 131-137144.
[3] Yikang He, Peng Zhou. Review of low Voltage traversing Technology for variable Speed constant Frequency doubly-fed Asynchronous Wind Power Generation system [J]. Journal of Electrical Technology, 2009 N24 (9): 140-146. Hui Li, Liao Y, Yao J, et al. Comparative study on Crossing Technology Scheme of Doubly-fed Wind Turbine under asymmetric Power Grid Fault [J]. Journal of Chongqing University, 2011N 34 (9): 77-86.
[4] Li Hui, Liao Y, Yao J, et al. Comparative study on Crossing Technology Scheme of Doubly-fed Wind Turbine under asymmetric Power Grid Fault [J]. Journal of Chongqing University, 2011N 34 (9): 77-86.
[5] Yong Wang, Junjiang Zhang, Xiuhui Chai, et al. Electromagnetic transition process and control strategy of doubly-fed wind turbine under the condition of voltage drop in power grid [J]. Journal of Electrical Technology, 2011 1 0 26 (12): 14-19.
[6] Yuanwei Qin, Shuang Liu. Research on low Voltage traversing of Doubly-Fed Wind Power Generation based on Crowbar [J] .Power Electronics Technology, 2011 / 45 (7): 127-130.
[7] Xiaodong Zhu, Lei Shi, Ning Chen, et al. Low voltage traversing of doubly-fed wind turbine with resistance and exit time [J]. Power system Automation, 2010 / 10 34 (18): 29-36.
[8] Ma Wen-long. Application of Crowbar protection in power grid fault traversing of doubly-fed asynchronous wind power system [J] .Electric Power Automation equipment, 2011N31 (7): 127-130.
[9] Yang Jin, John E. Fletcher, and John O'Reilly, "A series-dynamic-resistor-based converter protection scheme for doubly-fed induction generator during various fault conditions," IEEE Trans. Energy Conversion, vol. 25, no. 2, pp. 422-431, Jun. 2010.
[10] Christian Wessels, Fabian Gebhardt, and Friedrich Willhelm Fuchs, "Fault ride-through of a DFIG wind turbine using a dynamic voltage restorer during symmetrical and asymmetrical grid faults," IEEE Trans. Power Systems, vol. 26, no. 3, pp. 807-815, Mar. 2011.
[11] W. J. Chen, David Atkinson, Hamza Chaal, and Milutin Jovanovic, "Experimental and simulation comparison for timer action crowbar of doubly-fed induction generator," in 2011 IEEE Asia-Pacific Power and Energy Engineering Conf.
[12] K. E. Okedu, S. M. Muyeen, Rion Takahashi, and J. Tamura," Participation of facts in stabilizing DFIG with crowbar during grid fault based on grid codes," in 2011 IEEE conference and exhibition, Dubai, pp. 365-368.