Overview of HVRT technical measures for DFIG

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Abstract. A With the rapid increase of the proportion of double-fed induction wind turbines generator (DFIG), higher requirements are proposed for the continuous operation ability under external power grid failure. The paper first analysed the transient process of DFIG in cases of power grid voltage surge, proposed the related standard requirements for high voltage ride-through ability of several countries, including China, and then summarized and evaluated the various high voltage ride-through technical measures suitable for DFIG, and finally forecasted the high voltage ride-through technology development trend.

1. Introduction
Northwest China Grid suffered large-scale trip accident of 598 turbines in 2011 which caused a loss of 837.34MW wind power, and made the whole grid frequency of Northwest China Grid cut down to 49.854Hz [1]. As for the causes of the accident, firstly, the turbines did not have the ability of low voltage ride-through; secondly, after some turbines snapped off, the excess reactive power made system voltage rise, but the turbines did not have the ability of high voltage ride-through. As a result, 274 turbines snapped off because of low voltage network, and 324 turbines snapped off because they failed to tolerate high voltage when the voltage in the machine rose to 110% of the rated voltage in the accident. Through the analysis of the large-scale turbine accident, great importance must be attached to the high voltage ride-through ability of wind turbine generators.

2. Transient process analysis of DFIG
In order to study the high voltage ride-through characteristics of DFIG, it was very necessary to analyze the transient response process of DFIG when power grid failure caused voltage surge.

It was assumed that power grid voltage had symmetry surge at \( t_0 \), DFIG stator voltage was \( V_s e^{j\omega t} \); when \( t < t_0 \), \( u_s = V_{se} e^{j\omega t} \); when \( t > t_0 \), \( u_s = V_{se} e^{j\omega t} + pV_{se} e^{j\omega t} \).

Where \( p = (u_s - V_{se})/V_{se} \) is the size of power grid voltage surge.

The stator voltage and flux linkage equations are as follows:

\[
\begin{aligned}
\frac{d\psi_s}{dt} &= R_s i_s + u_s \\
\frac{d}{dt} \left( L_s i_s + L_m i_r \right) &= u_s
\end{aligned}
\]

The following stator flux state equation could be obtained through equation (1):
\[
\frac{d\psi_s}{dt} = u_s - \frac{R_s}{L_s} \psi_s
\]  

(2)

Then, in turn, stator flux linkage equation when the grid voltage soared could be obtained:

\[
\psi_s = (1 + p) \frac{V_{se}}{j\omega_s} e^{j\omega_f t} - p \frac{V_{se}}{j\omega_s} e^{j\omega_f t_0 - (t-t_0)/\tau}
\]  

(3)

When grid voltage soared, the open circuit voltage corresponding to the rotor (ignoring \(1/\tau\) item) was as follows:

\[
u_{r0} = \frac{L_m}{L_s} \left[ s(1 + p)V_{se} e^{j\omega_f t} + (1-s) pV_{se} e^{j\omega_f t_0 - (t-t_0)/\tau} \right]
\]  

(4)

Analysis results were as follows: when the power grid failure cause voltage soar, DC component of the stator flux linkage and the negative sequence components produced by asymmetric fault would induce the larger voltage and impulse current in the rotor circuit; if no reasonable protective measure was taken, it might damage the rotor side converter; it might also make the converter DC side bus voltage rise, and burn up DC side capacitor.

3. High voltage ride through grid specifications

There are relatively rare studies of high voltage ride-through and the running characteristics of DFIG in China. Because European and American countries such as the United States, Canada, Australia, Denmark and the Scottish developed wind power earlier, Europe and the United States and grid operators, including WECC of the United States, AEMC of Australia, AESO of Canada, Energinet.dk of Denmark and Scottish Power of Scotland have formulated the relevant standards of wind power high voltage ride-through ability.

WECC of the US. Requires for the ability of running for 2s each time when the power grid voltage soars to 118% of the rated voltage, the ability of operating for 1s each time when the power grid voltage soars to 120% of the rated voltage, and continuous operation when the power grid voltage soars to 110% of the rated voltage [3]. AEMC of Australia regulates the ability of running for 0.06s each time when the power grid voltage soars to 130% of the rated voltage. Besides, AESO of Canada requires all of the above 5MW wind turbines should be able to run continuously when grid-connected site voltage is 90%~110% of the rated voltage [4]. Energinet.dk of Denmark requires for the ability of operating for 0.2s each time when the voltage soars to 120% of the rated voltage [5]. Scottish Power of Scotland requires for the ability of operating for 0.8s each time when voltage soars to 120% of the rated voltage, and continuous operation when the voltage soars to 110% of the rated voltage [6].

State Grid Corporation in China also developed the corresponding standards of high voltage ride-through for wind power plants in December 2016. It requires wind turbines to keep continuous operation when the per unit value of grid-connected site power frequency voltage \(U_T\leq1.1\), the ability of operating for 10s each time when \(1.1<U_T\leq1.15\), the ability of operating for 200ms each time when \(1.15<U_T\leq1.2\), and full-load operation when \(U_T > 1.2\) [7]. High Voltage ride through grid specifications is show in fig.1.
4. The existing high voltage ride through technologies

Based on the analysis from the perspective of energy, when power grid failure caused voltage surge, DFIG could not conduct normal transmission to power grid. Because DFIG had large inertia, variable propeller system required a certain time to adjust, so short-term adjustment range was limited, and caused excess wind energy, while it was obvious that the wind energy could not be effectively released only through regulating ability of the DFIG itself.

Currently, there are two kinds of common methods. One is to realize high voltage ride-through ability of DFIG through the control method technique of improving rotor side converter; Another one is to increase hardware auxiliary circuit to release excess energy of the system. The section first introduced the improved control method technology without increasing hardware auxiliary circuit, and then introduced stator side and rotor side and other methods of voltage ride-through by adding hardware auxiliary circuit respectively according to different installation positions of hardware auxiliary circuit.

4.1. The control method of improving rotor side converter

Many experts and scholars at home and abroad are studying and exploring the methods of high voltage ride-through of DFIG by only improving the rotor converter and grid side converter control strategy, without increasing hardware circuit. Literature [8] proposed the compensation dosage control method of adding stator exciting current change on DFIG controller, which could make necessary corrections for decoupling circuits. Literature [9] proposed the direct dynamic current control technology that used stator terminal voltage disturbance to compensate the dynamic impact of rotor current, which could limited the dynamic oscillation of rotor current to a certain extent. Literature [10] proposed a kind of degaussing control method suitable for the oriented vector control of DFIG power grid voltage, which could reduce the oscillation of stator and rotor current. Besides, such method could effectively reduce the impact of transient DC component in stator flux linkage on DFIG when the power grid voltage surged slightly. Although the control strategies proposed in the above literatures improved rotor current control ability during power grid fault, they also increased the input voltage of rotor, and no extra energy of DFIG was released. Thus, these methods could play a role only when power grid voltage surged within small range.

Literature [11] proposed the compensation technology based on transient state flux linkage of DFIG that introduced same frequency voltage in rotor terminal voltage. The technology could eliminate the induction electric potential of DC component and negative sequence components of stator flux linkage in the rotor circuit when power grid voltage surged, and then control the rotor loop current, but the method had weak compensating control ability. Literature [12] improved the method.
Crowbar was input when voltage surged instantaneously; rotor side converter began operating when rotor side current attenuated to the allowable scope; the degaussing current made flux linkage DC component attenuate rapidly, and sent out a certain amount of reactive power to the grid at the same time. In such method, Crowbar action time was only 11.16ms, which could guarantee rotor side converter restore control timely, thereby helping power grid voltage recover, and achieve high voltage ride-through of DFIG.

Literature [13] proposed the rotor side current phase angle compensation control technology. The technology could solve the problem of possible damage of the converter caused by rotor over-current during the grid voltage recovery period after Crowbar exited. Such technology aimed at symmetrical fault of power grid, but it ignored the influence of the transient process of transition of stator flux linkage when voltage soared. In fact, there are more asymmetric faults in practice, so the method application condition is limited.

Literature [14] proposed the method in which the asymmetric system was decomposed into positive and negative sequence component, and then positive and negative sequence current double d-q control was conducted on their respective d-q axis decoupling control. There was bigger error in the negative sequence current extracted by the method; the application of wave trap in positive and negative sequence decomposition caused the breakdown time delay, so the dynamic performance of the converter in the process of recovery was affected. Literature [15] designed a kind of unbalanced control method of DFIG, and put forward new harmonic current control technology. The technology simplified the positive and negative sequence current instruction value algorithm of the rotor under the various enhanced control ability control target through positive sequence d+ shaft power grid voltage orientation. Besides, it didn’t need unified regulation on the current, negative sequence decomposition of rotor side, and strengthened the continuous operation ability of DFIG under the asymmetric fault.

Under larger range of grid voltage surge, DFIG machine terminal voltage fluctuations will cause sharp oscillation in flux linkage, so the reactive power control technology is also very necessary for realizing the high voltage ride-through of DFIG. Literature [16] proposed the new reactive power optimization control technology that could make the some excitation control of rotor side converter shift to grid side converter. Such technology increased the capacity of the grid side converter, could improve the power factor and voltage stability, effectively reduced DFIG loss, and enhanced the high voltage ride-through ability of DFIG.

4.2. Stator side method

1. Series dynamic braking resistor (SDBR) between stator and power grid

During normal operation, \( R_{\text{SDBR}} \) doesn’t work when bypass switch is closed. When power grid failure makes voltage soar, \( R_{\text{SDBR}} \) can accelerate the stator flux linkage attenuation, and then accelerate the attenuation of voltage and current induced by rotor side, and protects DFIG. However, series \( R_{\text{SDBR}} \) operation at stator side will make the machine side voltage of DFIG increase and resistance loss increase. Therefore, the method is only applicable to the small grid voltage gain. Its topology structure is show in fig.2.

![Fig.2 Series dynamic braking resistor between stator and power grid](image-url)
2. Series dynamic voltage restorer (DVR) [17]
   During normal operation, DVR doesn’t work. When power grid failure makes voltage soar, DVR guarantees the voltage stability of the DFIG machine side by making series transformer compensate corresponding fault phase voltage. The series DVR can ride through any fault type. Besides, in the whole process of fault, rotor side and grid side converter can provide DFIG with excitation, but it needs additional voltage type inverter and series transformer, which increase the hardware cost of DFIG, and is more difficult to implement. Its topology structure is show in fig.3.

![Fig.3 Series dynamic voltage restorer](image)

4.3. Rotor side method
1. Install crowbar circuit
   For DFIG, the most commonly-used method is to increase protection circuit (such as a Crowbar circuit) in rotor side. The choice of reasonable crowbar resistance, the control strategies and switch can improve the high voltage ride-through ability of DFIG, and reduce the bad influence of wind power plant on system voltage stability after inputting Crowbar circuit in the wide range input. The method is simple, effective, easy to implement, and economical. However, when Crowbar circuit inputs, DFIG is at the uncontrolled state of induction motor. During grid voltage recovery period, DFIG will absorb large amounts of reactive power from the power grid, so it is bad for power grid voltage recovery. Besides, the actual effect after the installation is quite very dependent on operating conditions and fault characteristics, and had very limited role of asymmetric fault. Its topology structure is show in fig.4.

![Fig.4 Install crowbar circuit](image)

2. Install improved Crowbar circuit (SDBR + Crowbar) [18]
   During normal operation, RSDBR doesn’t work. When grid voltage surge causes rotor side overflow, \( R_{SDBR} \) is input, when \( R_{SDBR} \) limits surge current and accelerate rotor current attenuation. When
voltage surge makes rotor current be beyond the adjusting range of $R_{SDBR}$. Crowbar bypass the rotor side converter was input. The combined action of $R_{SDBR}$ and $R_L$ can make the rotor over current decay faster; when current attenuates to the allowable scope of rotor side converter and rating value Crowbar and $R_{SDBR}$ exited respectively. The improved control technology reduces the input frequency and time of Crowbar, but it increases the hardware input and complexity of control. Its topology structure is show in fig.5.

Fig.5 Install improved Crowbar circuit (SDBR + Crowbar)

3. DC side series chopped wave energy dissipation device (Chopper circuit) \[^{19}\]

When grid voltage surges, rotor side converter over-current limits grid side converter power output, which will make DC side voltage rise, and possibly cause damage of DC side capacitor and power device. In order to solve the problem, a chopper circuit can be added in DC side; when grid voltage surges, unloading load is input to consume excess energy, and maintain a constant DC voltage. Its topology structure is show in fig.6.

Fig.6 DC side series chopped wave energy dissipation device

4. DC side series storage protection circuit (ESS) \[^{20}\]

Series storage protection circuit can store the excess energy during voltage surge, and send the stored energy to power grid at the end of the fault. The advantages of the method is as follows: without switching under different running conditions, it can avoid transient process caused by switch, and conduct continuous control on the system. The disadvantage is as follows: ESS can not effectively control rotor side current; only by increasing the capacity of rotor side converter, can the rotor be ensured no damage due to over current of converter. Increasing hardware and improving control
strategy increase the total cost, but it also creates better conditions for the realization of high voltage ride-through. Its topology structure is show in fig.7.

![Fig.7 DC side series storage protection circuit](image)

5. **Development direction of high voltage ride-through technology**

After analyzing the technologies of improving DFIG high voltage ride-through, and by combining with the present development situation of wind power technology in China, it is expected the technology will revolve around the following several aspects of research in the future:

1. State Grid Corporation has made enterprise standard in view of the high voltage ride-through ability of wind power plants, while national standard has not yet introduced. Therefore, at present, it is necessary to implement the relevant requirements of the standards in terms of manufacturing and wind power operating as soon as possible; especially the regions with weak power grid in China should perform high voltage through standard as soon as possible to ensure the safe operation of power grid.

2. To achieve the accuracy of the control strategy and the effectiveness of the protection device, it is necessary to improve the accuracy of transient mathematical model of DFIG and excitation frequency converter. How to build the transient mathematical model containing protective device (such as Crowbar, SDBR + Crowbar, Chopper and ESS) will be the research focus of DFIG high voltage ride-through technology.

3. Accurate judgment of power grid failure and rapid detection technology are the foundation of achieving DFIG high voltage ride-through operation control, so it is one of research directions of realizing DFIG fault crossing ability more effectively.

4. The above-mentioned protection devices have their own advantages and disadvantages. How to make full use of them and make them complement each other to achieve very good effect of fault ride-through will be the focus of future research. There are fewer literature researches currently.

6. **Conclusion**

At present, most of the wind power plant machine model in China use DFIG as the main body, so it is particularly important to improve the high voltage ride-through ability of DFIG under power grid failure. The paper systematically summed up and evaluated domestic and overseas related standards, the latest technology and research results in terms of DFIG high voltage ride-through ability, and forecasted the development direction of high voltage ride-through technology, and provided reference for the subsequent research work and engineering applications.

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