Design and Implementation of Crowbar Circuits Combined with Chopper Circuits for LVRT in Wind Farms

Xu Yifan¹a, An Aimin¹,²,³*, Zhao Yingying¹ and Chen Wei¹,²,³

¹ College of Electrical and Information Engineering, Lanzhou University of Technology, Lanzhou 730050
² Key Laboratory of Gansu Advanced Control for Industrial Processes, Lanzhou 730050, China
³ National Experimental Teaching Center of Electrical and Control Engineering, Lanzhou, Gansu, China

anaimin@lut.edu.cn
*Corresponding author’s e-mail: tianyatian1996@163.com

Abstract. This paper presents the advantages of LVRT technology where a crowbar circuit functions in combination with a chopper circuit. To enhance the low voltage ride-through (LVRT) performance of double-fed wind turbines, the advantage of the crowbar protection circuit, the DC-link chopper protection circuit, and rotor side control (RSC) are combined based on current LVRT technology. The crowbar circuit is fully utilized to protect the rotor circuit from overcurrent and plays the role of the chopper circuit to stabilize the DC bus voltage. In addition, this paper proposes a cooperative control strategy that is used in the control of the protection circuit during LVRT. Simulation results based on PSCAD/EMTDC demonstrate that the proposed method can significantly reduce crowbar switching times and LVRT time, and the control method is simple and feasible.

1. Introduction

As various sources of renewable energy have been connected to utility grids, global warming problems caused by greenhouse gas emissions have been reduced significantly[1]. For example, wind power systems account for a growing share of electricity generation[2]. The global cumulative installed wind power capacity increased from 6.1 GW in 1996 to 282.6 GW in 2012, and this is expected to reach 760 GW in 2020[3]. It is expected that wind power will dominate the new-resource power market in the future.

Doubly-fed wind induction generators are used in many wind farms. By replacing other wind generators that depend on a large speed range, active and reactive power can be adjusted independently and the need of excitation frequency converter capacity is small[4]. Wind energy power plants based on DFIG have been integrated extensively into the worldwide utility grid[5]. However, when a fault occurs in the grid, voltage dips to low levels, and when levels fall below 60% of normal voltage, problems can be expected. For example, stator voltage will decrease with voltage dips. It is coupled in the stator and the DFIG rotor; thus, a dip in stator voltage will cause a rapid increase of rotor current. In addition, voltage dip will cause the electromagnetic torque $T_{eq}$ to increase to abnormal levels, which will cause significant harm to the entire power grid system. To maintain power grid...
stability, new grid codes are currently in development. The grid code in China identifies the direction for wind power grid integration. This grid code requires that the wind turbine stay connected to the power grid and provide reactive power to the power grid in the event of a fault. Figure 1 shows the Chinese LVRT grid code. Chinese grid code requires that when the grid-side transformer voltage is above the thick line, the wind turbine must keep a connection to the grid. Among them, the minimum maintenance voltage is generally between 15% and 25%, and the longest time for LVRT is generally between 0.5 and 2s. Only when the grid fault time exceeds 2s, the generator is allowed to be removed from the grid.

Many studies have investigated ways to improve the capabilities of LVRT. For example, in the situations of moderate voltage sags caused by mild fault can be achieved by improving the DFIG control strategy. Literature [6-7] reduced the transient DC component in the stator flux linkage after a fault via magnetic linkage compensation, which achieved the transient controllability of DFIG is strengthened, and the controllable range of voltage dip is expanded. Therefore, the performance of LVRT for DFIG is improved. Literature [8], LVRT was improved using a demagnetization current controller under transient stability conditions. In addition current tracking control for RSC has been studied previously studied [9]. The advantage of the current tracking control is that flux linkage does not need to be observed.

However, in the event of a severe failure leading to a large drop in the extreme voltage of the generator, it is impossible to achieve LVRT by simply improving the control strategy of a doubly-fed wind generator. Therefore, LVRT with additional hardware circuits has been studied extensively. Currently, the rotor-based crowbar protection circuit is the most popular method to achieve LVRT based on DFIG[10]. The crowbar circuit is composed of the resistance. Crowbar circuit is used as the rotor side of the doubly-fed generator to protect the RSC. When a fault occurs in the grid, it causes the rotor current to increase, and the rotor-side converter stops working. The crowbar circuit is connected to the rotor circuit of DFIG to consume excess energy in the crowbar resistance. Using a chopper circuit is another approach for LVRT[11]. The chopper circuit is parallel to the DC capacity of the converter to suppress the DC bus voltage fluctuations to protect the RSC. The LVRT protection using crowbar and chopper circuits has been studied extensively. For example, Literature [12] combined LVRT with a crowbar circuit on the stator side and a chopper circuit in the DC-link. Literature [13] investigated LVRT methods with active crowbar current limiting and GSC reactive power output.

In this study, we integrated the above methods and combined the advantages of the crowbar protection circuit, the chopper protection circuit, and the control strategy in RSC. The comprehensive LVRT scheme of Crowbar resistance limiting rotor circuit overcurrent after fault, Chopper unloading...
resistance to suppress DC bus overvoltage and RSC control to output reactive power to the grid. The comprehensive LVRT scheme was compared to the single protection provided by the crowbar circuit. In addition, we prove the superior performance of the proposed integrated control protection strategy.

2. Modeling doubly-fed wind turbines
Double-fed induction generators (DFIG) are the currently most widely used generators in wind power generation. The stator windings are directly connected to the power grid, and the rotor windings are connected to the power grid by a back-to-back four-quadrant converter. The electromagnetic torque of the generator is controlled by the rotor-side converter to achieve variable running speed and constant frequency. Therefore, this generator is called a variable speed constant frequency wind generator. By controlling the reactive power and decoupling the active power and reactive power control by independently controlling the rotor excitation current, the rotor-side converter only needs to deal with the slip power in the rotor loop. Therefore, the capacity of the converter is approximately 25-30% of the system rating value, which is a unique advantage. DFIGs are an important driving part of semi-coupled variable speed wind power systems. Due to its small attrition rate and simple control strategy, it has been widely used in many power grids. Generally, when a grid experiences a low-voltage dip, the crowbar protection circuit is set to bypass the rotor-side converter to protect the entire system, and the chopper circuit can effectively optimize the response.

The electromagnetic torque of the generator is controlled by a rotor converter to make it run at variable speed. The IGBT in the crowbar and chopper circuits is controlled by the control signal provided by the control system. The main circuit topology of DFIG is shown in Figure 2.

![Figure 2. Main circuit topology of DFIG.](image)

DFIGs feed the stator and rotor windings of the motor connected to the AC power supply. It usually adopts a winding induction motor structure. According to convention, in order to facilitate the analysis, when studying the DFIG mathematical model, the generator's space harmonics, magnetic circuit saturation and core loss are ignored and the influence of frequency and temperature changes on the generator winding is not considered. In designing control methods and studying dynamic characteristics, the most widely used generator model is a synchronous rotating coordinate system, all the physical quantity of the positive direction is the use of motor convention, voltage, current positive direction formed by the magnetic field for the positive direction of the magnetic field, rotor-side parameters are converted to the stator side. The mathematical model analysis of a doubly-fed motor is expressed as follows.

The stator voltage winding equation is given as:
The rotor winding voltage equation is given as:

\[
\begin{align*}
    u_A &= R_A i_A + p\psi_{sA} \\
    u_B &= R_B i_B + p\psi_{sB} \\
    u_C &= R_C i_C + p\psi_{sC}
\end{align*}
\]  

The rotor winding voltage equation is given as:

\[
\begin{align*}
    u_A &= R_A i_A + p\psi_{rA} \\
    u_B &= R_B i_B + p\psi_{rB} \\
    u_C &= R_C i_C + p\psi_{rC}
\end{align*}
\]

Here, \(i_A, i_B, \) and \(i_C\) represents the stator-side three-phase current, \(u_A, u_B\) and \(u_C\) represents the three-phase voltage on the stator side, \(\psi_{sA}, \psi_{sB}\) and \(\psi_{sC}\) represents the stator-side three-phase magnetic chain, \(i_A, i_B, \) and \(i_C\) represents the three-phase current on the rotor side, \(u_A, u_B\) and \(u_C\) represents the three-phase voltage on the rotor side, \(\psi_{rA}, \psi_{rB}\) and \(\psi_{rC}\) represents the three-phase magnetic chain on the rotor side, \(R_A\) and \(R_C\) are constant and the rotor winding equivalent resistance, respectively, and \(p\) is the differential operator.

If the three-phase winding is symmetrical and the zero axis is neglected, the reference coordinate system can be transformed, which simplifies system analysis and facilitates computer simulations and digital realization of the relevant control strategy. Constant and rotor quantities are often converted to quantities in dq0 coordinate systems. Here, assume that the d-axis of the d-q coordinate system lags behind the q-axis and rotates at a synchronous speed; thus, the voltage equation of the doubly-fed induction generator in the d-q coordinate system is given as follows\[15\].

\[
\begin{align*}
    u_d &= R_d i_d + p\psi_{sd} - s\omega\psi_{sq} \\
    u_q &= R_q i_q + p\psi_{sq} + s\omega\psi_{sd} \\
    u_d &= R_d i_d + p\psi_{rd} - s\omega\psi_{rq} \\
    u_q &= R_q i_q + p\psi_{rq} + s\omega\psi_{rd}
\end{align*}
\]

The magnetic linkage equation is expressed as follows:

\[
\begin{align*}
    \psi_{sd} &= L_s i_d + L_m i_{rd} \\
    \psi_{sq} &= L_s i_q + L_m i_{rq} \\
    \psi_{rd} &= L_m i_d + L_r i_{rd} \\
    \psi_{rq} &= L_m i_q + L_r i_{rq}
\end{align*}
\]

where \(u_d, u_q, u_d\) and \(u_q\) represents the voltage of the rotor fixed by the d and q axes, \(i_d, i_q, i_{rd}\) and \(i_{rq}\) represents the rotor current of the d and q-axis; \(\psi_{sd}, \psi_{sq}, \psi_{rd}\) and \(\psi_{rq}\) represents the magnetic linkage of the rotor with fixed d and q axes; \(L_s, L_r\) and \(L_m\) stator winding self-inductance, rotor winding self-inductance and mutual inductance, \(\omega\) is the synchronous angular velocity, and \(s\) is slip rate.

Finally, the electromagnetic torque of a DFIG is simplified as follows:

\[
T_e = n_p L_m (i_q i_{rd} - i_d i_{rq})
\]
3. LVRT control strategy based on crowbar and chopper circuits

For DFIGs, the most famous LVRT method is to add a crowbar protection circuit to the rotor-side of the DFIG to protect the rotor-side converter. The crowbar circuit includes a series of power electronic devices. When the system fails, the magnetic coupling between the DFIG rotor and stator will cause the rotor current to change suddenly. Therefore, to protect the converter, a crowbar circuit is used to short-circuit the RSC, which consumes excess energy on the protection resistance.

The crowbar protection circuit can act as a passive or active circuit, where a passive crowbar circuit generally uses a thyristor as the switching element (the rotor-side frequency is not high). Once the crowbar action is done, it is very difficult to cut off. Thus, it has gradually been replaced by the active crowbar circuit. In the active crowbar protection circuit, SCR and IGBT with forced switching are generally used as switching elements that can turn the crowbar circuit on and off at any time.

Compared to the passive crowbar circuit, the active crowbar circuit adopts a gate-turn-off thyristor or insulation-gate bipolar transistor (IGBT), as well as other fully controlled devices. Thus, the active crowbar circuit can be cut off from the rotor-side at any time after the crowbar protection circuit is activated, which easily satisfies the grid code requirements in the initial stage of failure.

The working logic of the crowbar circuit [16] is as shown in Figure 3, which illustrates the following: (1) a slight power grid failure occurs; (2) a serious power grid failure occurs; (3) power grid fault deterioration; (4) the wind turbine is allowed to disconnect. In Fig 3, A, B, and C represent recovery from slight power grid failure; the fault is relieved; and the severe power grid failure is recovered, respectively.

![Crowbar circuit protection logic.](image)

Caused by the fault of power grid voltage drop, a slightly larger fault current is present in the stator and rotor winding of DFIG, in the process of to the DC bus capacitor charging, the rotor overcurrent causes the instability of the dc bus voltage, grid-side converter output power was limited, so it will unable to send the rotor-side excess energy into the power grid, the energy accumulated in the dc side will cause the DC bus voltage rise, threatens the safety of DC bus capacitor and semiconductor devices. Here, a DC chopper circuit should be used to overcome this problem. When the active power output of the rotor-side and grid-side converters is seriously unbalanced, the excess energy on the rotor-side can be absorbed by the unloading resistance, which can inhibit sudden changes in the DC bus voltage and maintain stable voltage.

The switching control signal of Chopper is determined by the collected DC bus voltage, and its judgment is based on: when the DC bus voltage exceeds the upper limit of the DC bus voltage, it is switched on when the DC bus voltage does not exceed the lower limit of the DC bus voltage. The upper and lower limits of the DC bus voltage are set up with thresholds of different sizes to achieve a certain delay and reduce unnecessary switching.
4. Comprehensive control strategy

According to the previous analysis, the control strategy of LVRT based on single crowbar or chopper has advantages and disadvantages. The LVRT capacity of the entire power generation system can be improved if crowbar circuit and chopper circuit are used together and the control strategy is adjusted according to different working conditions.

The control system for the crowbar and chopper circuits is shown in Figure 4.

The control strategies are divided into the following three categories according to the external conditions, e.g., grid voltage dip, balanced or unbalanced dip, and the active power of the unit at the time of voltage dip.

1. Terminal voltage drops to 0.8 pu

These conditions are generally referred to as sub-synchronous conditions, which are characterized by low power, low dip depth, and voltage balance dip. Here, there is only an instantaneous and slight overpressure flow on the rotor-side; thus, the crowbar and chopper circuits can be switched off, and the dynamic response can be improved by fine-tuning the controller’s parameters.

2. Terminal voltage drops to 0.6 pu

These conditions are generally referred to as near-synchronous speed states, which are characterized by moderate power, moderate dip depth, and balanced dip.

Here, the transient overpressure overcurrent of the rotor is not too severe; thus, there is no need to use the crowbar circuit. During the entire failure process, the chopper circuit can be used to realize the overvoltage protection of the DC bus. In addition, the motor-side converter can be switched on to control the reactive power support to emit capacitive reactive power.

3. Terminal voltage drops to 0.2 pu

This type of working condition is generally referred to as the hypersynchronous state, which is characterized by high power, deep dips, and unbalanced dips. Here, due to the large transient DC component of the stator flux linkage, high rotor overpressure and overcurrent will be generated, and the chopper circuit is insufficient to consume energy. In addition, the chopper circuit’s resistance temperature may increase sharply, which will cause accelerated aging and even burn out. Therefore, the chopper circuit cannot be switched immediately when a voltage dip occurs. First, the crowbar protection circuit used to working for a short period such that the system can avoid the most drastic dynamic process, and then immediately cut out the crowbar circuit. In addition, the chopper control
and rotor-side converter control reactive support are applied to satisfy the reactive capacity requirements during the failure.

By adopting this coordinated control strategy, the advantages of the crowbar and chopper circuits are fully utilized, and their respective limitations are compensated effectively, which reduces the out-of-control time of the entire system. The response time of the protection circuit and the overall stability of the system during the LVRT of the doubly-fed wind power generation system are improved.

An analytic hierarchy process to evaluate the influence of current and voltage after a fault was presented in [17] and [18]. This method describes the relationship between the rotor current value and the DC bus voltage during the fault and the resistance of the crowbar. When a fault occurs and the voltage plummets, the rotor current and DC bus voltage will rapidly increase to uncontrollable values. Such fluctuations can wreak havoc on the entire power generation system, especially its vulnerable electronics. Therefore, a method to evaluate rotor current ripple and DC bus voltage ripple is required.

[19] presented an index comprising two integrals:

\[ \text{Index} = K \left[ a_1 I_{r,\text{max}} - I_{r,\text{ref}} \right] + a_2 \left[ V_{\text{dc}} - V_{\text{ref}} \right] \int dt \]  

(6)

where \( I_{r,\text{max}} \) is the maximum value of the three-phase rotor current, \( V_{\text{dc}} \) is the DC bus voltage value, \( I_{r,\text{ref}} \) is the rotor current reference value of the DFIG, and \( V_{\text{ref}} \) is the DC bus voltage reference value. Here, \( a_1 \) and \( a_2 \) are constant coefficients that reflect the different weights of the two variables. The rotor current and DC bus voltage are important; thus, \( a_1 \) and \( a_2 \) are set to the same values in our case. \( K \) is a constant coefficient that only magnifies the index value to make the result easier to measure.

This improved method well reflects the continuous fluctuation of the rotor current and DC bus voltage; however, during the fault, the DC bus voltage suddenly appears a maximum value, the index value calculated by Equation (6) will be inaccurate. Otherwise, the DFIG system may be seriously damaged due to the large influx of voltage or current. We acknowledge this as a minor flaw in the methodology.

5. Simulation

To verify the effectiveness of the above DFIG system and its control strategy, a model of a doubly-fed wind power generation system was constructed using the PSCAD/EMTDC platform with combined crowbar and chopper circuits. The specific combination form is shown in Figure 5.

![Figure 5. Combined crowbar and chopper circuits.](image)

The parameters of the doubly-fed induction generator are given in Table 1.

| Parameter       | Value |
|-----------------|-------|
| Rated power     | 5MW   |

Table 1. Parameters of doubly-fed induction generator.
Rated line voltage 690V
Rated wind speed 11m/s
Number of generator poles 3
Stator winding resistance 0.0054pu
Rotor winding resistance 0.00607pu
DC-side capacity 5000uf

The relevant parameters of crowbar and chopper are given in Table 2.

Table 2. Crowbar and chopper circuit parameters.

| Parameter                  | Value   |
|----------------------------|---------|
| Crowbar resistance         | 0.4Ω    |
| Chopper resistance         | 0.45Ω   |
| Chopper input voltage      | 1200V   |
| Chopper cut-off voltage    | 1140V   |

As shown in Figures 6, when there is a slight voltage drop caused by a slight fault in the double-fed wind power generation system, the hardware protection circuit chopper and crowbar resistance are not cut into the circuit, and LVRT can be realized only by the rotor measuring converter’s control strategy.

When the fault expands further, which causes the terminal voltage to drop to 0.6 pu, the chopper circuit on the DC bus-side begins to switch and work with the rotor side converter. When the voltage drops to 0.4 pu due to a serious failure in the entire power generation system, the crowbar circuit also begins to cooperate with the chopper circuit to form a hardware protection circuit to complete the LVRT function. Figure 7 and 8 show the circuit control and protection status at different voltage drop levels.
Figure 7. Control and protection state when terminal voltage drops to 0.6 pu.

Figure 8. Control and protection state when terminal voltage drops to 0.2 pu.

By adopting different comprehensive LVRT control strategies according to voltage dips at different winding terminals, the RSC can be switched in time to play its role of injecting reactive power into the grid. By adopting this coordinated control strategy, the advantages of the crowbar and chopper circuits are fully utilized, and their respective limitations are effectively compensated. The response time of the protection circuit and the overall stability of the system during the LVRT of the doubly-fed wind power generation system are improved.

Note that the selecting the resistance size of the crowbar circuit is particularly important. Inappropitately large or small resistance values will affect protection circuit performance. If the resistance value is too small, the rotor overcurrent cannot be suppressed effectively. If the resistance is too large, it is possible to increase the attenuation rate of the rotor current, however, this will increase the rotor voltage, and excessive voltage at the rotor end of the doubly-fed generator will force the rotor measurement converter to work in an uncontrollable rectification state, which will undermine the stability of the system.

A simple crowbar resistance calculation method has been proposed previously [20]:

$$ \frac{U_{dc}}{\sqrt{6I_{r,lim}} - R_r} $$

(7)
Here, rotor leakage resistance of approximately 30 times the reference value is selected for the crowbar resistance.

By combining the proposed LVRT control strategy with the single crowbar protection scheme, the three-phase current of the generator set increases steadily between 0-0.1s, which is the starting stage of the generator. Assuming that the generator set fails at 0.4 s, under the integrated control strategy, the peak of three-phase short-circuit current of the generator is less than that of the single crowbar protection scheme, and the attenuation range is also less than that of the single crowbar protection scheme under the combined action of the RSC control and chopper circuit.

Figure 9. Comparative diagram of three-phase short-circuit current for a failure at 0.4 s.

Figure 10. Entire process of LVRT under proposed LVRT control strategy.
It can be known from the simulation that when the doubly-fed wind power generation system runs for 0.4s, the fault occurred. The fault will cause the three-phase short-circuit current to surge. However, the voltage on the side of the DFIG machine is protected by the RSC control strategy, and the voltage does not drop significantly. The doubly-fed wind turbine remains connected to the power grid. When the fault occurs within 0.625s, the power generation system is protected by a comprehensive control strategy, the three-phase current begins to increase gradually, and the voltage at the DFIG terminal remains stable. At 1.2s, the fault is removed from the power generation system. Under the joint action of Crowbar and Chopper hardware circuit protection, the generator is always been connected with the power grid. The LVRT function is realized.

6. Conclusion
In this paper, we presented a theoretical analysis and simulation of the crowbar protection and chopper circuits, and considered the influence of a DFIG inverter control strategy. The analysis and simulations indicate that a comprehensive control strategy that involves an effective chopper circuit combined with the crowbar hardware circuit provides effective low voltage. This method can be used in the case of different terminal drops. In addition, this method can reduce the loss of electronic devices and decrease rotor overvoltage, and further relieve grid voltage drops. The proposed method has obvious benefits relative to system stability of LVRT of DFIG.

Acknowledgments
This work was supported in part by the National Natural Science Foundation of China under Grant 61563032 and 61963025. Gansu Province Higher School Industry Support and Guidance Project 2019C-05

References
[1] Y. Ling and X. Cai, “Rotor current dynamics of doubly fed induction generators during grid voltage dip and rise,” Int. J. Electr. Power Energy Syst., vol. 44, no. 1, pp. 17–24, 2013.
[2] Cheng M, Zhu Y. The state of the art of wind energy conversion systems and technologies: A review[J]. Energy Conversion & Management, 2014, 88:332-347.
[3] V. Yaramasu, B. Wu, P. C. Sen, S. Kouro and M. Narimani, "High-power wind energy conversion systems: State-of-the-art and emerging technologies," in Proceedings of the IEEE, vol. 103, no. 5, pp. 740-788, May 2015.
[4] He Y, Zhou P. Overview of the low voltage ride-through technology for variable speed constant frequency doubly fed wind power generation systems[J]. transactions of china electrotechnical society, 2009. 24(09):140-146.
[5] Y. Lin, L. Tu, H. Liu, and W. Li, Fault analysis of wind turbines in China, Renew. Sustain. Energy Rev., vol. 55, pp. 482–490, Mar. 2016.
[6] Zhang J, Pan H. LVRT Control Strategy with Electromagnetic Transient Compensation for DFIG and Its Mechanical Safety Analysis, Motor and Control Application, 2015, 000(007):34-38.
[7] Yang S., Chen L., S et al. LVRT Transient Compensation Strategy for Doubly-fed Wind Turbines Under Asymmetrical Grid Faults. Automation of Electric Power Systems, 2014, 38(18):13-19.
[8] Dosoglu M K. A new approach for low voltage ride through capability in DFIG based wind farm[J]. International journal of electrical power and energy systems, 2016, 83(dec):251-258.
[9] Xiang D, Ran L, Tavner P J , et al. Control of a Doubly Fed Induction Generator in a Wind Turbine During Grid Fault Ride-Through[J]. IEEE Transactions on Energy Conversion, 2006, 21(3):p.652-662.
[10] Yang S., Zhou T., Chang L., et al. An analytical method for the response of DFIG under voltage dips[C]// IEEE Energy Conversion Congress & Exposition. IEEE, 2015.
[11] Ling Yu, Cai Xu, Wang Ning-bo. Combination of Stator Crowbar and DC-Link Discharge Resistor for Fault Ride-Through (FRT) of DFIG[J]. Electric Power, 2013.

[12] Wei Fang, Liu Qihui, Xie Mengli. A Comprehensive Low Voltage Ride Through Control Strategy of Wind Turbine Driven Doubly-fed Induction Generator Adapted to Multi-type Faults. Automation of Electric Power Systems, 2013, 37(05):23-28+133.

[13] Zhu Yongli, Tang Bingwei. Simulation and Analysis of Low Voltage Ride Through Capability of Doubly Fed Induction Generation with Combined Protection Strategy. Low Voltage Apparatus, 2013, (08):31-35.

[14] Yanbin Q U , Gao L , Guangfu M A , et al. Crowbar resistance value-switching scheme conjoint analysis based on statistical sampling for LVRT of DFIG[J]. Journal of Modern Power Systems and Clean Energy, 2019, 7(3):558-567.

[15] S. Reza Kalantarian and Hossein Heydari, An analytical method for selecting optimized crowbar for DFIG with AHP algorithm, in Proc. of Power Electronics, Drive Systems and Technologies Conference, pp.1-4, Feb. 2011.

[16] Pannell G , Zahawi B , Atkinson D J , et al. Evaluation of the Performance of a DC-Link Brake Chopper as a DFIG Low-Voltage Fault-Ride-Through Device[J]. IEEE Transactions on Energy Conversion, 2013, 28(3):535-542.

[17] Cardenas R , Rubén Pena, Alepuz S , et al. Overview of Control Systems for the Operation of DFIGs in Wind Energy Applications[J]. IEEE Transactions on Industrial Electronics, 2013, 60(7):2776 – 2798.

[18] Mali S , James S , Tank I . Improving Low Voltage Ride-through Capabilities for Grid Connected Wind Turbine Generator[J]. Energy Procedia, 2014, 54:530-540.

[19] Diaz-González, Francisco, Hau M , Sumper A , et al. Participation of wind power plants in system frequency control: Review of grid code requirements and control methods[J]. Renewable and Sustainable Energy Reviews, 2014, 34:551-564.

[20] Hu S, Lin X, Kang Y, et al. An Improved Low-Voltage Ride-Through Control Strategy of Doubly Fed Induction Generator During Grid Faults[J]. IEEE Transactions on Power Electronics, 2011, 26(12):3653-3665.