Low voltage and high voltage ride-through technologies for doubly fed induction generator system: Comprehensive review and future trends

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Abstract
The advantages, such as the mature control method, less volume of the converter and generator, make the doubly fed induction generator system prevalent in the wind power industry. Nevertheless, the doubly fed induction generator is more susceptible to grid faults and disturbances. The instantaneous high voltage fault may occur due to the excessive local reactive power after the doubly fed induction generator system achieving low voltage ride through, and then the wind turbine might be disconnected again. Hence, not only the low voltage ride through but also high voltage ride through capability should be required for the doubly fed induction generator system to meet the grid code requirements. A comprehensive review of the state of the art low voltage ride through and high voltage ride through technologies for the doubly fed induction generator system is presented. Firstly, different types of common low voltage ride through and high voltage ride through techniques are classified according to their features, i.e. auxiliary hardware, linear or nonlinear control strategies etc. The pros and cons of different low voltage ride through and high voltage ride through techniques are given. Furthermore, the latest developments of low voltage ride through and high voltage ride through technologies are introduced. Finally, the future trends of both the low voltage ride through and high voltage ride through technologies are discussed.

1 | INTRODUCTION

Wind energy has become one of the most extensively disseminated new energy sources owing to the clean and efficient characteristics. The wind power industry has developed rapidly in China since the beginning of the 21st century. The installed capacity of grid-connected wind power will be expected to reach 210 GW by the end of 2020 [1]. Wind energy development and utilisation have started to develop in a decentralised manner, especially at the end of the power grid. Due to the long distance of the transmission line, the impedance of the power grid seen from the wind turbines increases, and the short circuit ratio (SCR) becomes small, which is the main characteristic of the weak grid. As the proportion of grid-connected wind power is increased and scattered into the weak grid, operational characteristics of the power grid, such as weak inertia, low SCR, high grid impedance, weak electrical damping, and weak voltage support are developing. So, the safe and stable operation of the power grid with large-scale wind power faces significant challenges [2, 3].

The generator with full power converter (FPC) and doubly fed induction generator (DFIG) with partial power converter are two promising wind turbines in the wind power industry. The advantages of DFIG over the FPC wind turbines include the following. 1) DFIG wind turbines have a simple and straightforward design. 2) The generator/converter cost of the DFIG system is lowered due to 25–30% rated power converter. 3) DFIG can run both at the sub- and super-synchronous speed. 4) DFIG system needs a reduced size filter due to a partial converter contrary to the full-scale converter. 5) Low harmonics are injected into the grid due to the partial power converter in the DFIG system.
Reference [4] carry out a comprehensive review of the different wind power generation systems. The viable variable speed operation and part-size power converter make the DFIG prevailing in the wind power industry [5]. The DFIG stator windings are directly connected to the grid, and the rotor windings are connected through a back-to-back power converter to the grid. Thus, stator windings are always excited at constant grid frequency, and the rotor windings excitations are done through the variable frequency of power converter depends upon the sub-synchronous and super-synchronous wind speed. The direct connection of the stator windings to the grid makes the DFIG system more susceptible to voltage unbalance [6–9], low voltage fault [10–13] and grid distortions [14–17].

Literature [18–22] studied the low voltage ride-through (LVRT) requirements for the DFIG system studies. According to the grid code of China (GB/T 19963-2011) implemented in 2012, under the 20% voltage drop at the point of common coupling (PCC), the wind turbine must be grid connected for 625 ms and must have certain dynamic reactive power support capabilities. Nevertheless, the constraint of the operation time of reactive power compensation equipment to put into action in the power system and the excessive local reactive power after wind farm achieves LVRT causes the instantaneous high voltage fault of the system and the wind turbine may be disconnected again. Then, the safe and stable operation of the power system is challengeable under the aforementioned scenarios. Hence, wind turbines should not only require LVRT but also oblige high voltage ride-through (HVRT) capability to meet the grid code requirement. So, this paper briefly reviews grid fault ride-through (FRT), i.e. LVRT and HVRT techniques for the DFIG system. Furthermore, the future trends for FRT technologies for the DFIG system will be briefly revealed.

The remainder of the paper is organised as follows. The FRT requirements, according to different grid codes, are discussed in Section 2. Section 3 briefly studied the state of the art LVRT techniques for the DFIG system. The HVRT techniques for the DFIG system are discussed in Section 4. The comparative analysis of some traditional FRT techniques in the literature is carried out in Section 5. The future trends regarding both the LVRT and HVRT techniques for the DFIG system are put forward in Section 6. Finally, Section 7 is summing up with the conclusions.

2 | FRT REQUIREMENTS

Figure 1 shows a grid-connected DFIG system, where two-level control blocks, wind turbine (WT) level control, and converter level control, are adopted. The WT level control is responsible for computing the reference rotor speed on the basis of measured wind speed and optimum power-speed characteristic curve. Additionally, the WT mechanical power output is controlled by the WT level control using a pitch angle controller. The converter level control decouples the active and reactive power employing the vector control (VC) for the rotor side converter (RSC) and grid side converter (GSC). More details about the DFIG model and the schematic diagram of the VC for RSC and GSC are given in Appendix-A and Appendix-B, respectively.

The disconnection of large scale WTs may occur due to grid disturbance and cause instability in the operation of the DFIG system. If the WT does not have FRT capability and is disconnected from the grid due to a voltage fault in the power grid, it will inevitably cause a gap in the grid power, causing a chain reaction, and influencing the stability of the power system. The LVRT and HVRT requirements, according to different codes, are given in the following paragraphs of this paper.

2.1 | LVRT requirements

Literature [23] firstly proposed the LVRT requirement for the WTs in 2003, and the LVRT has been researched for more than one decade. LVRT has become a vital feature of the WT and is implemented by a transmission system operator (TSO) worldwide. The WT must be grid connected for a given period of time under voltage dips to maintain the stability of the power system. Furthermore, the WT must deliver reactive power to the grid for the voltage recovery. Figure 2 shows the stringent mandatory grid code requirements for several countries with
different voltage dip profiles (depth and duration). Additionally, Table 1 summarised the data used in Figure 2 according to the LVRT requirements for different countries. As can be seen in Figure 2 and Table 1, the LVRT grid code in Belgium, Germany, and Canada are rigorous and needs a WT to withstand zero PCC voltage for a specific duration of time. The LVRT grid code of Spain, Italy, and the USA are more challenging in terms of protection time, i.e. greater than 500 ms. Moreover, the WT must be connected to the grid for the duration of 625 ms under 80% voltage dips according to the grid code of China.

### 2.2 HVRT requirements

Australia firstly defined the HVRT requirements for grid-connected WTs. According to the grid code of Australia, when the grid voltage surges to 1.3 times the rated voltage, the WT should stay connected to the grid for 60 ms and provides sufficient fault recovery current.

The HVRT requirements are typically considered to be fulfilled at wind farms rather than at the WT level. According to the Chinese grid code (GB/T 19963-2011), the HVRT capabilities of WTs are put forward together with the LVRT requirements. Nevertheless, the Chinese grid code requirements are a WT level, and generically, if there is a temporary overvoltage at the PCC (1.30 p.u./0.5 s; 1.25 p.u./0.8 s; 1.15 p.u./8.0 s), WT needs to remain grid connected.

The German E.ON standard requires that the WT can maintain long-term offline operation when the grid voltage swells up to 1.2 times the rated voltage, and the WT must absorb a certain amount of reactive power and reactive current. The ability to ride through high grid voltage faults is then a mandatory requirement in current grid codes of various countries. Figure 3 depicts the HVRT requirements according to different grid codes. Australia and Spain have strict HVRT requirements, as can be seen in Figure 3.

### 3 LVRT TECHNIQUES FOR DFIG SYSTEM

Many LVRT techniques for the DFIG system have been proposed in the literature to comply with the grid code. The existing LVRT techniques can be categorised into the following three main groups: (1) protection-based- LVRT techniques; (2) reactive power injection-based LVRT techniques; (3) Software-based LVRT techniques. The first two groups come under the category of hardware based LVRT techniques in a broad sense. Wherein the additional hardware must be connected to the DFIG system to augment the LVRT requirements for the DFIG system. As demonstrated in Figure 2, many techniques were anticipated to bequeath the DFIG system with low voltage ride-through abilities. More explanation
3.1 Protection-based LVRT techniques

In the literature [24–46], different auxiliary protection devices have been used to supplement the LVRT requirements for the DFIG system, which will be explained in the following paragraph of the paper.

3.1.1 Crowbar

The classical protective device (connected between the DFIG rotor and RSC), called crowbar, is used to meet the LVRT requirements of the DFIG system. The crowbar is activated when the grid voltage dip is perceived. Then, the high rotor current flows into the resistor rather than RSC. Both passive and active crowbar can protect the RSC of the DFIG, but the advantages of fast transient response are associated with the active crowbar [24–26]. The selection of crowbar resistance (Re) is one of the most critical parameters of crowbar technology. The large value of Re can limit the high rotor current. Nevertheless, the small value of Re is selected to elude too high voltage in the rotor circuit. So a trade-off should be made between a maximum and a minimum value of Re [27–29].

Anti-parallel thyristor and diode-based crowbar is the most commonly used active crowbar technology [30]. The diode bridge crowbar, contrary to the thyristor-based crowbar, is less expensive. Three-phase dc crowbar is another type of active crowbar. Moreover, literature [31] and [32] provide a detailed discussion on the crowbar triggering. However, the DFIG equipped with crowbar technology acts as a squirrel cage induction generator during grid fault and cannot provide reactive power support to the grid and further degrades the grid voltage [33]. Three different types of crowbar are shown in Figure 5.

FIGURE 3  HVRT requirements in various grid codes

FIGURE 4  LVRT techniques for DFIG system
3.1.2 | Series dynamic braking resistor (SDBR)

A resistor with a parallel insulated gate bipolar transistor (IGBT) circuit connected between the DFIG and the grid constitutes an arrangement called SDBR, as shown in Figure 6(a). During the grid fault to eradicate the necessity for pitch control for the DFIG system, the SDBR works as an active power balancer. The most critical parameter of the SDBR is a series resistor. During grid faults scenarios, the series resistor improves the grid voltage to meet the LVRT requirements of the DFIG system. SDBR can be used effectively for augmenting the LVRT support of large wind farms. Furthermore, the SDBR can be centralised or distributed, and it eliminates the use of pitch control for wind farms or reactive power control [34]. Literature [35] combines some other devices with SDBR to improve the stability together with LVRT support. The modulated series dynamic braking resistor (MSDBR) eliminates the use of a crowbar and dc-link chopper. The parallel connection of two anti-series IGBTs having a braking resistor per phase constitutes the MSDBR module, as can be seen in Figure 6(b). Literature [36] introduced a new MSDBR. The pulse width modulator (PWM) controls the stator phase voltage independently. Stator voltage restorations maintain constant dc-link voltage, keep the current under the limits of over-current, and eliminates the overcharging in the dc-link capacitor. Different controllers have been proposed for SDBR to optimise the series resistance of the SDBR. Recently, [37] proposed the double braking resistors using fuzzy control to improve the DFIG performance under LVRT. An alternative hardware-based solution called stator-series passive resistive hardware (SSPRH) is recently proposed in [38]. The SSPRH comprises a passive resistor connected in parallel to a bypass static switch and is placed in series with stator windings. The schematic diagram of SSPRH is shown in Figure 6(c).

3.1.3 | dc-link chopper

During grid voltage dips, the dc-link voltage increases and may damage the dc-link capacitor and the power converter if no countermeasure is employed. A dc-link chopper is a parallel connected LVRT device (connected in parallel with the dc-link capacitor between RSC and GSC) to maintain the constant dc-link voltage. Figure 7(a) depicts the schematic diagram of the traditional dc-link chopper. A braking resistor in the dc-link chopper configuration is employed, which can accept the transient rotor current to maintain a constant dc-link voltage. The
inserting and quitting time of the dc-chopper is controlled by the series connected IGBT. Under normal operating conditions, the switch is an open state. Once the over-voltage across the dc-link is detected, the switch closes, and the excess of energy is dissipated in the resistor to limit the $V_{dc}\,$.

Literature [39] proposed a modified dc-link chopper, which has dual functionality, such as to reduce the rotor over-current together with dc-link over-voltage, as shown in Figure 7(b). The modified dc-link chopper keeps the stator and rotor transient current under the limits of over-current, and it can maintain the constant dc-link voltage. In the course of normal operation, the modified dc-link chopper maintains the constant voltage across the dc-link capacitor under any small disturbance. Recently a super-conductor (SC)-based dc-link chopper is proposed in [40] as depicted in Figure 7(c). In the proposed configurations, the dc-link chopper duty cycle controls the energy exchange between the SC and the DFIG system.

3.1.4 Fault current limiter (FCL)

FCL is mainly used to restrain the fault current of the DFIG system to an adequate range by rapidly introducing a series inductor in the failure path. Literature [41] provided a detailed study of different types of FCL. The FCL is commonly categorised into two kinds of non-super-conducting and superconducting FCL. The FCL comprises a switch, inductor, and arrester employed between RSC and DFIG rotor windings, as shown in Figure 8(a). Literature [42] proposed the superconducting magnetic energy storage with fault current limiter (SMES-FCL). The SMES-FCL owed fast response and effective fault current reduction. Moreover, literature [43] gave a comprehensive review of different types of FCL. Figure 8(b) illustrates the schematic diagram of SMES-FCL.

In the literature [44–46], the combined protection-based LVRT techniques had also been studied. The crowbar with the series RL, series dynamic braking resistor (SDBR), and the dc-link chopper have been proposed in [44], [45], and [46], respectively.

3.2 Reactive power injection-based LVRT techniques

Dynamic voltage restorer (DVR), static Var compensator (SVC), static synchronous compensator (STATCOM), and unified power flow controller (UPFC) are the most promising reactive power injection based devices which can tackle the LVRT capability of the DFIG system. They are customarily categorised into shunt compensation and series compensation based devices, which will be explained in the following paragraph of the paper.

3.2.1 Shunt compensation

Flexible ac transmission system (FACTS) devices are based on shunt or series compensation and mainly used in the power system for improving power transfer capability and stability [47]. Among different FACTS devices, STATCOM and SVC are the most popular and widely used shunt compensated FACTS devices.

SVC is the combination of a thyristor controlled reactor, and thyristor switched capacitor. Generally, the SVC can inject the reactive into the connected bus to improve the transient...
stability and damp the oscillation in a grid connected DFIG system. The bus voltage connected to the SVC is controlled by the reactive power dynamic variations. Figure 9 depicts the schematic diagram of the SVC for the DFIG system to meet the LVRT requirements.

The STATCOM is a power electronic device that works on the principle of voltage source converter (VSC). The STATCOM may comprise a two or three-level VSC. STATCOM injects/absorbs reactive to/from the grid to enhance the voltage regulation and improve the stability in steady-state conditions. Additionally, during fault conditions, the STATCOM can inject the maximum reactive into the grid. Contrary to SVC, the STATCOM has a high control bandwidth. Literature [48] proposed the STATCOM to realise the FRT of the DFIG system and its schematic diagram is depicted in Figure 10.

3.2.2 Series compensation

An alternative to shunt compensated FACTS devices, the DVR is a series compensated FACTS devices. The power rating of the DVR mainly depends upon the degree of grid voltage dips, which leads to high cost, and this is the major disadvantage of the DVR based LVRT solution. The schematic diagram of the typical DVR for LVRT support of the DFIG is shown in Figure 11. As can be seen in Figure 11 that the DVR essentially entertains as a voltage source inverter (VSI). The DVR is placed between the DFIG and the grid using a series injection transformer. Additionally, the DVR comprises a filter, energy storage unit, and a bypass switch.

Some researchers used the principle of DVR to optimise the LVRT performance of the DFIG system with low converter ratings. Literature [49] proposed a series compensation based LVRT solution for the DFIG system. The basic principle of the proposed configuration has an arrangement similar to the DVR. However, better LVRT performance for the DFIG system is achieved. Figure 12 shows a series GSC (SGSC) to enhance the LVRT of the DFIG system, proposed in [50]. The reduced power rating of SGSC, contrary to the DVR, is the main advantage of this protection scheme. Literature [51] proposed the SGSC connected at Y-point of the DFIG system without an injection transformer, as illustrated in Figure 13. There are some disadvantages to the proposed SGSC methods. Firstly, the control of back to back power converter is not decoupled with the SGSC control. So it is a tedious job to decouple the control of these converters. There must be circulating current between the GSC and the SGSC, which needs further control to suppress the circulating current; thus, the control algorithm is getting more complicated. The injection transformer is relatively bulky and costly for the overall system.

The combination of series and shunt voltage compensation, known as hybrid compensation, can also be used an LVRT technology for the DFIG system. Literature [52] proposed a unified power flow conditioner (UPFC) to improve the LVRT performance of the DFIG system. The DFIG system with the UPFC is shown in Figure 14. The advantages of the SVC and...
TABLE 2  Protection-based LVRT techniques for DFIG system

| Technology   | Cost | Complexity | Reliability | Response speed | ADC |
|--------------|------|------------|-------------|----------------|-----|
| Crowbar      | Low  | Low        | Low         | Slow           | No  |
| SDBR         | Low  | Low        | Low         | Slow           | No  |
| FCL          | High | High       | Medium      | Fast           | No  |
| DC-Chopper   | Medium| High       | High        | Fast           | No  |

STATCOM may be combined in the UPFC arrangement, but the hardware cost will be increased.

The comparisons of protection based LVRT solutions are given in Table 2 in terms of different parameters. Likewise, the comparasions of different reactive power injection based LVRT solutions for DFIG system are depicted in Table 3. ADC represents anti disturbance capability in Tables 2, 3, and 4. Based on the data given in Tables 2 and 3, a careful attention must be paid while selecting the LVRT techniques for the DFIG system.

3.3  Software-based LVRT techniques

Software-based LVRT techniques do not need any auxiliary device to ride through low voltage fault of the DFIG system. Therefore, software based LVRT techniques are used as an alternative to hardware-based LVRT techniques in the literature [55–80] and are explained in the following paragraph of this paper.

3.3.1  Modified vector control algorithms

In VC, the stator is customarily assumed to be constant and aligned with the d-axis of the stator frame of reference to simplify the design of the current controller of the RSC and GSC under steady-state conditions. Literature [53] proposed the feed-forward transient current control (FFTCC) scheme in aims to improve the LVRT capability of the DFIG system with a slight modification in a traditional VC. Literature [54] introduced the virtual resistance in the conventional VC of the RSC to guarantee the better LVRT performance of the DFIG system. A virtual damping flux based LVRT technique is proposed in [55]. Literature [56] proposed a radical LVRT control scheme, which during a grid fault momentarily stored some of the captured wind energy as the rotor inertia, while the rest of the energy is supplied to the grid to keep the dc-link voltage and rotor current under their threshold limits. Additionally, the proposed control released the excessive inertia during the post fault scenario for the normal operation restoration. Literature [57] designed a novel flux-linkage control strategy to improve the LVRT performance of the DFIG system. Literature [58] proposed a new inductance emulating-based LVRT technique to further enhance the DFIG performance under LVRT. Literature [59] modify the RSC controller by adding feed-forward current references control (FCRC) to improve the transient control and LVRT performance of the DFIG system.

3.3.2  Hysteresis control approach

A nonlinear feedback loop with two-level hysteresis comparators constitutes a hysteresis control approach is shown in Figure 15. When the error crosses the threshold tolerance band, the switching signals (δA, δB, and δC) will be generated for space vector modulation (SVM) and then supplied as input to the inverter. Simple control, high robustness, better accuracy, independent of load, and excellent dynamic performance are the advantages associated with the hysteresis control approach. Nevertheless, the dynamic performance of hysteresis control are speed, load, and time constant dependent. As can be seen in Figure 15, the RSC acquires the switching signals using vector-based hysteresis current regulator under the grid faults. Due to the more straightforward control structure and the intrinsic
peak current limiting features, the hysteresis current controller is superior to the predictive current controllers [60]. Literature [61] proposed the vector-based hysteresis and the advanced hysteresis control for the RSC of the DFIG system. The fast, steady state and excellent dynamic performance are guaranteed for the proposed hysteresis control as compared to the traditional VC. Application of the Hysteresis control approach is applied to SMES connected to the DFIG system is proposed in [62] under grid voltage sags and swell. Literature [63] introduced the hysteresis controller to improve the LVRT performance of the DFIG system. Nevertheless, the hysteresis current controller suffers some drawbacks like high chattering [64], significant harmonics [65], and extended operating time [66].

3.3.3 Advanced control techniques

There are also some advanced control techniques like sliding mode control (SMC), fuzzy logic control (FLC), model predictive control (MPC), and active disturbance rejection control (ADRC), which can guarantee the optimal LVRT performance of the DFIG system. The explanations regarding the aforementioned advanced controller techniques is given as follows.

SMC is a non-linear control technique that modifies the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to “slide” along a cross-section of the system’s normal behaviour. The SMC comprises an algorithm inherently robust to deviations in the parameters, non-linear models, external disturbances, and uncertainty. The FLC deals with perceptive that is approximate having linguistic values rather than brittle values. Fuzzy logic grips the idea of true value that ranges between entirely true and completely false (0-1). Predictive current control attracts much attention due to the increasing growth of digital signal processors. MPC uses the dynamic model of the system to predict its future assessment and optimise the control signal. The discrete model of the inverter is utilised to visualise its future behaviour for all possible control inputs, and therefore relating the one that is anticipated to minimise the cost function. The ADRC is a robust control scheme with strong anti-disturbance capability, high accuracy, fast response, and a simple structure. Using modern control theory, the tracking differentiator (TD), the extended state observer (ESO), and the state error feedback control law (SEF) significantly improve the robustness of the system. The schematic diagram of the ADRC is shown in Figure 16. The state of the art advanced control techniques to augment the LVRT for the DFIG system is discussed in the following paragraph of this paper.

The direct power controller based on MPC for the DFIG system under an unbalanced grid fault was proposed in [67]. Literature [68] proposed the MPC to improve DFIG system performance under LVRT. Literature [69] introduced the finite control set MPC into the GSC of the WT. Literature [70] gave a detailed analysis of the LVRT of the DFIG system using MPC. Handling the non-linear conditions during grid disturbances makes the MPC one of the most prevalent non-linear techniques for the LVRT support of the DFIG system. Further research needs to be investigated on the MPC-based LVRT techniques of the DFIG system.

Literature [71] proposed an FLC scheme to accomplish a better FRT capability of the hybrid energy system. Literature [72] and [73] proposed an FLC, which brings sufficient coordination between the dc-link voltage and battery energy storage systems (BESS) control to improve the LVRT capability of the DFIG system. The FLC-based FRT control for the DFIG system in both active and passive techniques may bring new research in this era.

SMC is recommended as an appropriate choice to further tackle the FRT requirement of the DFIG system [74]. Literature [75] proposed a second-order SMC-based LVRT technique for the DFIG system. Literature [76] and [77] proposed a high-order SMC to overwhelmed the chattering problem and the injected stator current harmonics into the grid to improve the LVRT performance of the DFIG system.

Literature [78] designed an ADRC controller for RSC of the DFIG system to improve the LVRT performance. Recently [79] and [80] designed ADRC based LVRT schemes for the DFIG system. Owing to the advantages like high anti-disturbance, fast response, and less chattering problems compared to SMC, the ADRC can be considered as a vital LVRT scheme for the DFIG system.

Likewise, Tables 2 and 3, the comparisons of different software based LVRT techniques in term of different parameters are given in Table 4. It can be seen in Table 4 that ADRC-based LVRT techniques have high anti disturbance capabilities and high response response speed. So, to tackle the LVRT for
4.1 Hardware-based HVRT techniques

Literature [81] implements the HVRT function of DFIG by appropriately inputting the crowbar circuit. Still, this control strategy increases the hardware cost, and the repeated switching of the crowbar circuit will have a more substantial influence on the output power of the system. Literature [82] and [83] proposed STATCOM and DVR to compensate for the voltage swell. The DVR can sustain constant grid voltage by compensating the voltage difference. STATCOM can keep constant grid voltage by controlling the power injected into the power grid. Later on, literature [84] proposed D-STATCOM to improve the DFIG performance under HVRT. Literature [85] proposed the series grid side SGSC connected to the DFIG stator terminal, which can suppress the stator flux transient dc component. Therefore, the SGSC has the potential to suppress rotor over-current, over-voltage, and electromagnetic torque fluctuation under symmetrical grid voltage swell. Literature [86] introduced the chopper circuit to keep the constant dc-link voltage under voltage swell. Literature [31] introduced a series resistance to the RSC to meet the HVRT requirements of the DFIG system. Nevertheless, the reduction in system efficiency and high system losses are the drawbacks associated with the proposed schemes. Literature [62] put forward the SMES as an HVRT technology for the DFIG system. The proposed SEMS improved DFIG dynamic performance. However, the high cost of SMES is still an issue.

4.2 Software-based HVRT techniques

Literature [87] used the resonant controller contrary to the traditional PI controller to achieve excellent dynamic performance and effectively reduce the transient impact of rotor current during grid faults. Literature [88] proposed a flexible and variable dc-bus voltage control strategy, which reduces the power loss of power converter during faults and improves the efficiency of the DFIG systems. Literature [89] proposed the asymmetrical HVRT control for the DFIG system. Literature [90] and [91] proposed active resistance and virtual impedance-based improved HVRT control for the DFIG system, respectively. In case of active resistance, the system losses will be increased, while the virtual impedance-based HVRT techniques need careful attention for parameter tuning and increases the system complexity. Literature [92] proposed an enhanced field-oriented control technique (EFOC) for the DFIG system to encounter the HVRT requirements. Nevertheless, under severe voltage swell conditions, the dynamic performance of the DFIG system might be degraded as the GSC is ignored in the proposed configuration. Literature [93] proposed the improved control strategy for GSC by modifying the reference dc-link voltage to enhance the DFIG system performance under HVRT. Literature [94] designed the d-axis and q-axis adaptive terminal sliding mode controllers (ATSMC) in the synchronous rotating coordinate system to enhance the HVRT capability DFIG system. The comparisons of hardware and software-based HVRT techniques are listed in Table 5. CWI represents the current wind.
industry. It can be seen in Table 5 that the hardware-based HVRT techniques have higher cost as compared to software-based HVRT techniques. However, the software-based techniques are not currently applicable in wind power industry.

5 | SIMULATION ANALYSIS: A CASE STUDY

In this section, the state of the art LVRT technologies for DFIG system are compared. The simulation results for DFIG system under one LVRT solution among the main groups (protection-based, reactive power injection-based and software-based) will be studied in this section. The simulation results for three FRT techniques such as, active crowbar, DVR and SMC will be compared in this section for grid connected DFIG system (see Figure 18). 9 MW wind farm with six 1.5 MW DFIG WT (developed in Matlab/Simulink) is provided for the simulation analysis, with wind speed is set at 15m/s. The three-phase to ground fault (with \( R_g = 0.5 \, \Omega \)) occurs at the center of 25 kV feeders at 0 s and is cleared at 0.1 s. Additionally, the limit of maximum rotor current is set at 2 p.u according to grid code requirements for LVRT.

Figure 19 shows the simulation results for the DFIG system employing the active crowbar as an LVRT solution. As can be seen in Figure 19(a) that the rotor current is kept well below the limit of overcurrent. The dc-link voltage is shown in Figure 19(b). It can be seen in Figure 19(b), that the dc-link voltage is also in the allowable limit of over-voltage. The crowbar can keep the dc-link voltage in allowable limits. However, the dc-link chopper is normally adopted in the commercial DFIG system to keep the smooth and regulated dc-link voltage. The reactive power is shown in Figure 19(c). Active crowbar cannot provide the reactive power support, as the reactive power generation mainly depends upon the RSC control. This is the main disadvantage of the crowbar.

Figure 20 shows the simulation results for the DFIG system employing the DVR as an LVRT solution. As can be seen in Figure 20(a) that the DVR can keep the rotor current in allowable limits of overcurrent by injecting series voltage during fault period. The dc-link voltage is shown in Figure 20(b). It can be seen in Figure 20(b), that the dc-link voltage is also in the allowable limit of over-voltage. However, more transient in dc-link voltage contrary to crowbar. The reactive power provided by DVR is given in Figure 20(c).

Figure 21 shows the simulation results for the DFIG system employing the SMC controller in RSC, as an LVRT solution. Figure 21(a) shows the rotor current, and is below the limit of over-current. The dc-link voltage is shown in Figure 21(b). It can be seen in Figure 21(b), that the dc-link voltage is well regulated contrary to crowbar and DVR. The reactive power power support is given in Figure 21(c). The performance of the SMC-based LVRT techniques in term of reactive power support during fault is not good as DVR.

| Technology          | Cost  | Complexity | Reliability | Voltage swell | CWI  | Grid faults   |
|---------------------|-------|------------|-------------|---------------|------|---------------|
| Software-based      | Low   | Low        | High        | Moderate      | No   | Symmetrical   |
| Hardware-based      | High  | High       | Low         | Severe        | Yes  | All           |

FIGURE 18 Structure of grid-connected DFIG system for simulation analysis

FIGURE 19 Simulation results for DFIG system with active crowbar. (a) Rotor current, (b) dc-link voltage, (c) reactive power
At present, to employ a large scale of environment friendly renewable energy into the power grid is the research focus of the academia and industry. As a matter of fact, all the WTs should have the ability to ride-through the grid low and high voltage faults according to the grid codes in most of the countries. Recently, the DFIG system operates in a weak grid rather than a strong grid. The voltage dips and swells in the weak grid may cause small signal instability issues and bring undesirable dynamics to the controller of the DFIG system. Furthermore, when the system loses the equilibrium point, the large signal instability problem might be caused by the small signal instability. Hence, under the voltage dips and swell, the stability concerns of the DFIG system under weak grid should be further investigated.

The overall impedance of the present grid with the newly installed wind farm would be decreased. Literature [95] studied the LVRT performance of the DFIG system with a rotor crowbar taking the grid impedance into considerations. The aforementioned study gave the conclusions that the crowbar resistance is influenced mainly by the grid impedance. Additionally, it has been recommended that under the aforementioned scenarios, the design rules for the crowbar resistance selection might be changed. Such a study might apply to the hardware-based LVRT and HVRT techniques such as SDBR and FCL.

Literature [96] proposed the novel cascade converter (CC) for improving the dynamic performance of the DFIG system in a strong grid. The proposed CC can work as an LVRT device and can also improve the DFIG system stability. However, the analysis of the proposed CC has been carried out in a strong grid. The CC can be used as an HVRT device in the strong grid and also can tackle the DFIG system LVRT and HVRT requirements in the weak grid. The reason might be that the CC is an active component and owing to the less power rating contrary to SGSC and other series compensation based devices.

For the reactive power compensation-based techniques, the grid impedance impact might be explored to meet the LVRT and HVRT requirements with the reduced grid impedance in the future grid. For software based LVRT and HVRT techniques, the contemporary trend is toward the most robust and reliable non-linear techniques.

The selection of suitable LVRT and HVRT technology for the DFIG system in terms of cost and complexity is still challengeable task. The trade-off between the cost and complexity
of the hardware-based and software-based techniques requires further investigations. One solution to the problem is the combination of hardware and software based techniques and carried out the analysis at different time-scale.

Furthermore, to achieve protection and then rationally arrange the reactive power support for the DFIG system, the accurate and fast identification of the fault types and attaining the amplitude, phase angle, and frequency of the fundamental voltage are the prerequisites and the key factors for the DFIG system. Under voltage dips and swell conditions, the traditional phase-locked loop (PLL) will have a phase-locking angle and frequency jitter. It is crucial to find a fast, accurate, robust, and predictive phase-locking and phase-sequence separation technology.

With the increase in power rating of the WT, the matrix converter can be used in the DFIG system instead of a two-level VSC due to the advantages like reduced size and weight, high reliability, and enhanced life span due to the absence of the dc bus. Likewise, the multi-level inverter has gained much attention recently in the field of inverter technology. The multi-level features of the aforementioned topology produced the smoother ac output voltage with staircase sinusoidal shape resulting in low harmonic distortion and reduction in the filter components in the high rated generator with FPC WT. There are many types of multi-level inverters such as half-bridge diode clamped inverters, full-bridge single-leg clamped inverters, cascaded inverters, hybrid multi-level inverters and modular multi-level inverters [97, 98]. So the multi-level inverter instead of the two-level inverter has the potential to improve the performance of the DFIG system under FRT. [99] used adaptive SMC for the DFIG system equipped with a matrix converter. [100] put forward a hysteresis based three-level NPC converter to improve the FRT performance of the DFIG system. [101] proposed an improved LVRT technique for the DFIG system based on a three-level converter. [102] used a hybrid multi-level converter instead of a traditional RSC to improve the FRT capability of the DFIG system. [103] studied the operation of the grid-connected DFIG system equipped with diode clamped multi-level inverter. The modern large-scale high power rated generator with FPC WT employing multi-level inverter has guaranteed lower total harmonic distortion. Nevertheless, the dynamic performance of the DFIG system under voltage sag and swell is not studied. The aforementioned techniques for the DFIG equipped with matrix and/or multi-level converter might increase the overall control complexity of the system. Further research might be explored employing matrix and multi-level inverter in the DFIG system instead of a traditional two-level RSC and/or GSC to further improve the performance of the DFIG system under the FRT in different grid codes.

Different LVRT methods have been extensively studied for the DFIG system and categorised into three types of protection-based, reactive power compensation-based and software-based LVRT techniques. The comparison of different LVRT methods has been provided. From the detailed discussion about the LVRT techniques for the DFIG system in this paper, it can be concluded that hardware-based solutions are more suitable as they are applicable in the current wind industry. However, the additional cost of hardware-based protection schemes is the main disadvantage associated with such types of LVRT techniques. On the other hand, the software-based solution can provide a cheap LVRT solution for the DFIG system, but the installation of the software-based LVRT techniques in the wind industry is still challenging.

The HVRT techniques for the DFIG system in the literature have been critically reviewed. The aforementioned techniques are roughly divided into hardware and software techniques. The comparison of different HVRT methods has been provided. From the detailed discussion about the HVRT techniques in this paper, it can be concluded that the HVRT requirement of the DFIG system exists in some grid codes, but it will be mandatory in future grid codes of most of the countries. Additionally, the new and emerging techniques for HVRT have been discussed. From the literature provided in this paper, it can be concluded that the hardware-based protection techniques (STATCOM and DVR) are more superior to the software based HVRT techniques. Finally, the future trends for the LVRT and HVRT techniques for the DFIG system have been discussed.

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References

1. Renewable Capacity Statistics: International Renewable Energy Agency (IRENA), Abu Dhabi (2019) https://www.irena.org/publications/2019/ Mar/Renewable-Capacity-Statistics-2019
2. Etxegarai, A., Eguia, P., Torres, E.: Impact of wind power in isolated power systems. In: 16th IEEE Mediterranean Electrotechnical Conference 928000, 63–66 (2012)
3. National Energy Administration: Announcement of the General Department of the National Energy Administration on Public Consultation on the National Standards, China (2019) http://www.nea.gov.cn
4. Cheng, M., Zhu, Y.: The state of the art of wind energy conversion systems and technologies: A review. Energy Convers. Manag. 88, 332–347 (2014)
5. Müller, S., et al.: Doubly fed induction generator systems for wind turbines. IEEE Ind. Appl. Mag. 8(3), 26–33 (2002)
6. Nian, H., Cheng, P., Zhu, Z.Q.: Independent operation of DFIG-based WECS using resonant feedback compensators under unbalanced grid voltage conditions. IEEE Trans. Power Electron. 30(7), 3650–3661 (2015)
7. Nian, H., et al.: Coordinated direct power control of DFIG system without phase locked loop under unbalanced grid voltage conditions. IEEE Trans. Energy Convers. 31, 2905–2918 (2016)
8. P. Cheng, Nian, H.: Collaborative control of DFIG system during network unbalance using reduced-order generalized integrators. IEEE Trans. Energy Convers. 30(2), 453–464 (2015)

9. Cheng, P., et al.: Direct stator current vector control strategy of DFIG without phase-locked loop during network unbalance. IEEE Trans. Power Electron. 32(1), 284–297 (2017)

10. Zhou, D., et al.: Reduced cost of reactive power in doubly fed induction generator wind turbine system with optimized grid filter. In: 2014 IEEE Energy Conversion Congress Exposition, 1490–1499 (2014)

11. Zhou, D., et al.: Optimized reactive power flow of DFIG power converters for better reliability performance considering grid codes. IEEE Trans. Ind. Electron. 62(3), 1552–1562 (2015)

12. Zhu, R., et al.: Dual-loop control strategy for DFIG-based wind turbines under grid voltage disturbances. IEEE Trans. Power Electron. 31(3), 2239–2253 (2016)

13. Chen, W., et al.: Doubly fed induction generator wind turbine systems subject to recurring symmetrical grid faults. IEEE Trans. Power Electron. 31(2), 1143–1160 (2016)

14. Y. Song, Nian, H.: Modulated control strategy and performance analysis of DFIG system under unbalanced and harmonic grid voltage. IEEE Trans. Power Electron. 30(9), 4831–4842 (2015)

15. H. Nian, Song, Y.: Direct power control of doubly fed induction generator under distorted grid voltage. IEEE Trans. Power Electron. 29(2), 894–905 (2014)

16. Y. Song, Nian, H.: Enhanced grid-connected operation of DFIG using improved repetitive control under generalized harmonic power grid. IEEE Trans. Energy Convers. 30(3), 1019–1029 (2015)

17. Y. Song, Nian, H.: Sinusoidal output current implementation of DFIG using repetitive control under a generalized harmonic power grid with frequency deviation. IEEE Trans. Power Electron. 30(12), 6751–6762 (2015)

18. Zakaiud, D., et al.: A review on Low Voltage Ride - though for DFIG Based Wind Turbines. In: PCIM Asia 2018: International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, pp. 269-274 (2018)

19. H. Howlader, A.M., Senjyu, T.: A comprehensive review of low voltage ride through capability strategies for the wind energy conversion systems. Renew. Sustain. Energy Rev. 56, 643–658 (2016)

20. Rini Ann Jerin, A., et al.: Review on FRT solutions for improving transient stability in DFIG-WTs. IET Renew. Power Gener. 12(15), 1786–1799 (2018)

21. Hu, Y.L., et al.: A review of the low-voltage ride-through capability of wind power generators. Energy Procedia 141, 378–382 (2015)

22. Ezzat, M., et al.: Low-voltage ride-through techniques for DFIG-based wind turbines: State-of-the-art review and future trends. IECON Proceedings Industrial Electronics Conference, pp. 7681-7686 (2013)

23. Erlich, I., Bachmann, U.: Grid code requirements concerning connection and operation of wind turbines in Germany. In: IEEE Power Engineering Society General Meeting 1–5 (2005)

24. Zhang, X., et al.: Response and protection of DFIG system under grid fault. In: Asia-Pacifi Power Energy Engineering Conference 1–5 (2010)

25. Morren, J., Member, S., De Haan, S. W. H.: Ridethrough of wind turbines with doubly-fed induction generator during a voltage dip. IEEE Trans. Energy Convers. 20(2), 435–441 (2005)

26. Zohoori, A., Moghani, J.S., Fathi, S.H.: An optimized crowbar for DFIG stability during voltage dips with crowbar or stator current feedback solution. In: IEEE Energy Conversion Congress and Exposition (ECCE), 3281–3287 (2017)

27. Xue-guang, Z., Dian-guo, X.: Research on control of DFIG with active power filters for enhancement of the stability of wind farm. IEEE Trans. Syst. J. 9(3), 922–932 (2015)

28. Huchel, L., El Moursi, M.S., Hasan, S.: Novel fault ride-through schemes for doubly fed induction generator-based wind turbine. IEEE Trans. Energy Convers. 30(2), 635–645 (2015)

29. Dong, H., et al.: Research on double-fed induction generator low voltage ride through based on double braking resistors using fuzzy control. Energies 11(5), 1–16 (2018)

30. Rahimi, M.: Analytical assessment of the impact of stator-series passive resistive hardware (SSPRH) on transient response and fault current contribution in DFIG based wind turbines. Electr. Power Syst. Res. 177, 105959 (2019)

31. Naderi, S.B., Neznebistky, M., Muttaqi, K.M.: A modified DC chopper for limiting the fault current and controlling the DC-link voltage to enhance fault ride-through capability of doubly-fed induction-generator-based wind turbine. IEEE Trans. Ind. Appl. 55(2), 2021–2032 (2019)

32. Mosaad, M.I., Abu-Siada, A., Elmagarr, M.: Application of supercapacitors to improve the performance of DFIG-based WECS. IEEE Access 7, 103760–103769 (2019)

33. Verma, M., La Ree, J.D.: A comprehensive overview, behavioral model and simulation of a fault current limiter. Dissertation, Virginia Polytechnic Institute and State University (2009)

34. Ngamroo, T., Karapoom, T.: Cooperative control of SFCL and SMES for enhancing fault ride through capability and smoothing power fluctuation of DFIG wind farm. IEEE Trans. Appl. Supercond. 24(5), 5700805 (2014)

35. Naderi, S.B., et al.: A review on fault current limiting devices to enhance the fault ride-through capability of the doubly-fed induction generator basedwind turbine. Appl. Sci. 8(11), 1–24 (2018)

36. Justo, J.J., Bansal, R.C.: Parallel R-L configuration crowbar with series R-L circuit protection for LVRT strategy of DFIG under transient-state. Electr. Power Syst. Res. 154, 299–310 (2018)

37. Yang, J., et al.: Protection scheme for doubly-fed induction generator during various fault conditions. IEEE Trans. Energy Convers. 25(2), 442–452 (2010)

38. Huchel, L., El Moursi, M.S., Zeineldeen, H.H.: A parallel capacitor control strategy for enhanced FRT capability of DFIG. IEEE Trans. Sustain. Energy 6(2), 303–312 (2015)

39. Hammons, T.J., Lim, S.K.: Flexible ac transmission systems (FACTS). Electric Power Systems Research 154, 299–310 (2018)

40. Abdul-Baqi, O., Nasiri, A.: Series voltage compensation for DFIG wind turbine low-voltage ride-through solution. IEEE Trans. Energy Convers. 26(1), 272–280 (2011)

41. Zhan, C., Barker, C.D.: Fault ride-through capability investigation of a doubly-fed induction generator with an additional series-connected voltage source converter. In: 8th IEEE International Conference on AC and DC Power Transmission, 79–84 (2016)

42. De Oliveira, I.A.C., et al.: Wind energy conversion system based on DFIG with series grid side converter without transformer. In: IEEE Energy Conversion Congress and Exposition (ECCE), 3281–3287 (2017)
Li, S., Huang, J., Sun, T.: Analytical LVRT analysis of DFIG with model predictive control. IEEE Trans. Energy Convers. 25(3), 836–843 (2010)

Hu, S., et al.: An improved low-voltage ride-through control strategy of doubly fed induction generator during grid faults. IEEE Trans. Power Electron. 26(12), 3653–3665 (2010)

Zhu, R., et al.: Virtual damping flux-based LVRT control for DFIG-based wind turbine. IEEE Trans. Energy Convers. 30(2), 714–725 (2015)

Xie, D., et al.: A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support. IEEE Trans. Power Syst. 28(3), 3302–3310 (2013)

Xiao, S., et al.: An LVRT control strategy based on flux linkage tracking for DFIG-based WECS. IEEE Trans. Ind. Electron. 60(7), 2820–2832 (2013)

Zhu, D., et al.: Inductance-emulating control for DFIG-based wind turbine to ride through grid faults. IEEE Trans. Power Electron. 32(11), 8514–8525 (2017)

Zhu, D., et al.: Feedforward current references control for DFIG-based wind turbine to improve transient control performance during grid faults. IEEE Trans. Energy Convers. 33(2), 670–681 (2018)

Mohseni, M., Islam, S., Masoum, M.A.S.: Fault ride-through capability enhancement of doubly-fed induction wind generators. IET Renew. Power Gener. 5(5), 368–376 (2011)

Mohseni, M., Islam, S.M., Masoum, M.A.S.: Enhanced hysteresis-based current regulators in vector control of DFIG wind turbines. IEEE Trans. Power Electron. 26(1), 223–234 (2011)

Yunus, A.M.S., et al.: Application of SMES to enhance the dynamic performance of DFIG during voltage sag and swell. IEEE Trans. Appl. Supercond. 22(4), 1–9 (2012)

Ling, Y.: Improvement of fault ride through capability of doubly-fed induction generator wind turbines with hysteresis controller. Wind Energy 38(6), 659–672 (2014)

Mishra, T., et al.: Comparative analysis of hysteresis current control and SVPWM on fuzzy logic based vector controlled induction motor drive. In: 1st IEEE International Conference Power Electronics Intelligent Control Energy Systems ICEPTICES, 2, 1–6 (2016)

Ting, N.S., et al.: Comparison of SVPWM, SPWM and HCC control techniques in power control of PMSG used in wind turbine systems. 2015 International Aegaean Conference on Electrical Machines and Power Electronics (ACEEMP), 2015 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM); and 2015 International Symposium on Advanced Electromechanical Motion Systems (ELECTROMOTION), pp. 69–74 (2016)

Kazem Mokarian, M., Malesani, L.: Current control techniques for three-phase voltage-source PWM converters: A survey. IEEE Trans. Ind. Electron. 45(5), 691–703 (1998)

Hu, J., et al.: Model-predictive direct power control of doubly-fed induction generators under unbalanced grid voltage conditions in wind energy applications. IET Renew. Power Gener. 8(6), 687–695 (2014)

Yuan, J., et al.: Research on low-voltage ride through control based on model predictive control. J. Eng. 2017(13), 2114–2118 (2017)

Shen, Y.-W., et al.: Finite control set model predictive control for complex energy system with large-scale wind power. Complexity, 2019, 1–13 (2019)

Li, S., Huang, J., Sun, T.: Analytical LVRT analysis of DFIG with model predictive control-based direct stator/rotor current controls. IET Renew. Power Gener. 13(13), 2462–2472 (2019)

Roy, A.K., Basak, P., Biswal, G.R.: Low voltage ride through capability enhancement in a grid-connected wind/fuel cell hybrid system via combined feedforward and fuzzy logic control. IET Gener. Transm. Distrib. 13(13), 2866–2876 (2019)

Kazhali, M., Isaac, S.J., Poongothai, S.: Improvement of low voltage ride through capability of grid-connected DFIG WTs using fuzzy logic controller. In: International Conference on Intelligent Computing and Applications 846, 349–359 (2019)

Rousch, T., El-Bachti, R.: Improvement low-voltage ride-through control of DFIG during grid faults. In: International Conference Multimedia Computing Systems, pp. 1596-1601 (2014)

Martinez, M.L., et al.: Sliding-mode control for DFIG rotor- and grid-side converters under unbalanced and harmonically distorted grid voltage. IEEE Trans. Energy Convers. 27(2), 328–339 (2012)

Benbourzid, M., et al.: Second-order sliding mode control for DFIG-based wind turbines fault ride-through capability enhancement. ISA Trans. 53(3), 827–833 (2014)

Zheng, X., Wei, W., Xu, D.: Higher-order sliding mode control of DFIG wind energy system under LVRT. In: Proceedings Asia-Pacific Power Energy Engineering Conference, 1–4 (2010)

Kerrouche, K.D.E., et al.: A comprehensive review of LVRT capability and sliding mode control of grid-connected wind-turbine-driven doubly fed induction generator. Automatika 57(4), 922–935 (2016)

Chowdhury, M.A., et al.: Robust active disturbance rejection controller design to improve low-voltage ride-through capability of doubly fed induction generator wind farms. IET Renew. Power Gener. 9(8), 961–969 (2015)

Yang, C., Yang, X., Sharda, Y.A.W.: An ADRC-based control strategy for FRT improvement of wind power generation with a doubly-fed induction generator. Energies 11(5), 1–19 (2018)

Beltran-Pulido, A., Cortes-Romero, J., Coral-Enriquez, H.: Robust active disturbance rejection controller for LVRT capability enhancement of DFIG-based wind turbines. Control Eng. Pract. 77, 174–189 (2018)

Zhang, X., Xie, Z., Cao, R.: Dynamic analysis of doubly fed induction generator during symmetrical voltage swells. In: Second International Conference on Mechanic Automation and Control Engineering, 1245–1248 (2011)

Taylor, P., Eskander, M.N., Amer, S.I.: Mitigation of voltage dips and swells in grid-connected wind energy conversion systems mitigation of voltage dips and swells in grid-connected wind energy conversion systems. IETE J. Res., 2014, 37–41 (2015)

Wessels, C., et al.: High Voltage Ride Through with FACTS for DFIG Based Wind Turbines. In: 13th European Conference on Power Electronics and Applications Barcelona, Spain, 1–10 (2009)

Li, G., Zheng, R., Chen, H.: Improvement of high-voltage-ride-through capability of DFIG based wind turbines with D-STATCOM. Appl. Mech. Mater. 453, 1773–1778 (2014)

Boukhirs, Y., et al.: High voltage ride-through capability using series grid side converter for doubly fed induction generator based wind turbines. In: 3rd International Renewable and Sustainable Energy Conference (IRSEC), 1–6 (2015)

Fortmann, J., et al.: High Voltage Ride Through of DFIG-based Wind Turbines. In: Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1–8 (2008)

Xu, H., Member, S., Zhang, W.: Improved vector control of DFIG based wind turbine during grid dips and swells. In: International Conference on Electrical Machines and Systems, pp. 511–515 (2010)

Liu, C., Chen, M.: Flexible control of DC-link voltage for doubly fed induction generator during grid voltage swell. In: IEEE Energy Conversion Congress and Exposition, pp. 3091–3095 (2010)

Li, R., Geng, H., Yang, G.: Asymmetrical high voltage ride through control strategy of grid-side converter for grid-connected renewable energy equipment. In: International Power Electronics and Application Conference and Exposition, pp. 496–501 (2014)

Xie, Z., et al.: High voltage ride through control strategy of doubly fed induction wind generators based on active resistance. In: IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia, pp. 2193–2196 (2012)

Xie, Z., Zhang, X., Zhang, X.: Improved ride-through control of DFIG during grid voltage swell. IEEE Trans. Ind. Electron. 62(6), 3584–3594 (2015)
92. Duggirala, V.N.A., Gundavarapu, V.N.K.: Dynamic stability improvement of grid connected DFIG using enhanced field oriented control technique for high voltage ride through. J. Renew. Energy 2015, 1–14 (2016)
93. Zheng, Z., Yang, G., Geng, H.: Dynamic stability improvement of grid-side converter for DFIG-based WECS. In: IECON Proceedings Industrial Electronics Conference, pp. 5282–5287 (2013)
94. Liu, X., Li, X., Jiao, D.: Theoretical study on control strategy of grid-connected high voltage ride through in doubly-fed wind farm. IEEE Access 7, 107453–107464 (2019)
95. Din, Z., et al.: Impact of grid impedance on LVRT performance of DFIG system with rotor crowbar technology. IEEE Access 7, 127999–128008 (2019)
96. Din, Z., et al.: Doubly fed induction generator with cascade converter for improving dynamic performance. In: 2018 IEEE Energy Conversion Congress and Exposition, ECCE, pp. 2568–2575 (2018)
97. Zhang, J., et al.: Hybrid multilevel converters: Topologies, evolutions and verifications. Energies 12(4), 1–29 (2019)
98. Zhang, J., et al.: Fault diagnosis and monitoring of modular multilevel converter with fast response of voltage sensors. IEEE Trans. Ind. Electron. 67(6), 5071–5080 (2020)
99. Alalei, A., et al.: Adaptive sliding mode control of DFIG fed by matrix converter during grid faults. In: IEEE Conference on Energy Conversion (CENCON), pp. 133–138 (2017)
100. Peng, L., Francois, B., Li, Y.: Low voltage ride-through of high power DFIG wind turbine using three-level NPC converters. In: 35th Annual Conference of IEEE Industrial Electronics, pp. 609–614 (2009)
101. Aziz, B. A., et al.: Improvement FRT capability of DFIG wind energy based on three level converter. Int. J. Curr. Eng. Technol. 5(44), 2277–4106 (2015)
102. Amorim, A.E.A., et al.: A new hybrid multilevel converter for DFIG-based wind turbines fault ride-through and transient stability enhancement. Electr. Eng. 102(2), 1035–1050 (2020)
103. Hossam-Eldin, A.A., et al.: Operation of grid-connected DFIG using SPWM and THPWM-based diode-clamped multilevel inverters. IET Gener. Transm. Distrib. 14(8), 1412–1419 (2020)

APPENDICES A
The equivalent circuit of the DFIG is shown in Figure A.1. Based on Figure A.1, the stator and rotor voltage, and stator and rotor flux can be expressed as

\[ V_s = R_s I_s + \frac{d\psi_s}{dt} + j\omega_s \psi_s \]  
(A.1)

\[ V_r = R_r I_r + \frac{d\psi_r}{dt} + j(\omega - \omega_s)\psi_r \]  
(A.2)

\[ \psi_s = L_s I_s + L_m I_r \]  
(A.3)

\[ \psi_r = L_s I_s + L_m I_r \]  
(A.4)

where \( R_s \) and \( R_r \) is the stator and rotor resistance, respectively; \( \psi_s \) and \( \psi_r \) is the stator and rotor flux linkage, respectively. \( L_s \) and \( L_m \) is the stator and rotor self inductance, and mutual inductance, respectively. Figure A.2 shows the vector control scheme for the RSC and GSC; more detail about it can be found in [95].
**Figure A.1** Equivalent circuit of the DFIG machine

**Figure A.2** Schematic diagram of vector control. (a) RSC, (b) GSC.