SVU-International Journal of Engineering Sciences and Applications (2023) 4(2): 7-23
Print ISSN 2785-9967 | Online ISSN 2735-4571
DOI 10.21608/SVUSRC.2023.180183.1089

# Improved LVRT Techniques for Grid-Connected DFIG Wind Turbines: A Technical Review

**Ali H. Kasem Alaboudy[1], Heba A. Mahmoud[2], Adel A. Elbaset[3], Montaser Abdelsattar[4, □]**

**Abstract**: Wind energy currently represents a very important source of renewable energy sources (RESs). Among other RESs, Wind Energy Conversion Systems (WECS) with Doubly Fed Induction Generators (DFIG) have become more competitive globally. Due to their improved dynamic performance, flexible regulation of active and reactive power, superior power quality, variable speed operation, and four-quadrant converter operation. Grid-connected DFIG-based WECS are vulnerable to disruptions in the grid because of the direct connection of stator windings to the grid. The ability of the wind turbine (WT) to maintain connectivity during grid faults refers to the low-voltage ride-through (LVRT). When DFIG-based WTs are used to power networks, the grid codes require that they stay connected and support the stability of the system in a range of transient grid fault scenarios. As a result, DFIG-WTs are subjected to various protective measures to improve LVRT capacity. To increase DFIG's LVRT capabilities, a lot of good research has taken place in the literature. So, this study centers on exploring the recently emerging LVRT techniques for DFIG-WTs to help wind energy producers/operators select the appropriate technique through critical analysis. According to a wide range of articles, LVRT techniques can be classified into two groups: exterior and interior techniques; each group has its merits and demerits. Also, a thorough discussion has been made to assess the performance. Different case studies using MATLAB/SIMULINK are presented to show the performance of the selected techniques with an explanation of the effectiveness of each technology during grid faults. Finally, this paper suggests guidelines and recommended technical designs for the LVRT techniques for DFIG-WTs to cope with local grid codes.

**Keywords:** RESs; Wind Energy; DFIG; LVRT Techniques.

## 1 Introduction

Until today, the renewable energy sources (RESs) have made significant progress in recent years to fulfill rising energy demands [1]. This is due to multiple benefits such as cheap cost, high efficiency, minimal environmental consequences, and limitless energy sources. Among them, wind energy plays a vital role and has grown at the quickest pace [2, 3]. Where in 2019, 60 GW of installed wind energy capacity was added and 92 GW of installed capacity was added in 2020, despite the coronavirus. By 2025, the global wind energy council (GWEC) predicts even a higher yearly growth of about 94 GW [4, 5]. Wind turbines (WTs) are becoming more common in electrical power networks as wind energy develops. The four fundamental kinds of WTs are: fixed-speed WTs restricted variable-speed-controlled WTs, DFIG-WTs, and complete variable-speed-controlled WTs. In practical applications, DFIG-WTs are the most popular among the four kinds of wind turbines [6, 7].

---

Received: 11 December 2022 / Accepted: 21 January 2023.

□Corresponding Author,
Montaser Abdelsattar, Montaser.A.Elsattar@eng.svu.edu.eg
[1]Faculty of Technology and Education, Suez University, Suez, Egypt.
[2]Faculty of Technology and Education, Sohag University, Sohag, Egypt.
[3]Faculty of Engineering, Minia University, El-Minia, Egypt and Faculty of Engineering, Heliopolis University, Cairo, Egypt.
[4]Faculty of Engineering, South Valley University, Qena, 83523, Egypt.

### 1.1. Literature review

The emergence of efficient wind turbine generators (WTGs) such as the permanent magnet synchronous generator (PMSG) and DFIG has led to a tremendous rise in power generation.

Among all the WTGs, DFIG has number of benefits including variable speed and constant frequency operating, a power control (active/reactive), and power converter ratings are being reduced [8, 9]. As a result of its excellent performance, DFIG is the most extensively used WTG and is unquestionably a market leader. Although benefits of DFIG-WTs, they are extremely susceptible to grid voltage deviations for various grid failures [10-13].

The DFIG stator currents quickly rise over the rated values when a DFIG experiences a sudden decrease in grid effort [14].This is due to the magnetic connection between the stator and the rotor circuits. These currents have the potential to harm the power converter's power electronic equipment.

Furthermore, the electromagnetic torque of the DFIG begins to fluctuate with significant amplitudes; even a minor variation in the grid has an impact on the DFIG's performance. This aspect of DFIG has given rise to the LVRT capability feature. The capacity of a wind turbine generator to stay connected to the grid, and in certain circumstances support it, when the grid is experiencing a fault is known as LVRT capability [15]. To put it in another way, it is WTs' capability to ride through grid fault problems.

During grid voltage failure situations, the focus had previously been on the protection of DFIG-WTs by tripping the turbine. However, the power system is not permitted to disconnect the majority of WTs from the grid. The cause has a significant impact on the power system's ability to operate in a steady and secure manner [16]. As a result, in order to ensure the stable operation of the power system, in certain countries (such as Germany), network operators have revised the grid code by incorporating new standards [17, 18].Turbines should remain linked to the grid during grid failures, according to the new requirements. In order to maintain electrical systems running safely and reliably. Furthermore, WTs must produce reactive current during voltage drops in order to maintain grid effort. This voltage control must be turned on within 20 milliseconds after detecting voltage sag. The voltage dip determines the quantity of reactive current required. WTs must continue to provide active power that is at least 20% higher than the rated power per second after the fault has been addressed [19].

In order to comply with such grid requirements, it is major for the generators to have an improved LVRT capability. As a result, several researchers provided several LVRT-optimized approaches in Refs. [20–25]. To safeguard generators, the solutions employ extra circuitry. A crowbar circuit, direct current (DC) chopper, superconducting fault current limiter (SFCL), series dynamic brake resistor (SDBR), and other circuits may be fitted. Overcurrent suppression, machine torque oscillations, and DC link overvoltage are all included in these approaches. The most common method is to use a crowbar. During a fault, this method draws all of the needed reactive power from the grid, which is extremely undesirable. Furthermore, the controls are separated from the rotor, rendering the system inoperable. Because of the crowbar circuit's flaws, researchers have been looking for other protective mechanisms to improve LVRT capabilities. Various topologies have been proposed over the years.

In Refs. [26-28], LVRT techniques based on power injecting devices are introduced. In such techniques, devices like static synchronous compensators (STATCOM), dynamic voltage restorers (DVR), static synchronous series compensators (SSSC), and thyristor-controlled series compensator (TCSC), are utilized to regulate/optimize grid voltages. These devices can be tuned to push/set active and reactive powers in four quadrants, which will consequently improve its LVRT capabilities of wind generators. Using these devices adds to the system extra equipment/size, which has a negative impact on the compactness feature of the system. Control topologies-based solutions have been shown to be more successful in overcoming these difficulties.

In Refs. [29–32], A combined virtual resistance and degaussing test method is said to have been used. In these topologies, various system controllers are developing to reject perturbations in different parameters like rotor current, electromagnetic torque, and DC-link voltage under fault circumstances in these ways. Because of their potential to efficiently address nonlinear problems, artificial intelligence (AI) approaches have also been investigated. The researchers also gave several categories of LVRT approaches in Refs. [21, 33-35]. However, it is critical to examine thoroughly various LVRT strategies in order to select the optimum option for meeting network needs.

### 1.2. Contribution of paper

As explored in the preceding subsection, several published papers reviewed various LVRT techniques with an in-depth description. Techniques are categorized into numerous classes, which are backed by simulation findings. Other articles follow the evolution of LVRT technology. The review of LVRT techniques can serve as a reference to analyse the existing control methods and identify the prospects for further improvements in this area.

As a result, compared to the many papers previously mentioned, this paper is distinguished by covering most of the LVRT technologies, which meet the requirements of different network codes, while a significant portion was dedicated to LVRT protection circuits and hybrid combinations. However, this paper has mainly focused on dividing LVRT solutions into protection circuits, Flexible Alternating Current Transmission System (FACTS) device-based methods, traditional control methods, and advanced control techniques. Wherefore the lack of comparative analysis results may restrict its application value. Therefore, the analysis results and discussions show the potential of LVRT techniques and provide future research directions based on this work.

***This paper*** gives a comprehensive review and evaluation of the proposed LVRT techniques used in DFIG-WTs to analyse the current level of LVRT techniques is provided with emphasis on their benefits and drawbacks. ***The primary contributions to the paper can be summarized as follows:***

- Present an overview of LVRT techniques for DFIG-WTs that have recently appeared with critical analysis.
- A thorough examination of the numerous characteristics of the techniques used.
- Discuss the effects of LVRT techniques in line with grid codes.
- Using MATLAB/SIMULINK to discuss the influence of the most promising LVRT techniques on DFIG performance.

### *1.3. Layout of paper*

The following is a breakdown of the paper structure: Modelling of a grid-connected DFIG-WT shown in **Section 2. Section 3** discusses the primary contributions of LVRT approaches, including classifications, merits, and demerits, as well as assessments based on grid codes. In **Section 4**, we explore how to increase LVRT capabilities during grid failures by employing better protective strategies using MATLAB/Simulink. The simulation results for LVRT techniques are provided in **Section 5**. The guidelines and recommended technical designs for the LVRT techniques for DFIG-WTs to cope with local grid codes are highlighted in **Section 6.**

## 2 Grid-Connected DFIG-WTs Modelling

In DFIG-WTs, the DFIG stator winding and the grid are directly linked [36]. The turbine controlled by back-to-back power converters, which comprise the rotor side converter (RSC), grid side converter (GSC), and a DC-link capacitor, as shown in **Fig. 1.**

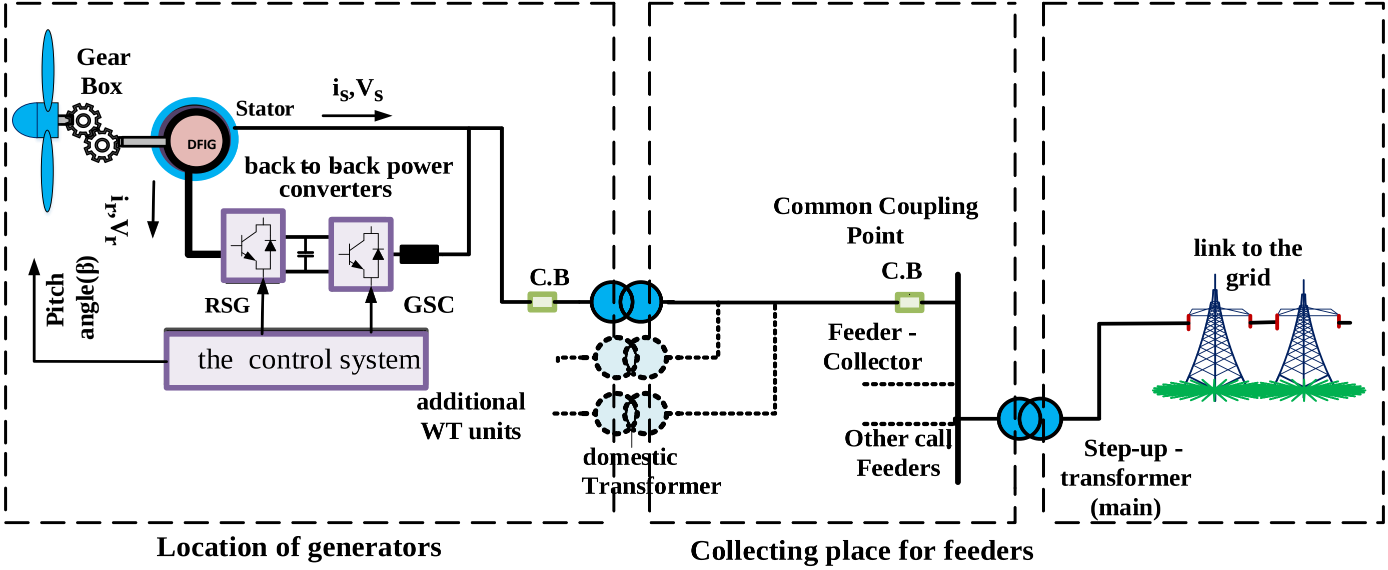

**Fig. 1** The graphic diagram of the grid-connected DFIG -WTs.

The modelling equations are as follows [37]:

$$\vec{V_s} = R_s\ \vec{i_s} + d\vec{\psi_s}/d_t + j\omega_s\ \vec{\psi_s} \quad (1)$$

$$\vec{V_r} = R_r\ \vec{i_r} + d\vec{\psi_r}/d_t + j(\omega_s - \omega_r)\vec{\psi_r} \quad (2)$$

$$\vec{\psi_s} = L_s\ \vec{i_s} + L_m\ \vec{i_r} \quad (3)$$

$$\vec{\psi_r} = L_m\ \vec{i_s} + L_r\ \vec{i_r} \quad (4)$$

The current, voltage, flux, resistance, and inductance are represented as, $\vec{i}$ ,$\vec{V}$,$\vec{\psi}$, R, L, respectively The letters s and r stand for the stator and rotor, respectively. From **Eqs. (3)** ***and (4)***, a list of the stator and rotor currents as follows:

$$\vec{i_s} = \vec{\psi_s}/\dot{L_s} - K_r\ \vec{\psi_r}\ /\ \dot{L_s} \quad (5)$$

$$\vec{i_r} = -K_s\ \vec{\psi_s}/\dot{L_r} - \vec{\psi_r}\ /\ \dot{L_r} \quad (6)$$

## 3 LVRT Techniques

Systematic taxonomy of LVRT optimization techniques is presented as seen in **Fig. 2** which includes **(1)** Exterior LVRT techniques. There are three parts of the exterior techniques that are protection-based techniques, Flexible Alternating Current Transmission System(FACTS)-based Techniques and hybrid techniques. **(2)** Interior LVRT techniques include control strategies-based techniques. The goal of this classification is to offer a more detailed classification, evaluate the various techniques based on their effectiveness and provide a tabular breakdown of the various methods. The next subsections will go over the various techniques.

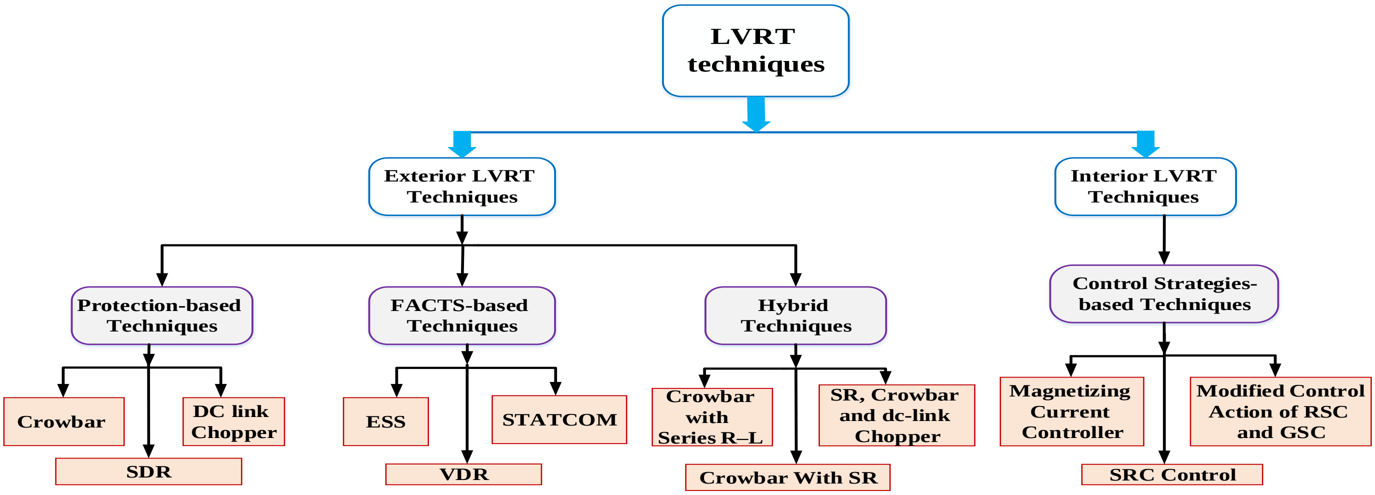

**Fig. 2** Systematic taxonomy of LVRT optimization techniques.

### *3.1 Exterior LVRT techniques*

Crowbar, series resistor (SR), chopper circuit, and other approaches are examples of these techniques. They are divided into rotor and stator side protection circuits based on how they are connected. Initially, the rotor side was home to nearly all of the protective circuits. This configuration, however, resulted in the machine's uncontrolled operation and absorbed a lot of reactive power during breakdowns. To solve these concerns, efforts were made on the stator side to link protective circuits, with promising results [29, 38-42 & 43–45]. All the designs described in this category attempt to meet the requirements of grid codes. Furthermore, consideration is made to have provisions in place to limit excessive reactive power absorption. An overview of various methods is given below.

### *3.1.1 Protection based techniques:*

These techniques include the following:

- *The crowbar protection technique:*

**Figure 3** depicts the conventional diagram for crowbar protection [46, 47]. The crowbar purpose is to keep the rotor current low during a fault so that, the power converter can be protected [48, 49]. In addition, as described in [50-52], there are several techniques based on crowbar protection.

- ➢ This method has the following advantage: It lowers overcurrent's in the rotor and stator.
- ➢ The following are some of the disadvantages of this solution:
  - ▪ DFIG-WTs are not controllable during grid disturbances.
  - ▪ The generator absorbs reactive power, causing grid voltage to deteriorate further, and the possibility of disconnecting the turbine from the grid. As a result, the likelihood of other turbines going offline increases, causing grid instability [53, 52]. Therefore, the crowbar connection time should be chosen carefully to improve the transient stability of DFIG-WTs.

Despite the crowbar disadvantages, many studies have been done to improve the crowbar's operation. In order to improve the performance of DFIG-WTs by ensuring active/reactive power control [54]. For example, to enable the RSC, an active crowbar proposed for disconnection at the correct time. The grid code requirements for reactive power injection could be met by disconnecting the crowbar after a few milliseconds [55-57].

- *The SR protection technique:*

The SR is made up of a series of resistors linked in series with the stator or rotor winding [28], as illustrated in **Fig.4.** The SR's priority is to keep the rotor current under control. It also protects the DC-link from over-voltage and torque oscillations by dissipating active power. In various experiments, SR proposed that, the DFIG be allowed to ride through extreme voltage dips, both symmetrical and asymmetrical, such as:

- ▪ Ref. [28] recommended a rotor current controller and dynamic resistors in series with the stator for unbalanced voltage dips.
- ▪ Ref. [58] proposed the use of SR in addition to correct rotor current reference values.

- On the stator side, a series passive-resistive network also explored in [59].This approach proved to have higher and more effective performance.

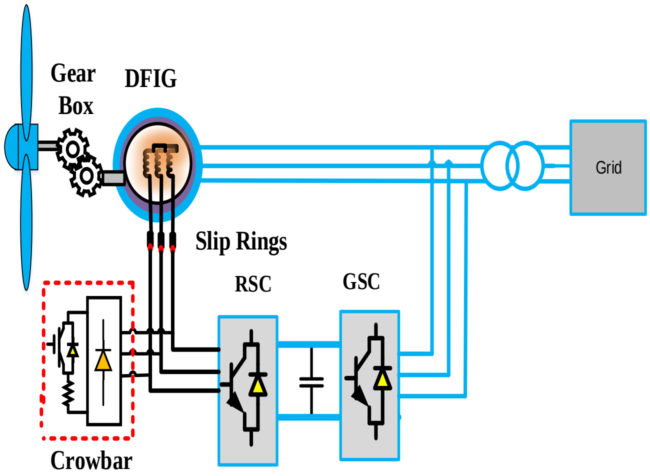

**Fig. 3** The crowbar protection technique [47].

- *DC link chopper protection technique :*

The chopper circuit is illustrated in **Fig. 4.** A DC-chopper is a circuit that consists of a switch and a resistor connected in parallel to the DC-link. When a grid malfunction is detected, the switch is closed and the resistor is connected in series with the DC-link capacitor, preventing overcharging at low grid voltage. The resistor will absorb the extra active power as shown in Ref. [53]. In Refs. [60, 61], the control-delay approach for DC- chopper is explored. In this approach, a present rotor current threshold releases the chopper's application, and feedback control restores shorter rectification duration. Wherefore, the rotor transient overcurrent and DC-link overcurrent cannot be restrained by a DC-chopper. However, the results of this sophisticated technique were unsatisfactory. The DC Link Chopper's inferior performance in LVRT compared to a normal crowbar is also shown.

Moreover, there are many protection-based techniques introduced in the literature. Thus, Tables 1 and 2 provide a critical analysis and comparison of various methods.

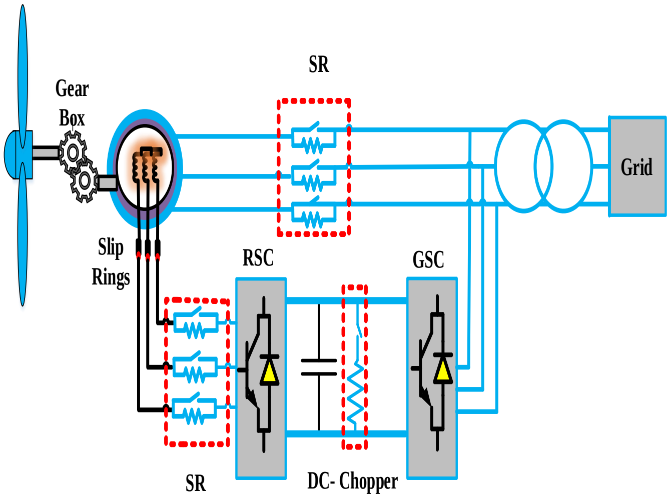

**Fig. 4** DFIG- WT with some protective techniques.

**Table 1.** Synopsis of studies based on the LVRT capability of rotor side protection techniques.

| Author | Technique | Features | Defects | Contribution |
|---|---|---|---|---|
| **Niu L, Wang X et al.[22]** | DC brake chopperwith DC link capacitor | ▪ Prevents the traces of stray inductance | ▪ Rise in the rating of the anti-parallel diodes in RSC | It demonstrated that a straightforward delayed control method was more effective. |
| **Pannell G et al. [23]** | Single phase crowbar circuits | • Possibility of current state of zero<br>• Prevents significant overvoltage | • Huge circuit<br>• Expensive<br>• Not controlled operation | Reduced uncontrolled operation time and better outcomes than the crowbar circuit |
| **Zou Z et al. [62]** | Super-capacitor and modified DC-link based on polypropylene | ▪ Compared to DVR, it is more cost effective.<br>▪ Simple.<br>▪ There is no sagging. | ▪ RSC that is more bulky | The supercapacitor-based system outperformed both the DC chopper and the polypropylene-based modified DC link in both faults. |
| **Mendes VF et al.[63]** | gate-controlled series capacitor (GCSC) in series with rotor | • Suppression of RSC inrush currents.<br>• The operation is under control. | • This method makes system larger. | For single-phase faults, the DC link voltage profile is inferior to the crowbar-based approach. |
| **Yang L et al.[64]** | Inductor-type superconducting coil (SC) | -Power fluctuations become less noticeable in the steady state.<br>▪ Fault mitigation near the DFIG | ▪ Costly | The usage of optimal SC outperformed other auxiliary devices like batteries, STATCOM, and non-optimal SC. |

**Table 2.** Synopsis of studies based on the LVRT capability of stator side protection techniques.

| Author | Technique | Features | Defects | Contribution |
|---|---|---|---|---|
| **Haidar AMA et al. [39]** | Switch mode operation of DFIG | ▪ The stator is completely isolated from the grid | ▪ Reactive power<br>▪ absorption<br>▪ Power transmission is limited. | Compared to an unprotected system, MSDFIG yields better performance. |
| **Wei F et al. [40]** | R-type SFCL | • Hybrid<br>• Simple to operate | • Reactive power requirement | Limits quantities to suitable levels with success |
| **Zheng Z et al. [42]** | Switch type SFCL | ▪ No needs for an overvoltage bypass circuit.<br>▪ Improved control ability | ▪ Costs have increased<br>▪ The size has grown. | The SFCL switch type is superior in every way. |
| **Guo W et al. [65]** | R-type high temperature superconducting fault current limiter (HTSFCL) | • Better voltage and angle stability<br>• Less complicated | • Performance degrades when sag reaches 100% | Although HTSFCL allowed for LVRT the DVR, system provided more elasticity. |
| **Alaraifi S et al. [29]** | Low-rated SDBR on stator side | ▪ Less expensive than most other stator side protection<br>▪ High-speed synchronization | ▪ The price fluctuates a lot.<br>▪ Determining parameters is boring | The SDBR methodology produced best results than the supplementary rotor current (SRC) method at various SDBR levels. |

### *3.1.2 FACTS based techniques*

FACTS devices have the ability to regulate the parameters of transmission systems, allowing them to operate more efficiently. The static synchronous compensator (STATCOM) and the SSSC are two FACTS controllers that are rapidly gaining popularity in power systems. They employed to improve LVRT capability by compensating deep and shallow symmetric and asymmetric effort sags [26-28].

- *The static synchronous compensator technique:*

As illustrated in Fig. 5, the STATCOM is a shunt-connected device that employs power electronics to manage effort at its terminals by controlling the amount of reactive power introduced into or absorbed from the power system. As a result, in both steady state and transient-state conditions, high-performance voltage control is possible [66]. The STATCOM system needs to be installed at each wind turbine. As result, the control Strategy of each STATCOM will be complicated.

➢ Despite the fact that the STATCOM or STATCOM/energy storage system (ESS) is a common solution for improving LVRT capabilities, installing and maintaining this FACTS device in a wind farm will raise the total cost of the system.

- *The dynamic voltage restorer (DVR):*

As illustrated in **Fig. 6**, DVR is made up of a voltage source converter (VSC), inductors capacitors (LC) filters, and coupling transformers that are coupled in series with the grid to correct for effort dips in the gridline during disturbances. Indeed, the DVR topologies have allowed DFIG to effectively ride through significant effort dips. It is suggested that, it was connected to the generator in series to boost the stator voltage. As a result, the rotor current can be kept below the maximum allowable value. The DVR voltage can be controlled to the point where it absorbs all or almost all of the active power provided by the generator in order to optimize the generator injected reactive power [67]. However, it has numerous drawbacks:

- The DVR's rating should match the WT's rated output.
- DVRs are relatively costly since they require several auxiliary components.
- Increased of system size.

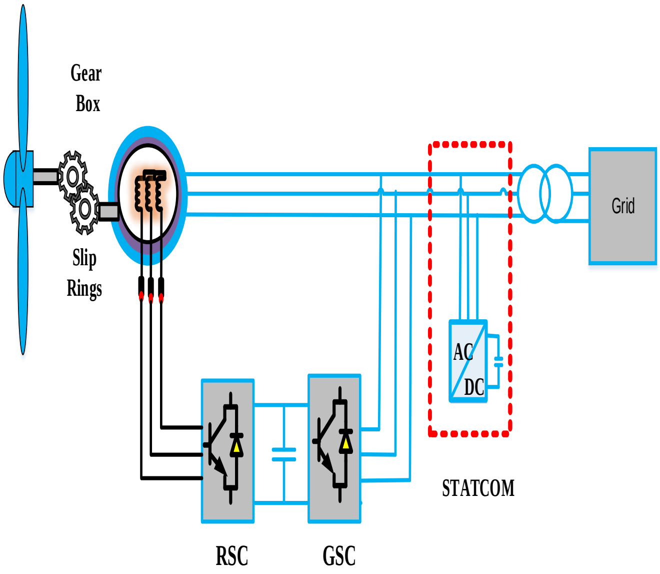

**Fig. 5** DFIG-WT with STATCOM.

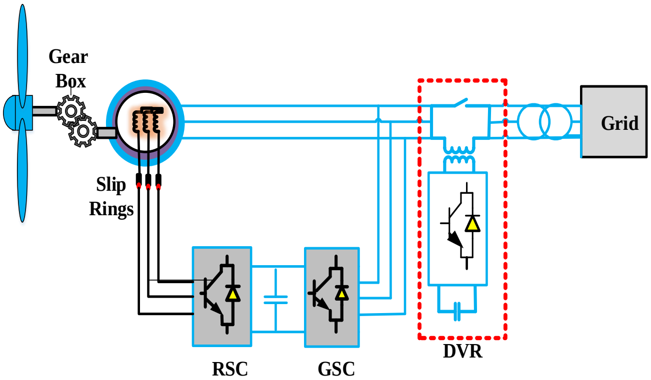

**Fig. 6.** DFIG-WT with DVR.

- *Energy storage system (ESS):*

As shown in **Fig. 7**, this method employs a bidirectional dc/dc converter in conjunction with a dc bus. In this configuration, the dc bus voltage is controlled by either GSC or storage converter. Some energy is conserved in this situation, while the remaining is exported to the grid via the GSC. In order for fault currents to pass through the DFIG rotor circuit, the RSC must be sized appropriately [68].

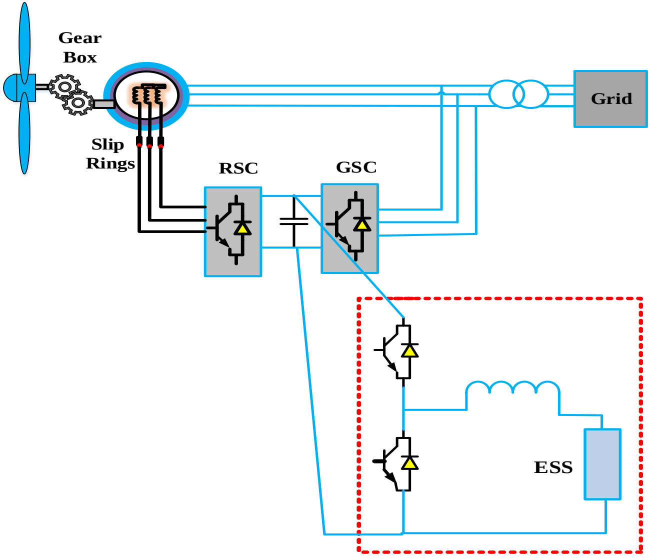

**Fig.7** DFIG-WT equipped with ESS.

Although an ESS can smooth the output power while stabilizing the DC link voltage. Overcurrent and electromagnetic torque oscillations are notoriously difficult to avoid. However, the system's cost and complexity will increase, as more energy storage devices are required [69-71].

### *3.1.3 Hybrid techniques*

Methods that rely solely on one methodology were in the preceding sections' references.Every technique has its own set of challenges. As a result, the proposed methods based on these methodologies are not without flaws.
However, But it has been noted that, a feature that cannot be offered by one approach is contributed by a different method. As a result, by combining two methods, the disadvantages of one can be eliminated. As a result, hybrid techniques are now on the table. The categories of hybrid approaches, which combine traditional methods in different ways, are as follows:

- *The crowbar integrated with the series R–L technique:*

In Refs. [52, 72-74], crowbar in conjunction with a dc-link chopper and/or a series dynamic resistor, respectively. The authors presented a mechanism for redirecting transient rotor current while regaining generator power control in 45 milliseconds, allowing DFIG-WT to fulfil grid-code requirements.

- *The crowbar integrated with the Series Dynamic Resistor (SDR):*

This is supported by Ref. [50]. The RSC is connected to the rotor winding by the SDR, which keeps generator power control until there are significant grid disruptions, in which case the crowbar is activated. Using a crowbar, on the other hand, results in the same conflicts, potentially destroying the converter and the dc-link capacitor.

- *The crowbar, S R and the dc-link chopper:*

The DFIG-WTs' reflexes during both symmetrical and asymmetrical effort sags are considerably improved by this technology [51].
All of these technologies aim to reduce crowbar uptime and increase LVRT capacity. In addition to the aforementioned, Table 3 lists the benefits and drawbacks of other hybrid techniques.

**Table 3.** Hybrid technique evaluation [32, 75-77].

| **Technique** | **Fuzzy controller with crowbar** | **RSC control with SDR** | **Active compensator with RCL** |
|---|---|---|---|
| **Features** | ▪ Swell mitigation may be possible<br>▪ Capable of dealing with a wide range of grid disturbances<br>▪ More rapid convergence | ▪ Simpler<br>▪ Cost-efficient<br>▪ Negative sequence oscillations are effectively dampened | ▪ Deep sags are minimized<br>▪ Enhancement performance |
| **Defects** | • Sagging can be reduced by up to 50% | • Losses in conduction during normal operation | • Including RCL could cause disturbances |

## *3.2 Interior LVRT techniques*

### *3.2.1 Control strategies based techniques*

The power generated from the DFIG-WTs is regulated by the vector control (VC). On the other hand, the VCs are not able to obtain LVRT capabilities since they are primarily designed for DFIG-WT steady-state operation.As a result, the updated VC must be used to meet grid code requirements. Many changes were recommended by the researchers. Consider the following:

- To increase the DFIG LVRT capabilities, Ref. [78] proposes a control method that combines transient compensators with a typical RSC current regulator. The control approach matched the RSC ac-side output voltage with the transient-induced voltage when a fault occurs, minimizing crowbar interruptions to a minimum.
- According to Ref. [79], during grid faults, which might produce stator and rotor overcurrent, the stator currents as the reference rotor current must be reduced. The gains of the RSC's PI current controllers were ideally set to reduce rotor over-currents.
- Also in [60, 80] the controllers for both the RSC and the GSC are built using a linear quadratic output feedback decentralized control approach in order to reduce oscillations and the peak value of the rotor current and the dc-link effort.
- Additionally, an adaptive internal paradigm controller with a variable gain adjustment method is presented in Ref. [81] to improve the DFIG's LVRT capability.
- Refs. [82-84] increased the WT's LVRT capabilities during voltage dips without affecting system stability; advanced control-based techniques have been presented and adopted. The majority of them explain several methods for achieving the aim. The DFIG system's transient responsiveness was also improved using a robust control technique and a hysteresis-based current regulator.
- Refs. [85,86] improved the DFIG-LVRT WT's capabilities, model predictive control is employed to improve system stability and flux tracking control utilizing an upgraded vector control technique. Internal model control was also proposed to improve the DFIG-LVRT WT's capabilities. The core idea is to use an appropriate coordinate transformation and a nonlinear control input to algebraically convert the nonlinear system dynamics into an analogous linear one before utilizing linear control techniques.
- However, a few of these strategies were just too complicated to be employed in practical applications, and they rely largely on the correct modelling and control parameters or the estimation of certain parameters, which may also jeopardize their resiliency [73].
- In addition to the foregoing, Table 4 summarizes the benefits and drawbacks of other control strategies based techniques, as well as inferences made from references.

**Table 4.** Comparison of control strategies-based techniques.

| Sr. | Author | Technique | Features | Defects | Contribution |
|---|---|---|---|---|---|
| 1 | **Alaraifi S et al. [29]** | SRC control | ▪ A less expensive option<br>▪ Simplicity | ▪ Relatively low results | This scheme is inferior to the SDBR scheme. |
| 2 | **VrionisTD et al. [30]** | Current magnetizing controller | • Quicker response<br>• No need for sag detection | • High turbine speed has a negative impact. | A successful ride through |
| 3 | **Wessels Cet al. [31]** | RSC and GSC control actions have altered. | ▪ Cost-efficient<br>▪ There is no need for overvoltage/<br>▪ Overcurrent protection. | ▪ Mechanical stress has increased. | The suggested strategy is proven more effective. |
| 4 | **Falehi AD et al. [32]** | Fuzzy controller with Genetic Algorithm (GA) tuning | • No additional hardware is required<br>• Even for greater dips, this is a cost-effective solution. | • Disturbances can make it difficult to perform.<br>• Complexity has risen | Effective improvement of LVRT capability |

As stated previously, to emphasize different aspects of the LVRT techniques outlined above. To address this problem, researchers looked into the causes for DFIG's failure to stay connected to a malfunctioning grid, as well as potential solutions to assist it. Grid codes have created standards for the operation of wind farms. According to these codes, Tables 5, 6 give a detailed evaluation of them in terms of the fundamental elements of LVRT improvement techniques [87, 6]. In these tables "√"denotes that, the utilized LVRT technology effectively controls the network fault impact, **"x"** denotes that, the utilized LVRT technology has no impact on the fault, and **"*"** denotes that, The utilized LVRT technology may exacerbate the network fault impact.

**Table 5.** Impacts of exterior LVRT techniques on low voltage faults.

| **LVRT Techniques** | **Rotor** | | | **Stator** | | **Support Power** | | **Increase DC-link Voltage** |
|---|---|---|---|---|---|---|---|---|
| | **Increase Current** | **Increase Voltage** | **Current Oscillations** | **Increase Current** | **Current Oscillations** | **Active** | **Reactive** | |
| **Crowbar Protection** | √ | X | √ | X | X | X | * | √ |
| **DC link Chopper** | * | X | X | X | X | X | X | √ |
| **SDR** | √ | √ | X | X | X | X | √ | √ |
| **ESS** | * | X | * | √ | √ | √ | √ | √ |
| **STATCOM** | X | X | X | * | * | X | √ | √ |
| **Fault Current Limiter** | X | X | X | √ | X | X | X | X |
| **Series GSC** | X | X | X | X | X | √ | X | √ |

**Table 6.** Impacts of Interior LVRT techniques on low voltage faults.

| **LVRT Techniques** | **Rotor** | | | **Stator** | | **Support Power** | | **Increase DC-link Voltage** |
|---|---|---|---|---|---|---|---|---|
| | **Increase Current** | **Increase Voltage** | **Current Oscillations** | **Increase Current** | **Current Oscillations** | **Active** | **Reactive** | |
| Battery Powered Applications (BPA) **Control** | √ | √ | √ | √ | √ | * | * | √ |
| **Vector control** | √ | X | √ | X | √ | X | X | √ |
| **crowd control** | X | √ | X | X | √ | X | X | √ |
| **Feedforward control** | √ | X | √ | X | √ | √ | √ | X |
| **Sliding mode control (SMC)** | √ | √ | √ | X | X | X | X | X |
| **decentralized nonlinear** control **(DNC)** | X | X | √ | X | √ | √ | √ | X |
| Input-to-state stability **(ISS )Control** | X | √ | √ | X | √ | √ | √ | X |
| **state-dependent Riccati equation (SDRE) Control** | √ | √ | √ | X | √ | √ | √ | X |
| **Fuzzy Control** | √ | X | √ | √ | √ | X | X | √ |
| proportional integra resonant**(PIR) Control** | X | X | √ | √ | √ | √ | X | X |
| (proportional integral-dual-frequency resonant)PI-DFR Control | X | X | √ | √ | √ | √ | X | √ |
| real-time neural inverse optimal **(RNIO) Coordinated** | X | X | X | X | X | X | X | √ |

However, it has been seen from Tables 5 & 6 that, some interior LVRT techniques may satisfy the requirements of grid codes but some of these strategies are too complex to be implemented and used in industrial applications. In fact, the schemes sorted under exterior LVRT techniques attempt to satisfactorily meet the requirements of grid codes; some are also inexpensive and simple to install. As a result, the following section will demonstrate various exterior LVRT techniques for improving DFIG-WTS performance. MATLAB/SIMULINK is used here to materlise and quatify the concepts of LVRT methods.

## 4. *Improving LVRT Capability of DFIG-WTS*

In this section, the exterior technologies that were utilized are discussed as follows:

### *4.1 SR protection technique*

SR protection is a method used on the rotor side of the DFIG. The SR made up of a series of resistors linked to the rotor winding as illustrated in **Fig. 8**. It uses power electronic switches to regulate the connection of resistance into the rotor circuit [88]. When there are faults, the resistor should be connected in series with the circuit for the rotor winding. When the SR inserted into the rotor circuit during a fault, the power from the induced efforts in the rotor that occur during the fault dissipated, limiting the rotor over current.

The rotor currents were constrained, which decreased the charging current to the DC-link capacitor. Overvoltage on the DC-link is less likely as a result. The resistance caused by SR will share the high voltage. The series topology will prevent converter control loss. As a result, the SR not only prevents rotor overvoltage from causing the RSC to lose control, but it also prevents the RSC from losing control. During the fault, however, there is no reason to halt the RSC.

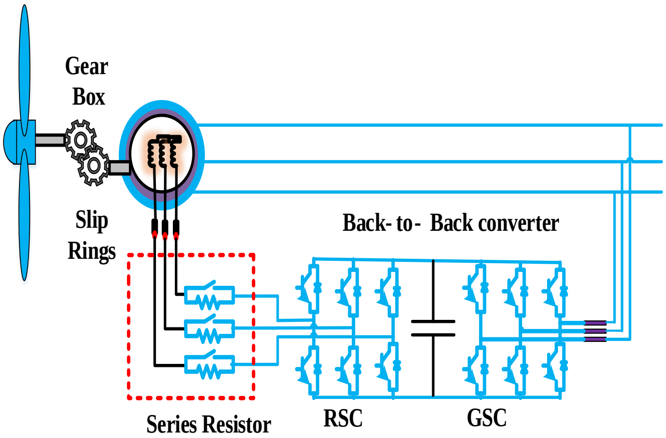

**Fig. 8** Topological structure of the SR protection technique

### *4.2 The Crowbar integrated with the DC-chopper*

As illustrated in **Fig. 9**, the protective technique includes two circuits: a DC-chopper and a crowbar. A crowbar is a set of resistors linked to the rotor winding. During a fault, the crowbar action started by raising the rotor current value by blocking the converter. As a result, current enters the DC-link through the freewheeling diodes, rapidly raising the voltage. For restricted overvoltage's, the DC-chopper is turned on during symmetrical and asymmetrical grid failures to safeguard the power electronic converter. Resistors have been added to the protective circuits to help reduce rotor current and DC-link overvoltage.

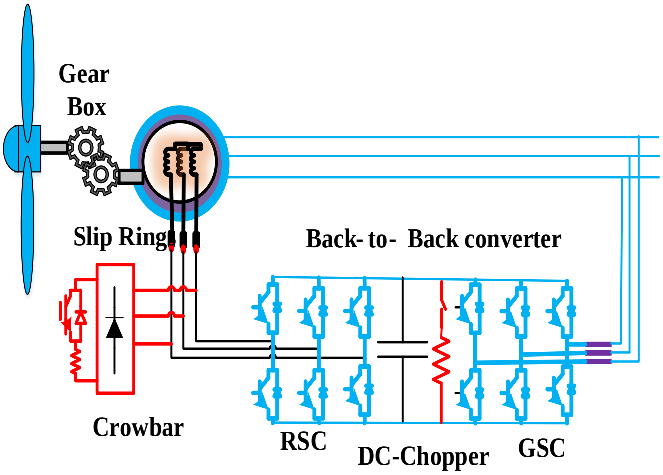

**Fig. 9** Topological structure of the crowbar integrated with the DC-chopper

Additionally, **Fig. 10** shows the detailed DFIG –WT simulation setup. A wind farm is connected to a 25 KV distribution system and exports electricity to a 120 KV grid via 30 kilometres of 25 KV feeders was the subject of the simulation. In MATLAB/SIMULINK, the wind farm is represented by a single DFIG machine model (6 * 1.5MW) using the 1.5 MW DFIG's parameters shown in Table 7.

**Table7.** Base and rated values for the system under investigation.

| Quantum | Amount |
|---|---|
| Base power | 10 MVA |
| Generator terminals' base voltage | 575V |
| Base frequency | 60 Hz |
| The generator's rotational speed base | 1200rpm |
| Rotational speed of the generator | 1.2 pu |
| Rated wind speed | 11 m/sec |
| Rated dc voltage | 1200 |

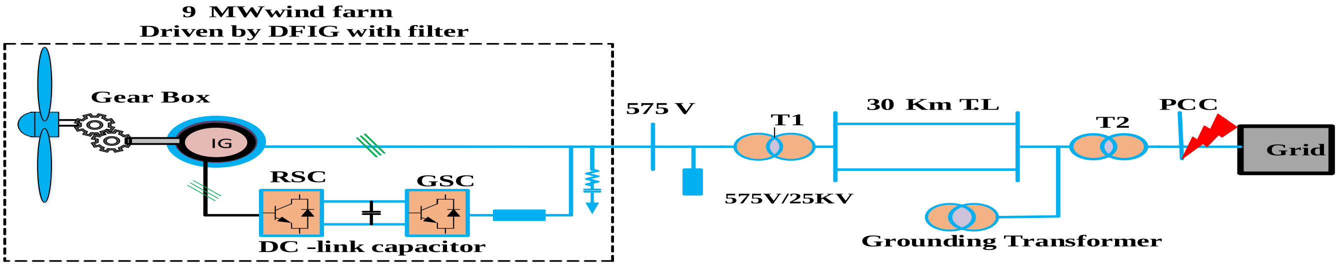

**Fig. 10.** A single-line schematic of the system under investigation.

## 5. Simulation Results

In this section, we will give the above-mentioned simulation findings in the various scenarios of grid faults, including symmetric and asymmetric faults.

### *5.1 The symmetrical fault: A case study*

### ➢ SR protection technique:

As shown in **Fig. 11**, a three-phase fault is simulated at the grid connection point, commencing at the time (t = 0.7s) until clearing at the time (t = 0.9s). This diagram depicts the system's response to a 0.95pu effort drop lasting 0.2s. Due to the presence of SR in the rotor winding~~.~~ In this simulation, the energy generated by the induced efforts in the rotor during the failure had been lost.~~.~~ As a result, there is a decrease in the rise in stator and rotor currents.. Therefore, the stator currents are lowered from 2.66 p.u. to 2.02 p.u. The rotor current pulse rate decrease from 2.5 to 1.21 per second. Additionally, there is a reduction in DC-link effort and electrical torque oscillations. SR protection works better at boosting the damping currents at the generator terminals.

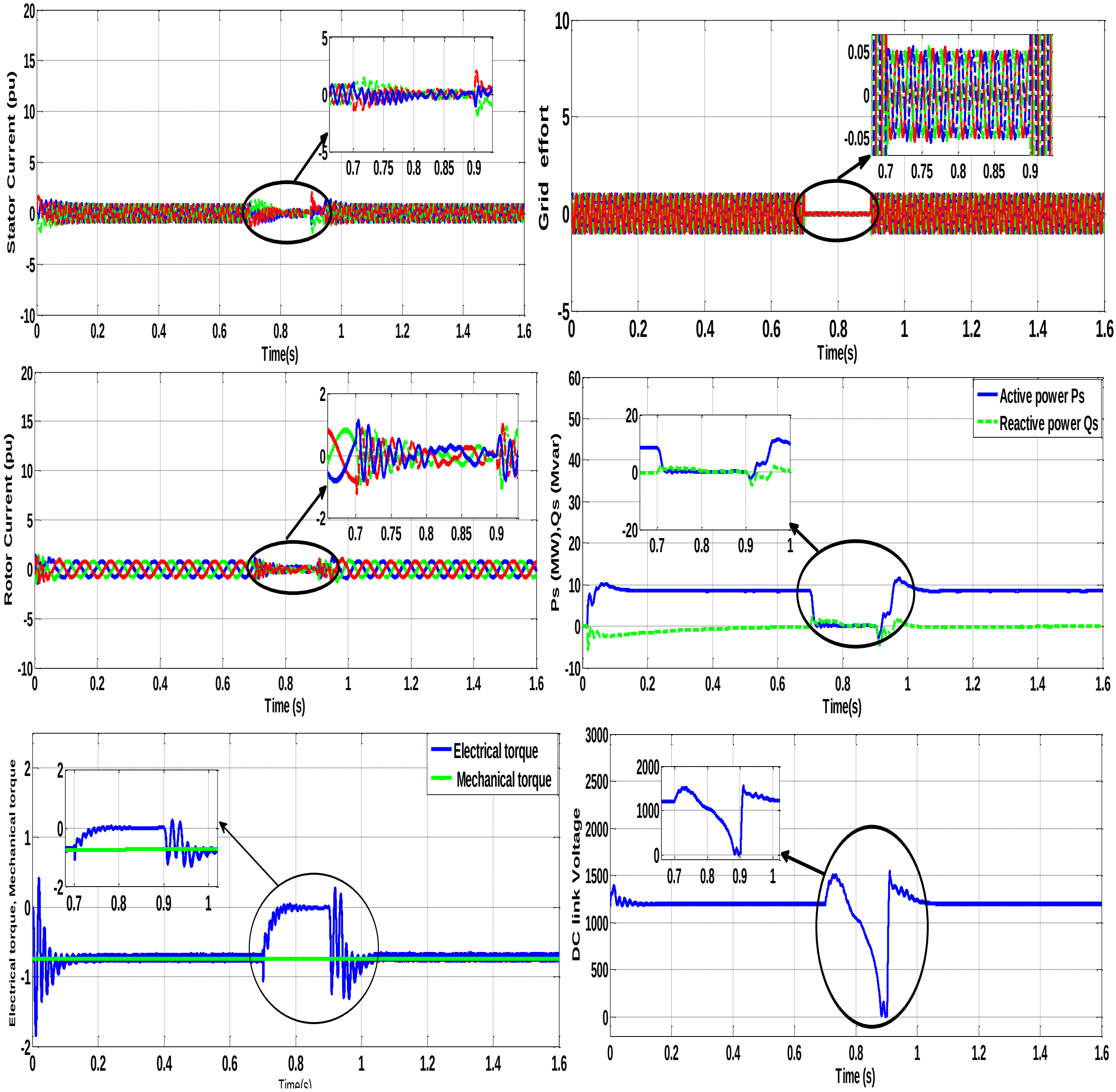

**Fig. 11.** A three-phase 0.95pu voltage drop for 0.2s using the SR protection technique.

- **The crowbar integrated with the DC-chopper:**

**Figure 12** depicts the system's response to a 0.95pu voltage decrease lasting 0.2 seconds. The rotor currents that rise owing to the initial rotor current peak initiate the crowbar firing. The safeguard normally disables the converter's electronic switches. However, through the freewheeling diodes, current and energy continue to flow into the DC-link, resulting in a very rapid voltage rise. The DC-Chopper is consequently activated to prevent over-effort.. The stator currents pulse rate decrease from 2.66 p.u. to 1.81 p.u. During the most dangerous phase by including parallel resistance in the rotor circuit and by connecting resistance in parallel with the DC-link. The rotor currents pulse rate decrease from 2.5 to 1.42 p.u The improved state-transient response feature is then significantly demonstrated while utilizing the approach.

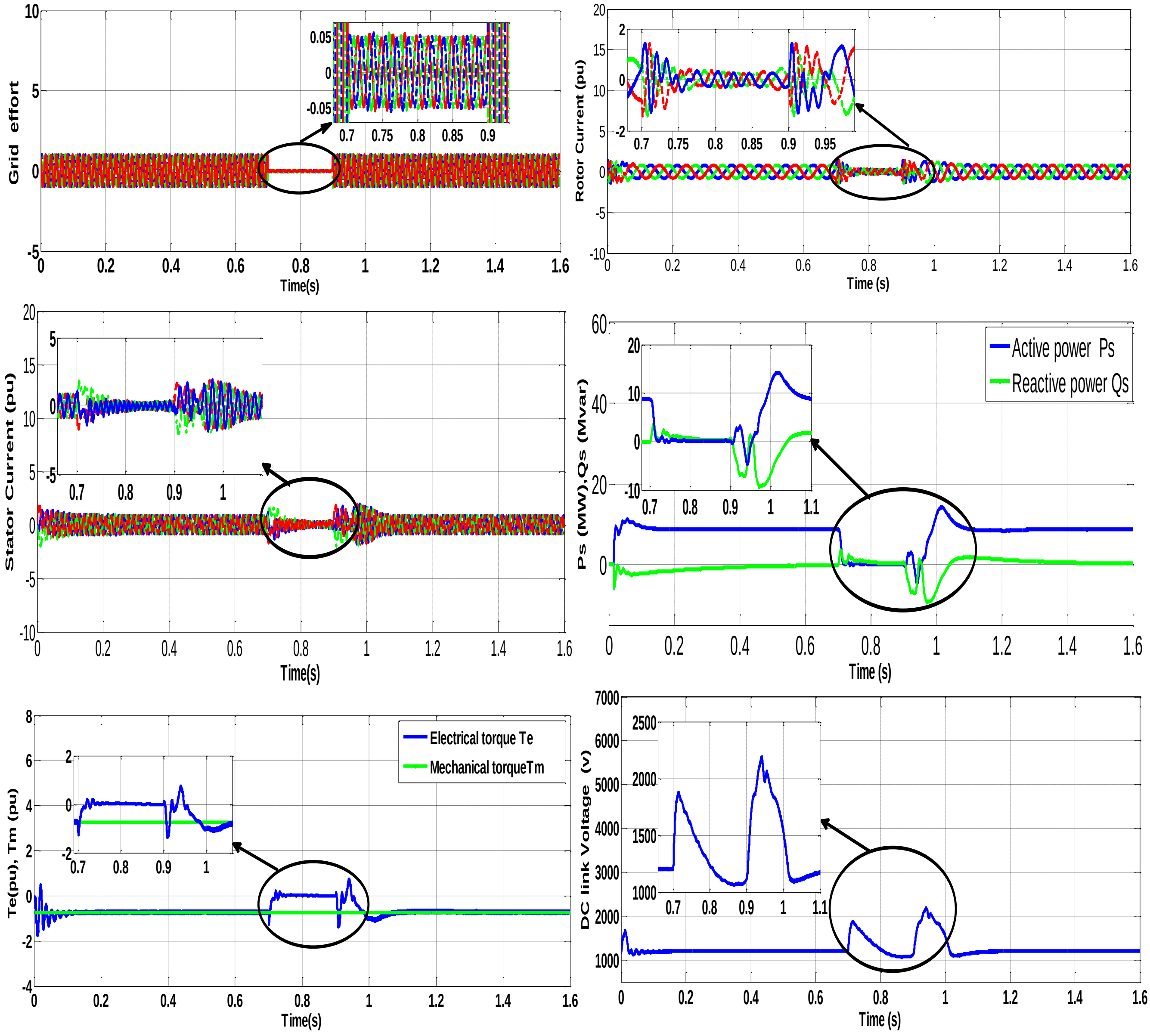

**Fig. 12**. A three-phase 0.95pu voltage drop for 0.2s using the crowbar integrated with the DC-chopper.

### *5.2 The asymmetrical fault: A case study*

- **SR protection technique:**

A double-phase (phase-b and phase-c) fault is simulated at t = 0.7s, and **Fig. 13** depicts the system reactions under asymmetrical fault circumstances. The SR is efficient in dissipating the induced voltage in the rotor when phase's b and c are short-circuited together. The stator currents dropped from 2.09pu to 1.04pu. In addition, at the most dangerous phase, the rotor currents pulse rate decrease from 1.91pu to 1.104pu. As a result, SR minimizes DC-link effort and electrical torque variations greatly.

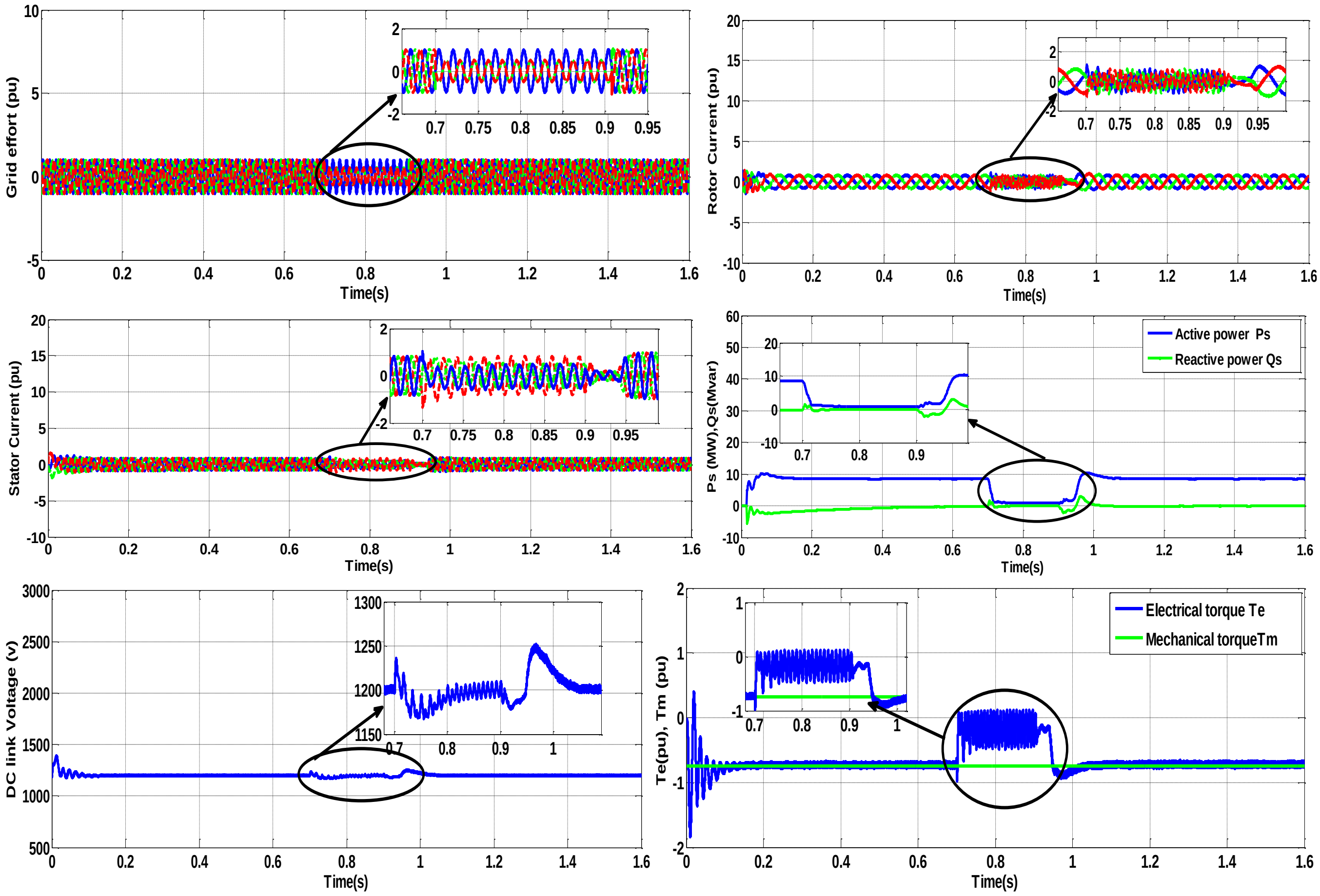

**Fig. 13.** A Short circuit from phase b to phase c for 0.2s using SR protection technique.

### ➢ The crowbar integrated with the DC-chopper

**Figure 14** depicts the system responses in the presence of asymmetrical faults. Short-circuiting occurs in phase's b and c. reduced stator currents to 1.38pu from 2.09pu. at the most dangerous phase when the DC chopper and crowbar switches are triggered simultaneously. For the most serious phase, the rotor currents are reduced from 1.91pu to 1.06pu, resulting in a considerable reduction in DC-link effort and electrical torque variations as indicated in fig.14.

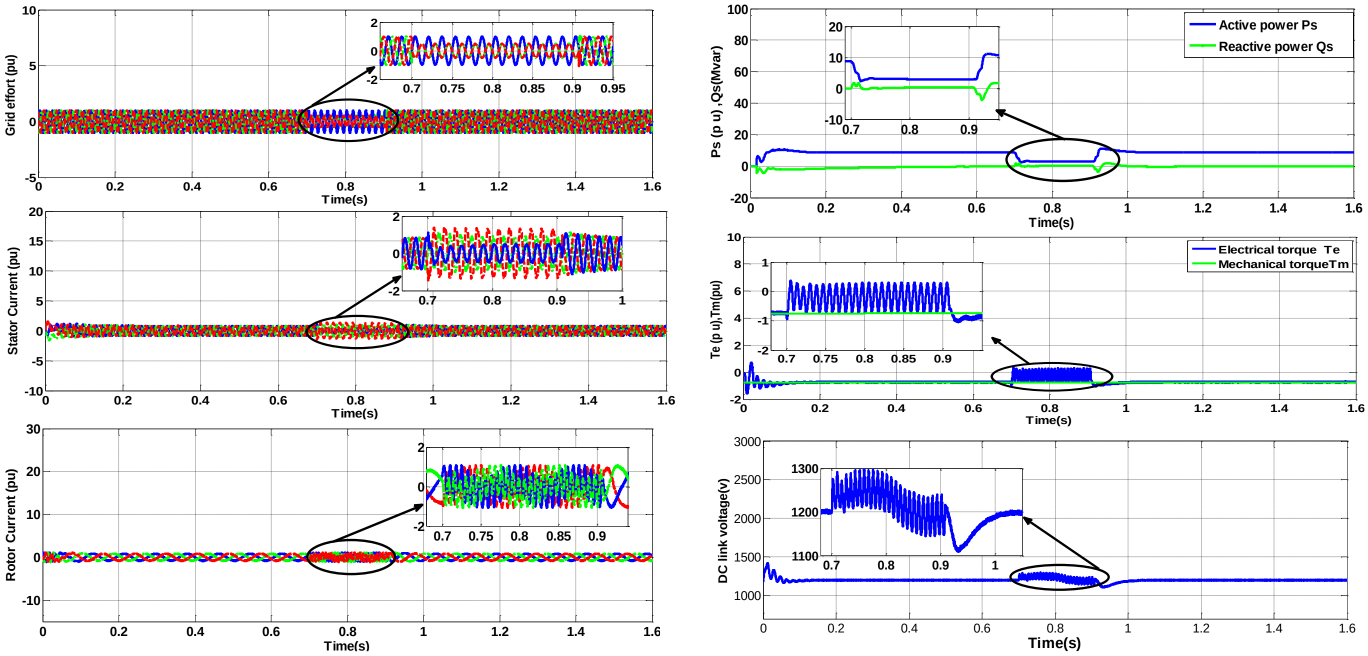

**Fig.14**. A short circuit between phases b&c for 0.2s using the crowbar integrated with the DC-chopper.

The simulation results demonstrate that, the SR is helpful during balanced and unbalanced grid failures because it reduces rotor over current, torque oscillations, and DC-link over effort compared to the other scheme. Thus, it supports the system's stability under grid failures. In addition, the SR is reducing rotor currents more effectively than a crowbar or DC-chopper protection. During the fault, both techniques have reactive power and electrical torque changes. They are substantially bigger for crowbar protection. When compared to crowbar protection, the electrical torque ripple is smaller with SR protection.

## 6 Conclusions and Future Trend Exploration

**In this paper**, a thorough discussion of the recently emerged LVRT techniques for DFIG-WTs has been presented. Improving LVRT capability has become critical because of the rising penetration of wind power into the grid. So, in this paper, various LVRT techniques have been described elaborately. The features, pros, and cons of these LVRT techniques have been provided to cleraly evaluate these technologies in line with grid codes. Basically, LVRT techniques can be separated into two categories: 1) exterior LVRT techniques (protection-based, FACTS-based & hybrid techniques) and 2) interior LVRT techniques like control strategies-based techniques.

Exterior LVRT techniques are extensively employed in previously installed WTs for simplicity. However, cost considerations continue to be a key impediment to the adoption of these technologies. Hybrid approaches can help improve LVRT by overcoming the shortcomings of one method by inserting the benefits brought by the other. In fact, interior LVRT techniques adjustments can provide greater control effects during low grid effort. As the LVRT capability of DFIG-WTs can be enforced without any external supplementary circuit, interior techniques have better economic benefits over exterior LVRT techniques. Thus, interior techniques are preferable in freshly erected WTs, considering the cost factor advantages. The simulation performances of the exterior LVRT techniques are analysed in this paper. The SR protection technique and the crowbar integrated with the DC-chopper are considered here. Both strategies enforce great LVRT performances in fault situations. However, the SR protection technique has been shown to be more effective than the crowbar integrated with the DC-chopper.

Finally, guidelines and recommended technical designs for LVRT technologies for DFIG-WTs to cope with local grid codes have been formed based on detailed discussions conducted in this paper:

- Recent grid regulations require wind turbines to remain grid connected while providing reactive power assistance. As such LVRT capability of DFIG-WTs need to be equippped to efficiently fulfil emerging grid requirments.
- Some LVRT techniques are limited to symmetric faults. Asymmetric faults are more common than symmetric faults, as stated in the grid codes. As a result, these techniques should be capable of handling asymmetric defects as well.
- The techniques used should be simple and cost-effective.
- Almost every method has been developed for a rigid grid. However, the infrastructure that connects the wind farms is often weak. As a result, future approaches must be built to meet the needs of a weak power grids.

The future direction of LVRT solutions is to use Exterior LVRT techniques are widely used in pre-installed wind turbines for simplicity. However, economic concerns still act as a major barrier to Exterior LVRT techniques, and the difficulties in modifying the original control structure also restrict the application of external installations. Although external modifications are not the future direction of LVRT solutions, the installation of external LVRT devices with specific functions is necessary.

Internal control techniques apply advanced control theories to strengthen the LVRT capability of DFIG-WTs. internal control modifications can provide better control effects during grid voltage dips. Because the LVRT capability of DFIG-WTs can be enhanced without any external auxiliary circuits. Thus, internal control techniques are preferred in newly installed wind turbines, and they have broad prospects for future development.

In terms of advantages in the cost factor and the flexibility in modification, internal control techniques will make substantial progress in the future. New control theories will also be proposed to provide more flexible and effective performance during grid voltage dips. The LVRT solutions combined with artificial intelligence will be a hot field. For example, artificial intelligence techniques can endow DFIG-WTs with the ability to achieve online optimal tuning, and supplementary learning structures can be implemented in DFIG-WTs to improve the LVRT capability. In addition, external protection circuits combined with internal control techniques should be studied in detail to meet the requirement of modifying existing DFIG-WTs.

## References

[1] Montaser Abd El Sattar, Ameena Al Sumaiti, Hamdi Ali, Ahmed A. Zaki Diab, "Marine predators algorithm for parameters estimation of photovoltaic modules considering various weather conditions", Neural Computing and Applications, Vol. 33, pp. 11799–11819, 2021.

[2] Montaser Abd El Sattar, Wessam Arafa Hafez, Adel A. Elbaset, and Ali H. Kasem Alaboudy, "Economic Valuation of Electrical Wind Energy in Egypt Based on Levelized Cost of Energy", International Journal of Renewable Energy Research, Vol. 10, No. 4, pp. 1879-1891, December ,2020.

[3] Ahmed A. Zaki Diab, Hamdi Ali, H.I. Abdul-Ghaffar, Hany A. Abdelsalam, Montaser Abdelsattar, "Accurate parameters extraction of PEMFC model based on metaheuristics algorithms", Energy Reports, Vol. 7, p.p. 6854-6867, 2021.

[4] GWEC. Global Wind Report 2021; GWEC: Brussels, Belgium; p. 80. Available online: https://gwec.net/global-wind-report,2022.

[5] IEA. Renewables 2019: Analysis and forecast to 2024; International Energy Agency: Paris, France, 2019; ISBN 978-92-64-36998-6. Available online: https://iea.blob.core.windows.net/assets/a846e5cf-ca7d-4a1f-a81b-ba1499f2cc07/Renewables_2019.pdf accessed on 18 February 2022.

[6] Saeed, M.A.; Khan, H.M.; Ashraf, A.; Qureshi, S.A. "Analysing electiveness of LVRT techniques for DFIG wind turbine system and implementation of hybrid combination with control schemes". Renew. Sustain. Energy Rev. Vol.81, pp.2487–2501**,** 2018.

[7] Hansen, A.D.; Iov, F.; Blaabjerg, F.; Hansen, L. "Review of Contemporary Wind Turbine Concepts and Their Market Penetration". Wind Eng. Vol.28, pp.247–263. 2004.

[8] Rolan A, Pedra J, Corcoles F "Detailed study of DFIG-based wind turbines to overcome the most severe grid faults". Electr. Power Energy Syst. Vol.62, pp.868–878, 2014.

[9] Nian H, Song Y "Direct power control of doubly fed induction generator under distorted grid voltage". IEEE Trans. Power Electron Vol.29 (2), pp. 894–905, 2014.

[10] Dittrich A and Stoev A "Comparison of fault ride-through strategies for wind turbines with DFIM generators". In: 2005 European conference on power electronics and applications, pp. 1–8, 2005.

[11] Gao W, Wang G and Ning J "Development of low voltage ride-through control strategy for wind power generation using real time digital simulator". In:IEEE/PES power systems conference and exposition (PSCE), Seattle, WA, pp. 1–6, 2009.

[12] Ling Y and Cai X "Rotor current dynamics of doubly fed induction generators during grid voltage dip and rise", International Journal of Electrical Power & Energy Systems, Vol.44, pp. 17–24, 2013.

[13] Yang J, Dorrell DG and Fletcher JE "A new converter protection scheme for doubly-fed induction generators during disturbances". In: 34th IEEE annual conference on industrial electronics (IECON), pp. 2100–2105, 2008.

[14] Morren J and De Haan SWH "Ride through of wind turbines with doubly-fed induction generator during a voltage dip", IEEE Transactions on Energy Conversion, Vol. 20, pp. 435–441, 2005.

[15] Rahim AHMA, Nowicki EP "Supercapacitor energy storage system for fault ride-through of a DFIG wind generation system". Energy Conv. Manga, Vol.59, pp. 96–102, 2012.

[16] Zhan C and Barker CD "Fault ride-through capability investigation of a doubly-fed induction generator with an additional series connected voltage source converter". In: The 8th IEE international conference on AC and DC power transmission (ACDC), pp. 79–84, 2006.

[17] Hansen AD, Michalke G, Sorense P, et al. "Co-ordinated voltage control of DFIG wind turbines in uninterrupted operation during grid faults". Wind Energy, Vol.10, pp.51–68, 2007.

[18] Erlich I, Winter W and Dittrich "A Advanced grid requirements for the integration of wind turbines into the German transmission system". In: IEEE power engineering society general meeting, pp. 1–7, 2006.

[19] K.-H. Kim, Y.-C. Jeung, D.-C. Lee and H.-G. Kim, "LVRT scheme of PMSG wind power systems based on feedback linearization,"IEEE transactions on power electronics, Vol.27, pp. 2376-2384, 2012.

[20] AlsmadiYMet al "Detailed Investigation and Performance improvement of the dynamic behaviour of grid-connected DFIG-based wind turbines under LVRT conditions". IEEE Trans. in Apple, Vol. 54(5), pp. 4795–4812, 2018.

[21] Tohidi S, Mohammadi-ivatloo B "A comprehensive review of low voltage ride through of doubly fed induction wind generators". Renew Sustain Energy Rev., Vol. 57, pp. 412–419, 2016.

[22] Niu L, Wang X, Wu L, Yan F, Xu M "Review of low voltage ride-through technology of doubly-fed induction generator". J Eng., Vol. 3(16), pp. 3106–3108,2019.

[23] Pannell G, Zahawi B, Atkinson DJ, Missailidis P "Evaluation of the performance of a dc-link brake chopper as a DFIG low-voltage fault-ride-through device". IEEE Trans. Energy Conv., Vol. 28(3), pp.535–542, 2013.

[24] Duong M, Leva S, Mussetta M, LeKH "A Comparative study on controllers for improving transient stability of DFIG wind turbines during large disturbances". Energies, pp.11:480, 2018.

[25] Din Z, Zhang J, Zhu Y, Xu Z, El-Naggar an "Impact of grid impedance on LVRT performance of DFIG system with rotor crowbar technology". IEEE Access, Vol. 7, pp.127999–128008, 2019.

[26] Benali A, KhiatM,Allaoui T, DenaïM "Power Quality improvement and low voltage ride through capability in hybrid wind-PV farms grid-connected using dynamic voltage restorer". IEEE Access, Vol. 6, pp.68634–68648, 2018.

[27] Mokryani G, Siano P, Piccolo A, Chen Z "Improving fault ride-through capability of variable speed wind turbines in distribution networks". IEEE Syst. J, Vol. 7(4), pp.713–722, 2013.

[28] Mohammadi J, Afsharnia S, Vaez-Zadeh S "efficient fault-ride-through control strategy of DFIG-based wind turbines during the grid faults". Energy Convers Manage, Vol. 78, pp.88–95, 2014.

[29] Alaraifi S, Moawwad A, Moursi MSE, Khadkikar V "Voltage booster schemes for fault ride through enhancement of variable speed wind turbines". IEEE Trans. on Sustain Energy, Vol. 4(4), pp. 1071–1081, 2013.

[30] Vrionis TD, Koutiva XI, and Vovos NA "A genetic algorithm-based low voltage ride-through control strategy for grid connected doubly fed induction wind generators". IEEE Trans. Power Syst., Vol. 29(3), pp.1325–1334, 2014.

[31] Wessels C, Gebhardt F, Fuchs FW "Fault ride-through of a DFIG wind turbine using a dynamic voltage restorer during symmetrical and asymmetrical grid faults". IEEE Trans. Power Electron, Vol. 26(3), pp. 807–815, 2011.

[32] Falehi AD, Rafiee M "Enhancement of DFIG-wind turbine's LVRT capability using novel DVR based odd-nary cascaded asymmetric multi-level inverter". Int .J. Eng. Sci. and Tech., Vol. 20, pp.805–824, 2017.

[33] Maga, J., Jadhav, and H.T., “Improving fault ride through capability of DFIG connected wind turbine system: a review”. In: International conference on power, energy and control, pp 613–618, 2013.

[34] Jutso JJ, Mwasilu F, and Jung JW “Doubly-fed induction generator based wind turbines: a comprehensive review of fault ride-through strategies”. Renew. Sustain. Energy Rev., Vol. 57, pp. 447–467, 2015.

[35] Mahela OP, GuptaN, Khosravy M, PatelN “Comprehensive overview of low voltage ride through methods of grid integrated wind generator”. IEEE Access, Vol. **7**, pp 99299–99326, 2019.

[36] A. A. B. M. Zin, M. P. HA, A. B. Khairuddin, L. Jahanshaloo, and O. Shariatic, “An overview on doubly fed induction generators′ controls and contributions to wind based electricity generation,” Renewable and Sustainable Energy Reviews, Vol. 27, pp. 692-708, 2013.

[37] Morren J.; Sjoerd W. “Short-Circuit Current of Wind Turbines with Doubly Fed Induction Generator”.IEEE Trans. Energy Convers., Vol. 22, pp.174–180, 2007.

[38] Haidar AMA, Muttaqi KM, and Hagh MT “A coordinated control approach for DC link and rotor crowbars to improve fault ride-through of DFIG-based wind turbine”. IEEE Trans. Ind Appl, Vol. 53(4), pp. 4073–4086, 2017.

[39] Wei F, Vilathgamuwa DM, Shing CS “Design of mode switching scheme for low-voltage ride-through of doubly fed induction generators”. IET Renew. Power Gener., Vol. 9(2), pp.109–119, 2015.

[40] Elshiekh ME, Mansour DEA, Azmy AM “Improving fault ride-through capability of DFIG-based wind turbine using superconducting fault current limiter”. IEEE Trans. Appl Superconductivity, Vol. 23(3), 2013.

[41] Zheng Z, Huang C, Yang R, Xiao X, Li C “A low voltage ride through scheme for DFIG-based wind farm with SFCL and RSC Control”. IEEE Trans. Appl. Supercond, Vol. 29 (2), pp.1–5, 2019.

[42] Guo W, Xiao L, Dai S, Li Y, Xu X, Zhou W, Li L “ LVRT capability enhancement of DFIG with switch-type fault current limiter”. IEEE Trans. Ind Electron, Vol 62(1), pp.332–342, 2015.

[43] Okedu KE, Muyeen SM, Takahashi R, Tamura J “Wind farms fault ride through using DFIG with new protection scheme”. IEEE Trans. Sustain Energy, Vol. 3(2), pp. 242–254, 2012.

[44] Rashid G, Ali MH “Nonlinear Control-Based Modified BFCL for LVRT capacity enhancement of DFIG-based wind farm”. IEEE Trans. Energy Convers, Vol. 32(1), pp. 284–295, 2017.

[45] Hossain ME “Low voltage ride through capability improvement methods ford FIG based wind farm”. J. Electr. Stst. Inform. Tech, Vol. 5(3), pp. 550–561, 2018.

[46] M. Rahimi and M. Parniani, “Efficient control scheme of wind turbines with doubly fed induction generators for low-voltage ride-through capability enhancement,”IET Renewable Power Generation, Vol.4, pp. 242-252, 2010.

[47] .K.A. Lima, A. Luna, P. Rodriguez, E.H. Watanabe and F. Bleiberg, “Rotor voltage dynamics in the doubly fed induction generator during grid faults, ”IEEE Trans. Power Electronics, Vol.25, pp. 118-130, 2010.

[48] Morren J, de Haan SWH. “Short-circuit of wind turbine with doubly fed induction generator” .IEEE Trans. Energy Convers, Vol.22, pp. 174–80, 2007.

[49] Kayikci M, Milanovic JV,“Assessing transient response of DFIG-based wind plants-the influence of model simplifications and parameters” IEEE Trans. Power Syst., Vol.23 , pp.545–554, 2008.

[50] Vidal J, Abad G, Arza J, Aurtenechea S, “Single-Phase DC. Crowbar topologies for low voltage ride through fulfillment of high-power doubly fed induction generator-based wind turbines” Energy Convers IEEE Trans. Vol.28, pp.81- 768, 2013.

[51] Liang J, Howard DF, Restrepo JA, Harley RG,“Feed-forward transient compensation control for DFIG wind turbines during both balanced and unbalanced grid disturbances” IEEE Trans. Power Vol.49 , pp. 1452–63, 2013.

[52] Montaser Abd El Sattar, Wessam Arafa Hafez, Ali H. Kasem Alaboudy and Adel A. Elbaset, “Fuzzy Logic Controlled Shunt Active Power Filter for Power Quality Improvement of an Egyptian Electrical Network Connected Wind Energy System”, International Journal for Innovative Engineering and Management Research, Vol.10, No. 08, p.p. 134-145, Aug. 2021.

[53] S. Tohidi and M.-I Behnam, “A comprehensive review of low voltage ride through of doubly fed induction wind generators,” Renewable and Sustainable Energy Reviews, Vol.57, pp. 412-419, 2016.

[54] Rahimi M, Parniani M. “Coordinated control approaches for low-voltage ride through enhancement in wind turbines with doubly fed induction generators” IEEE Trans. Energy Convers. Vol.25, pp. 873–83, 2010.

[55] Lopez J, Gubia E, Olea E, Ruiz J, Marroyo L. “Ride through of wind turbines with doubly fed induction generator under symmetrical voltage dips” Ind .Electron IEEE Trans., Vol.56, pp. 4246–54, 2009.

[56] Zhang X-g Xu D-g. “Research on control of DFIG with active crowbar under symmetry voltage fault condition”, Electric Mach Control, Vol.1, pp. 020, 2009.

[57] Pannell G, Atkinson DJ, Zahawi “Minimum-threshold crowbar for a fault ride-through grid-code-compliant DFIG wind turbine” Energy Convers IEEE Trans. ,Vol.25, pp. 9-750, 2010.

[58] Rahimi M, Parniani M. “Low voltage ride-through capability improvement of DFIG-based wind turbines under unbalanced voltage dips, ”Int. J Electr. Power Energy Syst., Vol.60, pp.82–95, 2014.

[59] Yan X, Venkataramanan G, Wang Y, Dong Q, Zhang B. “Grid-fault tolerant operation of a DFIG wind turbine generator using a passive resistance network”, Power Electron IEEE Trans., Vol.26, pp.905-2896, 2011 .

[60] Nielsen JG, Blaabjerg F. “A detailed comparison of system topologies for dynamic voltage restorers,” Ind. Appl.IEEE Trans., Vol.41, pp.80-1272, 2005.

[61] Tohidi, Sajjad, and Mohammadi-ivatloo Behnam. “A comprehensive review of low voltage ride through of doubly fed induction wind” generators." Renewable and Sustainable Energy Reviews, Vol. 57, pp. 412-419, 2016.

[62] Zou Z, Liao J, Lei Y, Mu Z, Xiao X “Post fault LVRT Performance enhancement of DFIG using a stage-controlled SSFCL-RSDR”. IEEE Trans., Appl Supercond, Vol. 29(2), pp. 1–6, 2019.

[63] MOHAMMADPOUR, Hassan; ZADEH, Saeed Ghassem; TOHIDI, Sajjad. “Symmetrical and asymmetrical low-voltage ride through of doubly-fed induction generator wind turbines using gate controlled series capacitor”. IET Renewable Power Generation, Vol. 9.7, pp. 840-846, 2015.

[64] Yang L, Xu Z, Ostergaard J, Dong ZY, Wong KP “Advanced control strategy of DFIG wind turbines for power system fault ride through”. IEEE Trans. Power Syst., Vol.27 (2), pp. 713–722, 2012.

[65] KHAN, Umer-Amir, et al. “Modeling and Simulation using Simulink and Sim Power System of optimized HTS FCL location in a Smart Grid having a Wind Turbine connected with the grid”. Progress in Superconductivity and Cryogenics, Vol.12, pp. 17-20, 2010.

[66] Gkavanoudis SI, Demoulias CS. “A combined fault ride-through and power smoothing control method for full-converter wind turbines employing super capacitor energy storage system, ” Electric Power Syst. Res.;Vol.106, pp.62–72, 2014 .

[67] S.M. Muyeen, R. Takahashi, T. Murata, J. Tamura, M.H. Ali, Y.Matsumura, A.Kuwayama and T. Matsumoto,“Low voltage ride through capability enhancement of wind turbine generator system during network disturbance,”IET Renewable Power Generation, Vol.3, pp. 65-74, 2009 .

[68] Wenyong G, Liye X, Shaotao D. “Enhancing low-voltage ride-through capability and smoothing output power of DFIG with a superconducting fault current limiter-magnetic energy storage system, "Energy Conv. IEEE Trans.; Vol.27, pp.95-277, 2012 .

[69] Elshiekh ME, Mansour DA, Azmy AM, “Improving fault ride-through capability of DFIG-based wind turbine using superconducting fault current limiter,” Appl. Super Cond IEEE Trans., Vol.23, pp. 5601204-5601204, 2013.

[70] C. Abbey, and G. Joos, “Super capacitor energy storage for wind energy applications,” IEEE Transactions on Industry Applications*;* Vol.43, pp.769-776, 2007.

[71] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt and R. VillafáfilaRobles, “A review of energy storage technologies for wind power applications,” Renewable and Sustainable Energy Reviews, Vol.16, pp. 2154-2171, 2012.

[72] Geng H, Liu C, Yang G. “LVRT capability of DFIG-based WECS under asymmetrical grid fault condition,” IEEE Trans. Ind. Electron; Vol.60, pp. 509-2495, 2013.

[73] Liu X, Kong X. “Nonlinear model predictive control for DFIG-based wind power generation,” IEEE Trans. Autom. Sci. Eng.; Vol.99, pp.1–10, 2013.

[74] Barambones O. “Sliding mode control for wind turbine power maximization,” Energy; Vol.5, pp. 2310-2330, 2010.

[75] Mohammad pour H, Zadeh SG, Tohidi S “Symmetrical and asymmetrical low voltage ride through of doubly fed induction generator wind turbines using gate controlled series capacitor”. IET Renew Power Gener, Vol. 9(8), pp. 840–846, 2015.

[76] Karaipoom T, Ngamroo I “Optimal superconducting coil integrated into DFIG wind turbine for fault ride through capability enhancement and output power fluctuation suppression”.IEEE Trans. Sustain Energy, Vol. 6(1), pp. 28–42, 2015.

[77] Rahimi M, ParnianiM “Low voltage ride-through capability improvement of DFIG based wind turbines under unbalanced voltage dips”. Electr. Power Energy Syst., Vol. 60, pp. 82–95, 2014.

[78] Liang, Jiaqi, Wei Qiao, and Ronald G. Harley. “Feed-forward transient current control for low-voltage ride-through enhancement of DFIG wind turbines”. IEEE Transactions on Energy Conversion, Vol. 25.3, pp.836-843, 2010.

[79] Jing S, Yuejin T, Yajun X, Li R, Jingdong L,“SMES based excitation system for doubly-fed induction generator in wind power application, ” Appl. Super Cond IEEE Trans., Vol.21, pp.8-1105, 2011.

[80] Ibrahim AO, Nguyen TH, Lee DC, Kim SC “faults ride-through technique of DFIG wind turbine systems using dynamic voltage restorers,” IEEE Trans. Energy Convers,Vol.26, pp. 82-871, 2011 .

[81] Hossain MJ, Saha TK, Mithulananthan N, Pota HR, “Control strategies for augmenting LVRT capability of DFIGs in interconnected power systems, ” IEEE Trans. Ind. Electron;Vol.60, pp.22- 2510, 2013.

[82] Xiao S, Yang G, Zhou H, Geng H, “An LVRT control strategy based on flux linkage tracking for DFIG-based WECS, ” IEEE Trans. Ind. Electron; Vol.60,pp. 32-2820, 2013.

[83] Soares O, Gonçalves H, Martins A, Carballo A. “Nonlinear control of doubly-fed induction generator in wind power systems, ” Renew. Energy, Vol.35, pp. 70-1662, 2010.

[84] Rahimi M, Parniani M. “Transient performance improvement of wind turbines with doubly fed induction generators using nonlinear control strategy,”IEEE Trans. Energy Convers, Vol.25, pp.5-524, 2010.

[85] Long T, Shao S, Malliband P, Abdi E, MacMahon RA. “Crowbar less fault ride through of the brushless doubly fed induction generator in a wind turbine under symmetrical voltage dips,” IEEE Trans. Ind. Electron; Vol.60, pp.41-2833, 2013.

[86] Mohsen M, Islam SM, Masoum MAS. *“*Enhanced hysteresis-based current regulators in vector control of DFIG wind turbines,” IEEE Trans. Power Electron; Vol.26, pp. 34-223, 2011.

[87] Jerin, A.R.A.; Kaliannan, P.; Subramanian, U.; El Moursi, M.S. “A Review on FRT solutions for improving transient stability in DFIG-WTs”. IET Renew. Power Gener. Vol.12, pp 1786–1799. 2018.

[88] Howlader AM, Urasaki N, Yona A, Senjyu T, Saber AY “A review of output smoothing methods for wind energy conversion systems, ” Renew. Sustain Energy Rev.,Vol.26, pp.46-135, 2013.