International Journal for Modern Trends in Science and Technology, 8(10): 140-148, 2022
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ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0810025
Available online at: http://www.ijmtst.com/vol8issue10.html

A Review on Fault Ride-Through Capability Enhancement Techniques of DFIG Based Wind Energy Conversion System

Somendra Kumar Singh | Dr. Satyendra Singh | Rakesh Sharma

Department of Electrical Engineering, Institute of Engineering & Technology Lucknow, India
Corresponding Author: somendrasinghjnp@gmail.com

To Cite this Article
Somendra Kumar Singh, Dr. Satyendra Singh and Rakesh Sharma. A Review on Fault Ride-Through Capability Enhancement Techniques of DFIG Based Wind Energy Conversion System. International Journal for Modern Trends in Science and Technology 2022, 8(10), pp. 140-148. https://doi.org/10.46501/IJMTST0810025

Article Info
Received: 02 October 2022; Accepted: 17 October 2022; Published: 26 October 2022.

ABSTRACT

This paper provides an overview of several approaches used to improve the fault ride-through (FRT) capabilities of wind turbines (WTs) based on doubly-fed induction generators (DFIGs) during transient condition. Due to the sensitivity of the DFIG-based WT system to grid disturbances, a number of FRT techniques based on the installation of additional protection circuits, reactive power injecting devices, and certain control approaches have been presented in the literature. Protection circuits or control structures are frequently used to reduce unwanted dc-link overvoltage and generated rotor overcurrent during grid disruption. The reactive power injection devices, meanwhile, overcome any reactive power shortages to enhance the transient performance of the DFIG based WT and automatically constrain the rotor current and the dc-link voltage. The Doubly Fed Induction Generator, which is mainly utilized today in wind turbines, is particularly susceptible to grid disturbances and can harm the power electronic converters owing to over voltage and overcurrent. Protection components that shut off the machine in the event of a problem are therefore very necessary. But because wind energy penetrates the grid so heavily in certain situations, the system's reliability suffers, which is unacceptable. The wind turbine can be linked to the system during the voltage dip using the FRT method. This is accomplished by implementing either hardware or software on the rotor side and grid side of the converter. This will stop the converter from tripping and give the DFIG with uninterrupted functioning during severe grid voltage disturbances. The purpose of this research is to analyze various FRT control strategies.

KEYWORDS:Doubly Fed Induction Generator (DFIG), Dynamic voltage restorer (DVR), Static compensator (STATCOM), Unified power flow controller (UPFC), Crowbar, Wind turbine (WT).

1. INTRODUCTION

Wind power is one of the most important renewable energy sources for the production of electricity. One of nature's most plentiful renewable energy sources is wind. The oil crisis and the maturing of natural resources, which call for more transmission capacity and better ways to preserve system reliability, sparked an improvement in wind power research in the previous century. The energy demand must be met by renewable energy sources like wind, which have significant environmental, social, and economic benefits, in order to have sustainable growth and social advancement. Fortunately, the objective of lowering greenhouse gas emissions is closely related to the development and uptake of renewable energy sources [1].

In light of the ongoing pollution, the efforts to decrease it are encouraging. The capacity of installed wind turbines (WTs) has dramatically increased recently [2-4]. Large WT grid integration, however, can have adverse impacts on the grids that are weak or faulty [5]. The rise in fault current levels and voltage drops at the wind generator terminals caused by the trend of integrating more WTs may cause WTs to be disconnected, which has an impact on the stability of the power system both during and after fault clearance [6-8].

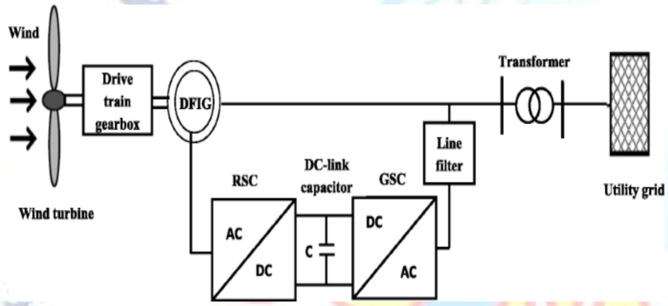

Figure -1 Basic diagram of DFIG [14]

Based on the methods of speed control, WTs may be divided into four fundamental categories: fixed-speed wind turbines, limited variable-speed-controlled wind turbines, doubly fed induction generator (DFIG)-based wind turbines (DFIG-WTs), and full variable-speed-controlled wind turbines [9,10]. Due to their benefits such as easy installation, low cost, variable-speed constant frequency, and independent management of reactive and active power, DFIG-WTs are the most frequently used of these four types of wind turbines in practical applications [11]. A DFIG's schematic diagram is displayed in Figure 1. The rotor is connected to the power grid via a back-to-back voltage source converter, which consists of a rotor-side converter (RSC) and a grid-side converter, while the stator is directly connected to the power grid (GSC). In order to maximize power capture, RSC is used to regulate the active and reactive power that is delivered. GSC is used to maintain the direct current (DC)-link voltage as well as manage the active and reactive power provided [12,13].

Grid voltage fluctuations and disturbances can affect DFIG-WTs. The abrupt shift in DFIG bus voltage during grid voltage dips immediately affects the stator and GSC. Large voltages will be induced in the rotor windings by perturbations in the stator, which will cause uncontrolled rotor current. The DC-link voltage could significantly increase due to the rotor overcurrent. Both DC-link overvoltage and rotor inrush current can harm wind turbines [15] and trigger the trip of DFIG-WTs. Low-voltage ride-through (LVRT) capability is defined as the capacity to maintain continuous operation during voltage dips and to reduce re-synchronization issues after the clearing of faults.

In order to be connected to the grid, wind generating systems must meet to certain standards. The fundamental prerequisites for better penetration are effective fault ride through capabilities. Voltage instability issues arise if the power system is unable to supply the reactive power demand, which can happen during failures and the connection of heavy loads. When the voltage magnitude of at least one of the buses falls as the reactive power injection increases, a system experiences voltage instability. The potential instability appears as a steady decline in some buses' voltages. Voltage instability may result in loss of load in a particular location, tripping of transmission lines and other components by their protective mechanisms, cascading outages, and in turn loss of synchronism of some generators [16]. This paper provides an overview of the different FRT techniques used to enhance the transient responsiveness of WTs powered by DFIGs.

A. FRT REQUIREMENT

The ability of WT to withstand transient disturbances during severe system or grid faults is referred to as Fault Ride-Through (FRT) capability. WT are expected to function and support grid stability during faults of short durations. Because of the moment of inertia caused by the rotor mass, it is particularly challenging to meet this criterion utilizing DFIG control [17].

These are the following requirements of the FRT [18]:

i. To ensure continuous operation during voltage dips as well as minimize resynchronization problems after the clearance of fault is stated as FRTC.

ii. It prevents converters from overcurrent and overvoltage.
iii. Grid code is maintained.
iv. Minimize possible stress.
v. Transient SC current is reduced.

The voltage at the PCC versus time plot in Figure 2 illustrates the LVRT feature. When the voltage profile in Figure 2 is met or when the voltage is not in a trip region, WT will continue to maintain system connection [18].

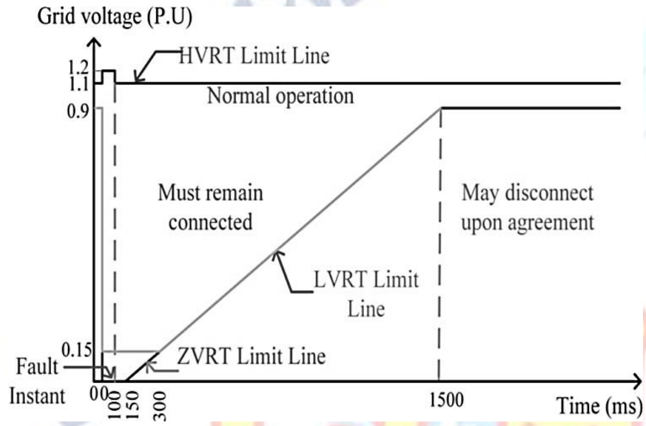

Figure-2 LVRT curve [19]

B. Fault Ride Through Composition –

The following Voltage Ride-Through (VRT) indicated in (i) - (iii) describes the three voltage deviation patterns that make up FRT [19]:

i. ZVRT (Zero Voltage Ride Through) -when the grid's voltage is zero.
ii. LVRT (Low Voltage Ride Through) -when the grid's voltage is between 15 to 25%.
iii. HVRT (High Voltage Ride Through) - when the voltage exceeds the nominal value by up to 120%.

C. GRID CODE NECESSITIES FOR WTs –

According to grid regulations, wind farms must be able to withstand abnormal wind conditions and contribute to power system control in the same way as traditional power-producing facilities. For wind turbines, the grid connection specifications are as follows [20]:

a. **Frequency and Voltage Operating Ranges-**Grid codes mandate that all generating units be able to operate intermittently between a frequency range around the grid's nominal frequency, typically between 49.5 and 50.5 Hz (for 50 Hz systems, such as those in Europe), and between lower/higher frequency range down/up to a cut -off level, typically between 47.5 and 52 Hz.

b. **Voltage Regulation and Reactive Power Control**- In order to keep the balance of reactive power and the power factor at the PCC within the acceptable range, wind farms must manage their output reactive power. Grid regulations also stipulate that each wind turbine must regulate its own terminal voltage to maintain an incentive using an Automatic Voltage Regulator (AVR).

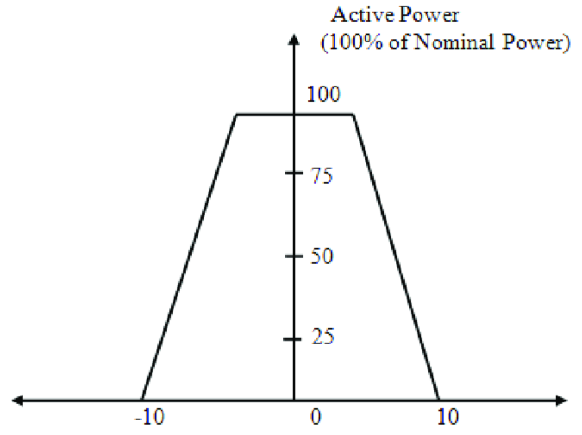

Figure-3 WG's reactive power limiting curve [20]

c. **Low Voltage Ride Through** - Wind turbines must remain linked to the grid during grid failures for a predetermined period of time before being permitted to disconnect. Additionally, using reactive power correction, wind turbines must support the grid voltage during both symmetrical and asymmetrical grid voltage sags.

d. **High Voltage Ride Through** - According to HVRT grid code, wind turbines need to be able to maintain a connection to the electricity grid for a predetermined period of time if the grid voltage rises above its upper limit value.

e. **Frequency and Active Power Control**-Grid regulations mandate that wind farms offer a specific level of active power control in order to maintain a steady frequency in the power system.

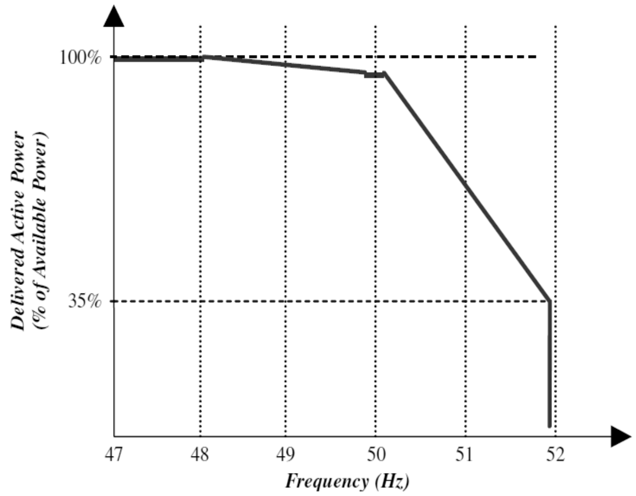

Fig.-4 active power regulations with frequency control [20]

f. **Power Quality Capability** - Wind farms must maintain steady voltage or current harmonics within certain bounds in order to supply power of the desired quality. Another problem with the electric grid's voltage quality related to wind power generation is flicker. System voltage fluctuations have an impact on the grid-connected wind turbine's power quality.

2. FRT CONTROL STRATEGIES OF DFIG BASED WTs –

To comply with the grid, numerous LVRT methods for the DFIG system have been proposed. These techniques can be categorized in three main groups [21]:

1. Protection Circuit- Based
2. Reactive – Power Injecting Devices Based
3. Control Approaches Based/Software Based

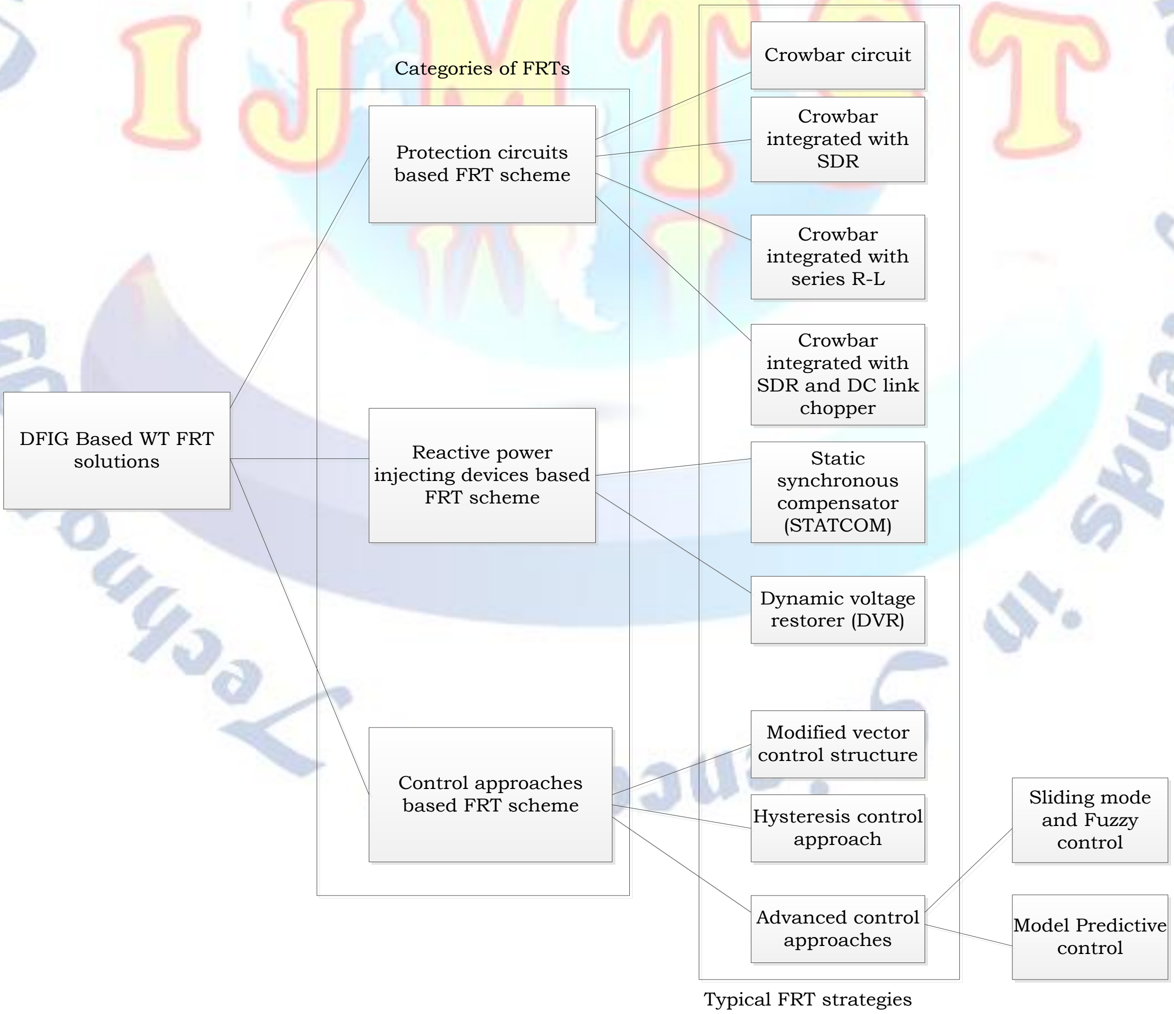

Figure-5 Different types of wind turbine's electrical system arrangements [22]

1. **Protection Circuit Based FRT Technique** - In this scheme various techniques are used to support the FRT requirements –
   - i. Crowbar
   - ii. Series Dynamic Breaking Resistors(SDBR)
   - iii. DC Link Chopper
   - iv. Fault Current Limiter (FCL)

i. ***CROWBAR***– By short-circuiting the rotor windings of the DFIG during grid failures, a crowbar circuit is used to safeguard the RSC as shown in Figure-6 According to grid codes, this method was employed in DFIG fitted with rotor crowbar, which can stay on the grid and limit currents and voltages [23].

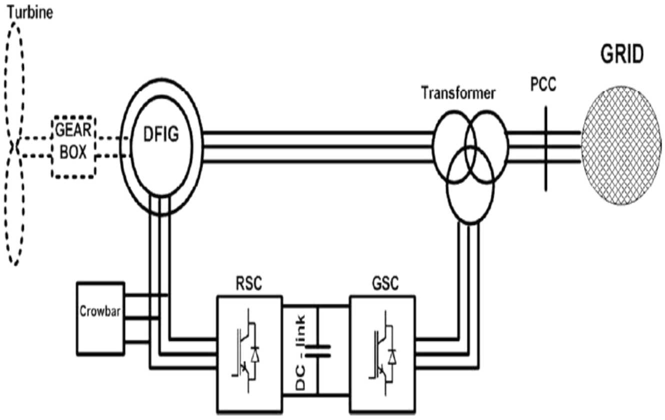

Figure-6 DFIG with Crowbar [23]

ii. ***Series Dynamic resistor (SDBR)***– A configuration known as SDBR is created by connecting a resistor to the grid and an IGBT circuit in parallel, as depicted in Figure 7. The SDBR acts as an active power balancer in the event of the grid fault to eliminate the need for pitch control for the DFIG system. A series resistor is the SDBR's most essential element. The series resistor raises the grid voltage to meet the LVRT specifications of the DFIG system in grid fault scenarios [24].

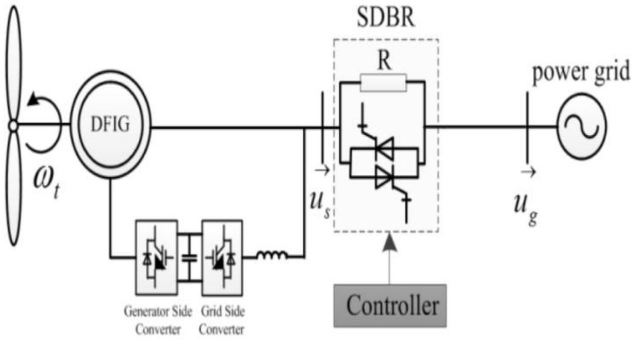

Fig.-7 DFIG with SDBR [25]

iii. ***DC Link Chopper*** – The dc link capacitor is coupled in parallel with a device known as a DC chopper, often referred to as braking resistance, to control excessive voltage and current under abnormal conditions. Figure-8 depicts the method's schematic. The dc-link brake chopper shorts the dc-link through a power resistor when the voltage on the dc-link exceeds a certain threshold level [26].

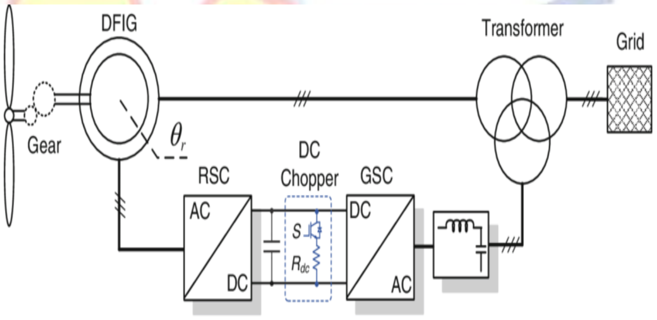

Figure-8 DFIG with DC Link Chopper [27]

iv. ***Fault Current Limiter (FCL)***-The rising fault current levels brought on by the high levels of WT integration into the power grids raise the demand for FCL. Many other FCL types have been proposed and developed recently, including solid state FCL, transformer coupled bridge-type FCL (BFCL), resonant circuit and SFCL (Superconducting FCL).

2. ***Reactive – Power Injecting Devices Based –***

   In this scheme to tackle the FRT capability of DFIG various devices and FACTS controllers are used –

   - (i) DVR (Dynamic Voltage Restorer)
   - (ii) STATCOM (Static Synchronous Compensator)

(iii) SVC (Static VAR Compensator)
(iv) UPFC (Unified Power Flow Controller)

(i) ***DVR (Dynamic Voltage Restorer)* -** The DVR is made up of the VSC that is voltage source converters, an energy storage system, switching control of converters and in this case, a coupling or booster transformer connected in series with the AC system. DVR's primary function is to control and balance voltages and harmonics elimination from source to load. This system is used to solve various problems of power quality and performance issues including [28].

- Sags in voltage
- Voltage Swells
- Voltage Instability
- Power Factor Improvement
- Blackouts
- Harmonics in the voltage

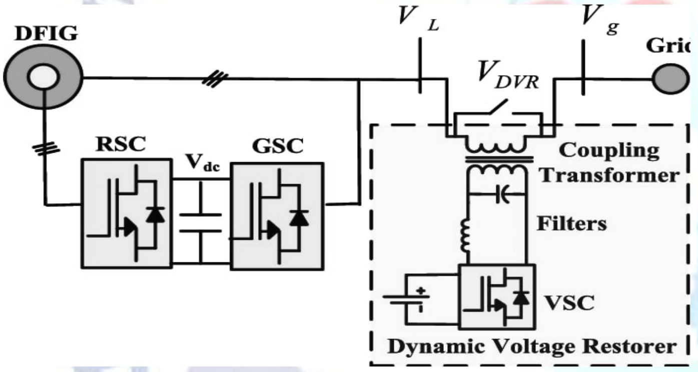

Fig-9 DFIG with DVR [29]

(ii) ***STATCOM (Static Synchronous Compensator)* -** STATCOM is a power electronic device that controls the flow of reactive power over a power network and so improves the stability of the power network by employing force commutated devices like IGBT, GTO, etc. STATCOM is a shunt device, which means that it is shunt connected to the line. Synchronous in STATCOM refers to the ability to generate or absorb reactive power in synchronization with the need to maintain the power network's voltage. A connection transformer coupled in shunt with the ac system and a dc energy storage device, a VSC make up the STATCOM arrangement. In reaction to a voltage drop, the STATCOM continually and autonomously generates a regulated reactive current, promoting the grid voltage's stability [27].

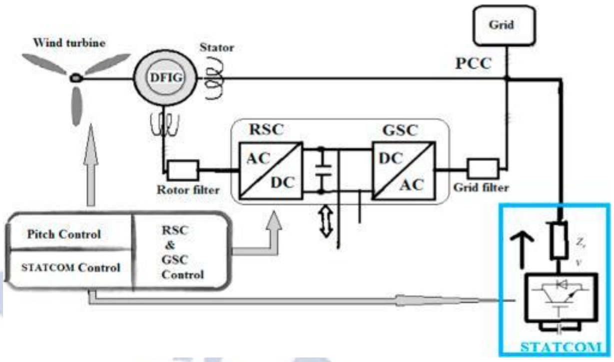

Fig.-10 DFIG with STATCOM [30]

(iii) ***Static VAR Compensator (SVC)*** – SVC connected to DFIG is shown in fig. 11 SVC is the combined form of both Thyristor controlled reactor (TCR) and Thyristor switched capacitor (TSC). In order to increase transient stability and reduce oscillation in a grid-connected DFIG system, the SVC can often inject reactive power into the linked bus. The reactive power dynamic variations regulate the bus voltage connected to the SVC.

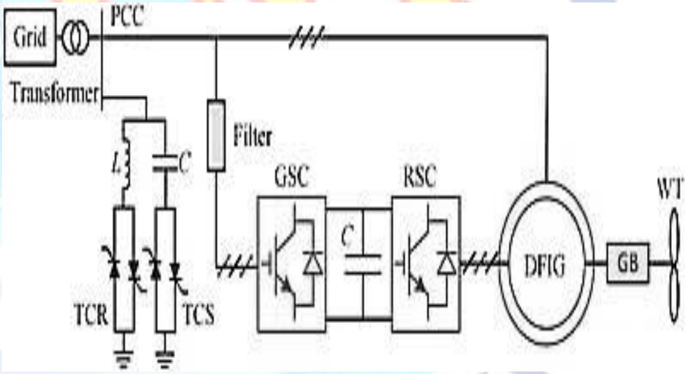

Fig .11– DFIG with SVC [31]

(iv) ***Unified Power Flow Controller (UPFC)*** – Another LVRT technology for the DFIG system is hybrid compensation, which combines series and shunt voltage compensation. A unified power flow controller (UPFC) was suggested in the literature as a way to enhance the LVRT performance of the DFIG system. Figure 12 depicts the DFIG system with the UPFC.

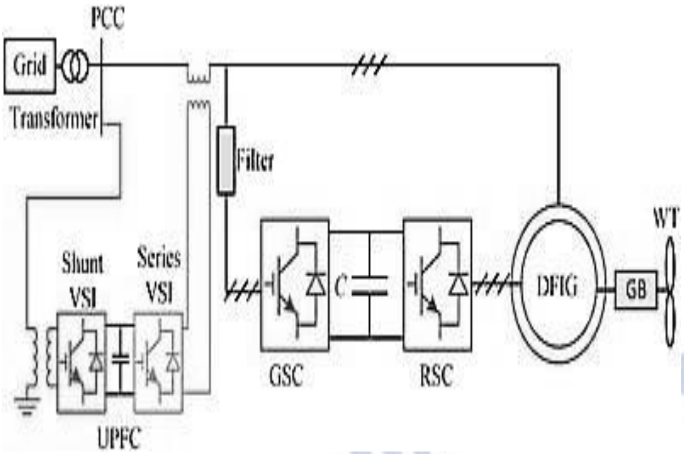

Fig .12– DFIG with UPFC [31]

3. ***Control Approaches Based/Software Based-*** These techniques do not need any additional devices to FRT of DFIG. These are based on software. These techniques are-

i. Hysteresis control approach
ii. Advanced control approach
iii. Modified control approach

i. ***Hysteresis control approach-*** Figure 13 illustrates a hysteresis control approach that consists of a nonlinear feedback loop with two-level hysteresis comparators. The switching signals (S_A, S_B, and S_C) will be produced for space vector modulation (SVM) and then supplied as input to the inverter after the error crosses the threshold tolerance band. The hysteresis control strategy has benefits such as easy control, high robustness, greater accuracy, independence from load, and outstanding dynamic performance [32].

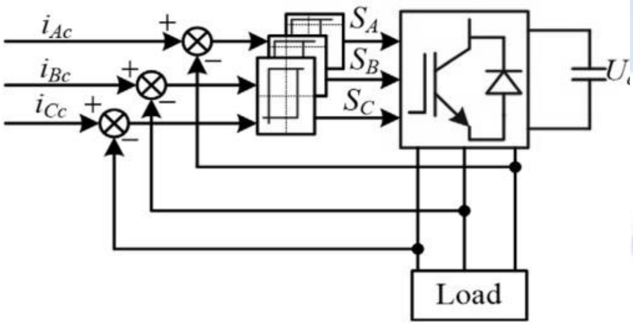

Figure-13 RSC current controller with hysteresis

ii. ***Advanced control approach-*** The best LVRT performance of the DFIG system can be ensured by using advanced control techniques as sliding mode control (SMC), fuzzy logic control (FLC), model predictive control (MPC), and active disturbance rejection control (ADRC).

A thorough MPC-based analysis of the LVRT of the DFIG system was provided in [33]. The MPC is one of the most widely used non-linear algorithms for the LVRT support of the DFIG system because it can handle the non-linear situations during grid disturbances. The MPC-based LVRT algorithms used by the DFIG system require additional study. According to [34] and [35], an FLC would increase the LVRT capacity of the DFIG system by bringing about sufficient coordination between the dc-link voltage and battery energy storage systems (BESS) regulation. This age may see new study due to the FLC-based FRT control for the DFIG system in both active and passive ways. SMC is suggested as a suitable option to address the FRT requirement of the DFIG system in more detail [36].

According to the [37], an ADRC controller was created for the RSC of the DFIG system to enhance LVRT performance. The ADRC can be regarded as a crucial LVRT scheme for the DFIG system because of its benefits such as high anti-disturbance, quick reaction, and fewer chattering issues than SMC.

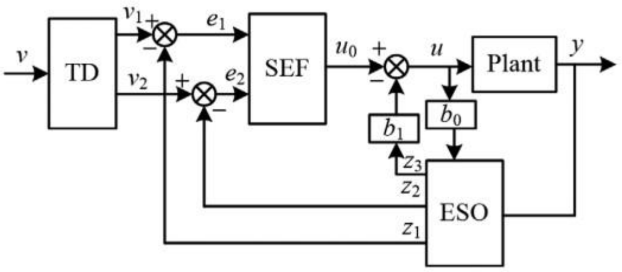

Figure-14 ADRC scheme

iii. ***Modified control approach/Vector control (VC) -*** To make the design of the current controller for the RSC and GSC under steady-state circumstances simpler, the stator flux is typically assumed in VC to be constant and aligned with the d-axis of the stator frame of reference. With a little modification to a conventional VC, the feed-forward transient current control (FFTCC) scheme in an effort to increase the LVRT capabilities of the DFIG system [38].

Table- I COMPARISON OF VARIOUS FRT TECHNIQUES

Technology Used	Reliability	Complexity	Response speed	Cost
SDBR	Low	Low	Slow	Low
Crowbar	Low	Low	Slow	Low
FCL	Medium	High	Fast	High
DC Chopper	High	High	Fast	Medium
SVC	High	Medium	Slow	Medium
UPFC	Medium	Very High	Fast	Very High
DVR	Medium	High	Fast	High
STATCOM	Medium	High	Fast	High
Hysteresis control	High	Low	Slow	Low
Modified control	Low	High	Slow	Low
SMC	High	Low	Slow	Low
FLC	High	Low	Moderate	Low
MPC	High	Medium	Moderate	Low
ADRC	High	Medium	Fast	Low

3. CONCLUSION

This paper has explored the typical varieties and the potential applications of FRT for the DFIG system. For the DFIG system, many FRT strategies have been thoroughly explored and divided into three categories: protection-based, reactive power compensation-based and software-based FRT techniques. There has been a comparison of the various FRT techniques. It is clear from this paper's thorough study of FRT techniques for the DFIG system that hardware-based solutions are preferable since they are applicable in the current wind sector. However, the fundamental drawback of these kinds of FRT approaches is the added expense of hardware-based protection mechanisms. The software-based approach, on the other hand, can offer a low-cost FRT solution for the DFIG system, although it is currently difficult to implement software-based FRT techniques in the wind industry.

According to the research above, FRT is a crucial component for wind turbine systems to meet grid code requirements. Variations in grid voltage can affect DFIG. This can be avoided by implementing the proper control to prevent the converter from tripping during grid voltage faults. Voltage fluctuations, rotor current variations, torque changes, and dc link voltage fluctuations are all brought on by high current transients. These days, DFIGs with energy storage systems and FACTS devices are typical. However, this makes the system more expensive and complex. Flux tracking has undergone a variety of improvements, and the present feedback approach provides good performance characteristics. The control technique that enhances the FRT with less expense and complexity while providing strong reactive power assistance during faults should be the subject of further study.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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