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An Overview on the Issuesof Grid-Connected DFIG Wind Turbines: Analysis,Grid Codes and Improved LVRTMethods

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ABSTRACT: *Nowadays, electrical generation using the wind energy (WE) is increased in most countries which have windy region. This growth of wind generation is due to its free and environmental friendly without pollution. Normally,doubly fed induction generator (DFIG) based wind turbines is among the common WE generation architectures that preferably used because it has operated with variable wind speeds to obtain fixed-frequency with high reliability, and control active and reactive power injected to grid system via advanced control system. However, DFIGhas suffered from voltage fluctuations, converter damage, mechanical oscillations and stresses. Therefore, the wind generation should provide ancillary services for power grid and low voltage ride through (LVRT) for large wind generation to improve the generation system. There are many research works were studied to overcome these problems and improve DFIG operation such as LVRT modifications.* ***In this paper****, a comprehensive review of most previous published research works about analysis, modeling and improvement of LVRT of wind turbines with DFIG is presented. This review also includes methodologies of LVRT improvement and other DFIG solutions to enable researches to study and improve LVRTmethods in a summarized manner.*

KEYWORDS: *Renewable energy sources; Wind Energy (WE); Doubly Fed Induction Generator (DFIG);The issuesof Grid-Connected DFIG Wind Turbines; Low Voltage Ride through (LVRT) Improvement Methods.*

I. INTRODUCTION

Actually, there are several sources of renewable energy such as wind, solar, biomass, hydro, tidal, etc. Among the several renewable sources, wind energy is the fastest growing sustainable renewable energy, has stood out to be one of the most promising alternative sources of electrical power [1,2].The overall capacity of all wind turbines installed worldwide by the end of 2018 reached 597 GW, according to preliminary statistics published by World Wind Energy Association (WWEA). 50.1GW were added in the year 2018. All wind turbines installed by end of 2018 can cover close to 6% of the global electricity demand [3].There are several types of architectures electrical power generation based on Wind Energy has different generator technologies, structures, and control strategies .The most common type of generator in architectures is wind turbines equipped with doubly fed induction generator (DFIG)[4].

DFIG-based WTs is one of the most frequently prevalent grid-connected wind turbines, also becoming more prevalent, popular and dominant in wind farms and still dominant in the current market. Additionally, the market shows interest in variable speed concepts with power electronics will continue to dominate and be very promising technologies for large wind farms. The main advantage of this type is that it can produce electrical power from variable speeds of wind. This capability is obtained with controlling the frequency of the rotor windings via two back to back connected converters [5].These converters can be used for achieving more power quantity, quality and higher capacity, also decoupled control of active and reactive power and more grids friendly[6].

Although its spread widely, but theDFIG-based WT turbines suffers from very sensitive to grid disturbance like as voltage dips. Any abrupt drop of the grid voltage such as the symmetrical or asymmetrical faults may cause the stator currents dramatically increase beyond the rated values. Because of the magnetic coupling between stator and rotor, the stator fault currents are transmitted into the rotor causing uncontrollable excessive rotor over-currents. These currents can damage the power electronic devices of the power converter. Also, the electromagnetic torque of the DFIG starts to oscillate with high amplitudes causing mechanical stresses to the wind turbine system [7].

This can create issues such as destabilization of the power system network, the power flow at the connection point to the grid, voltage operating range, power factor regulation, frequency operating range, active and reactive power support to grid. One of the most important issues related to DFIG is the low voltage ride through (LVRT) or fault ride through (FRT) capability. It means that the ability of a wind turbine to remain connected to the grid to support voltage and frequency during and after the fault, respectively[8].Such Issues can considerably affect the performance of the DFIG gives a reflection on large-scale disconnections that may further weaken the grid and cause a considerable impact on the stable grid operation[9].

However, witnessed tremendous increase in the number and capacity of DFIG based Wind turbines integrated into their electric networks. Therefore, the Modern grid codes require wind turbines to not only withstand various grid disturbances, but also contribute to the network stability support as do conventional generation units [10]. Also, grid connection issues have posed several new challenges to strongly depend on their ability of complying with both market expectations and the requirements of grid codes.

Under this background, this paper reviews the following; Section 2 presents an overview of modeling of grid-connected DFIG wind turbine and in Section 3analysis of grid-connected DFIG issues is analyzed. The grid codes requirements for the LVRT is discussed in Section 4scientific solutions to these issues are then discussed in Section 5, provided by researchers entitled "LVRT Improvement methods for DFIG based WTs ".Finally, the conclusion is presented in Section 6.

II. MODELING OF GRID-CONNECTED DFIG WIND TURBINE

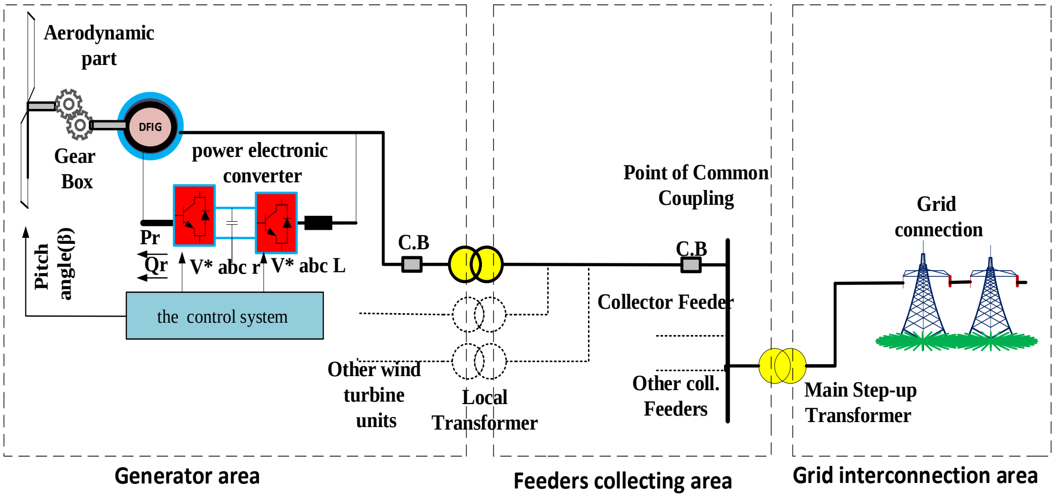
Humans have a long history of using wind energy. In1887, the first known wind turbine used to produce electricity is built in Scotland by Prof James Blyth of Anderson's College, Glasgow (now known as Strathclyde University) [11,12]and then its developed and growth has been largely used in the form of independent units or connected to the electricity grid. Seeing the bright future of the large scale wind turbine, among these turbines, DFIG is currently one of the most common wind turbine technologies installed in wind farms and widely used in new wind parks [13], which is used as hybrid system with other conventional energy sources.The following section describes the system connected to the electrical network and its operation method.

2.1 Modeling description

Fig. 1shows the schematic diagram of the grid-connected DFIG WT system. It is a wind turbine unit consisting of wind turbine blades, an electric generator, a power electronic converter and the control system and it's connected to distribution system exports power to electrical grid through feeder.

DFIG is naturally a wound rotor induction generator, and the rotor circuit is normally controlled by power electronic converter to enable variable speed operation.

Figure 1: *The schematic diagram of the grid-connected DFIG WT system*



DFIG stator winding typically directly connects to the grid while rotor winding is connected via slip-rings to power convertors [14]. The power electronic converter connecting the rotor windings to the grid consists of two voltage-source converters, i.e., rotor-side converter (RSC) and grid-side converter (GSC), between the two converters a DC-link capacitor is placed, as energy storage, in order to keep the voltage variations (or ripple) in the DC-link voltage small.The control objective/strategies implemented in the DFIG power converters is as follows:-

2.1.1Control of rotor-side converter

The rotor-side converter applies the voltage to the rotor windings for excitation to control the rotor currents such that the rotor flux position is optimally oriented with respect to the stator flux in order that the desired torque is developed at the shaft of the machine. The vector control for the generator can be embedded in an optimal power tracking controller for maximum energy capture in a wind power application [15].By controlling the active power of the converter, it is possible to vary the rotational speed of the generator, and thus the speed of the shaft of the wind turbine[16].

This can be used to track the optimum tip-speed ratio as the incident wind speed changes thereby extracting the maximum power. Also, it provides a varying-frequency excitation depending on the wind speed conditions. The induction generator is controlled in a synchronously rotating dq-axis frame, with the d-axis oriented along the stator-flux vector position in one common implementation. This is called stator-flux orientation (SFO) vector control. Consequently, the active power and reactive power are controlled independently from each other.

2.1.2 Control of grid side converter

The objective is to keep the DC-link voltage constant (this means that observer of DC-link voltage) and that is through enabling independent control of the active and reactive power flowing between the grid and the grid side converter[2].

2.2 Steady-state operation

In steady-state, the power exchanging between the DFIG and the grid is depending upon the rotor slip "s" and weather the machine speed is either over or below the synchronous speed. The mechanical, electrical power and the slip (s) of the DFIG could be obtained from the following equations:

$$p_r = p_m - p_s = T_m \omega_r - T_m \omega_s = -T_m \left(\frac{\omega_s - \omega_r}{\omega_s}\right) \omega_s = -sT_m \omega_s = -Sp_s \qquad (1)$$

Where,S is defined as the slip of the generator:

$$S = \frac{\omega_s - \omega_r}{\omega_s} \qquad (2)$$

The stator and rotor power are $P_s = P_m/(1–S)$ and $P_r = –S\,P_m/(1–S)$.Therefore, if the maximum slip is limited, say to 0.3, the rotor winding converters can be rated as a fraction of the induction generator rated power. This is typically around ±30% for DFIG in wind power generation systems and gives a slip range of ±0.3. The slip is assumed to vary from a sub-synchronous value of +0.35 to a super-synchronous value of –0.35. The rotor and stator power vary as the rotor slip changes from sub- to super-synchronous modes. Thus, the operating modes of DFIG as follows:

- **In the sub-synchronous mode**at lower wind speeds, the blades rotate at a sub-synchronous speed ($\omega r < \omega s$), $s > 0$).In this case, the rotor converter system will absorb power from the grid to provide excitation for the rotor winding. Where a stator circuitry is fed with active power.
- **In the super-synchronous mode**themachine operates at super-synchronous speeds ($\omega_r > \omega_s$), $s < 0$). In this case, both stator and rotor generated powers are fed to the grid(So it's called the doubly-fed induction generator (DFIG).
- **In the synchronous mode**When rotating at the synchronous speed ($S = 0$), the DFIG supplies all the power via the stator winding, with no active power flow in the rotor windings.

III. ANALYSIS OF GRID-CONNECTED DFIG ISSUES

In this section, the analysis of DFIG problem during grid voltage dips using mathematical representation and MATLAB/Simulink has been explainedto elucidate the DFIG issues[17].The proposed analysis contributes to understand the causes of the DFIG problem. The grid faults generated the voltage dips. Also, the nature of these voltages is different. In other words, asymmetrical dips are more harmful to the generator than are symmetrical dips, since they induce higher voltages in the rotor windings, not only do they have transitory components, such as those originated in symmetrical dips, but they also have permanent components that remain throughout the whole dip, causing to malfunction some protection systems[18].Therefore, the next sections will present an explanation for that.

3.1 Symmetrical voltage dips

3.1.1 Analysis of the DFIG issues using mathematical representation

Inthis case,when dips occur, the stator voltage amplitude declines from V_1 to V_2,This can be expressed in the following equation:

$$\vec{V_s} = \begin{cases} V_s\, e^{i\omega st} = V_1\, e^{i\omega st}\ for\ t < to \\ \qquad\qquad V_2 e^{i\omega st} for\ t \geq to \end{cases} \qquad (3)$$

As a consequence, the stator flux changes progressively from The forced flux, which rotates at synchronous speed, appears during the normal operation of the machine to The natural flux is a transient flux that appears during the voltage dips. It's initial Value is proportional to the voltage change and decays exponentially according to the stator time constant. It can be expressed as follows:

$$\vec{\psi_{sf}} = \begin{cases} \vec{\psi_{sf1}} = \dfrac{V_1}{i\omega_s} e^{i\omega st} \quad for\ t < to \\ \vec{\psi_{sf2}} = \dfrac{V_2}{i\omega_s} e^{i\omega st} \qquad\qquad for\ t \geq to \end{cases} \qquad (4)$$

Hence, the voltage induced by the forced flux is:

$$\vec{V_{rf}} = V_2 \frac{Lm}{Ls} s e^{i\omega st} \qquad (5)$$

The voltage induced by the natural flux is:

$$\vec{V_{rn}} \approx -\frac{Lm}{Ls}\frac{\omega}{\omega_s}(V_1 - V_2)e^{-t/\tau s} \qquad (6)$$

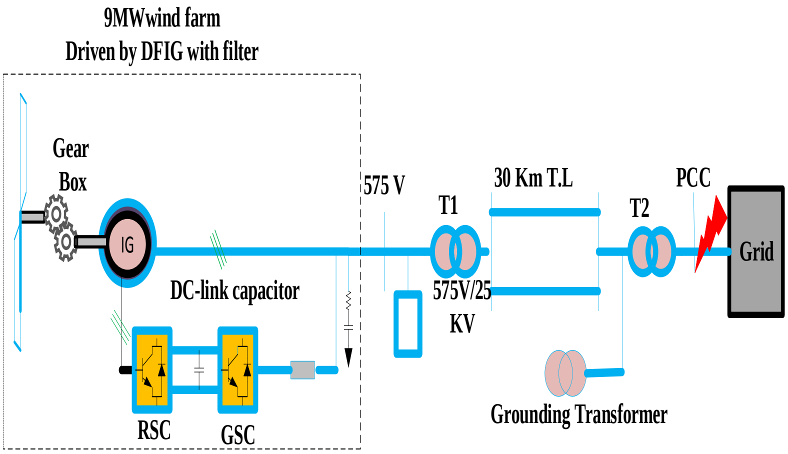
The V_{rf} is generated by the new grid voltage and its amplitudeis small whilethe V_{rn} is a transient term caused by the natural flux. Its amplitude can beimportant as it is proportional to the depth of the dip ($V_1 - V_2$). If the depth of the dip is small and the voltage induced bythe stator flux does not exceed the maximum voltage that therotor converter can generate, the current remains controlled.

In this case, as in the normal operation for larger dips, the voltage induced by the stator flux exceeds the maximum available tension of the converter and the controlof the current is lost transitorily. In this situation, there appearovercurrents that increase as the depth of the dip is bigger. Theworst case is the one corresponding to the full dip. In fact, the rotor converter power rating is quite proportionalto the accepted rate of the dip depth.

3.1.2 Analysis of the DFIG issues using simulation

The simulation work has been performed for wind farm that is connected to a 25 KV distribution system and exports power to a 120 KV grid through a 30 km, 25 KV feeders as shown by the single line diagram in **Fig.2.**

Figure 2: *Single line diagram for the studied system*



Consider the wind farm in MATLAB/Simulink (6 * 1.5MW) is lumped in one DFIG machine model and the parameter of the 1.5 Mw DFIG and system data are given in **Table 1.**

Table 1: *Base and rated quantities for the system under Study*

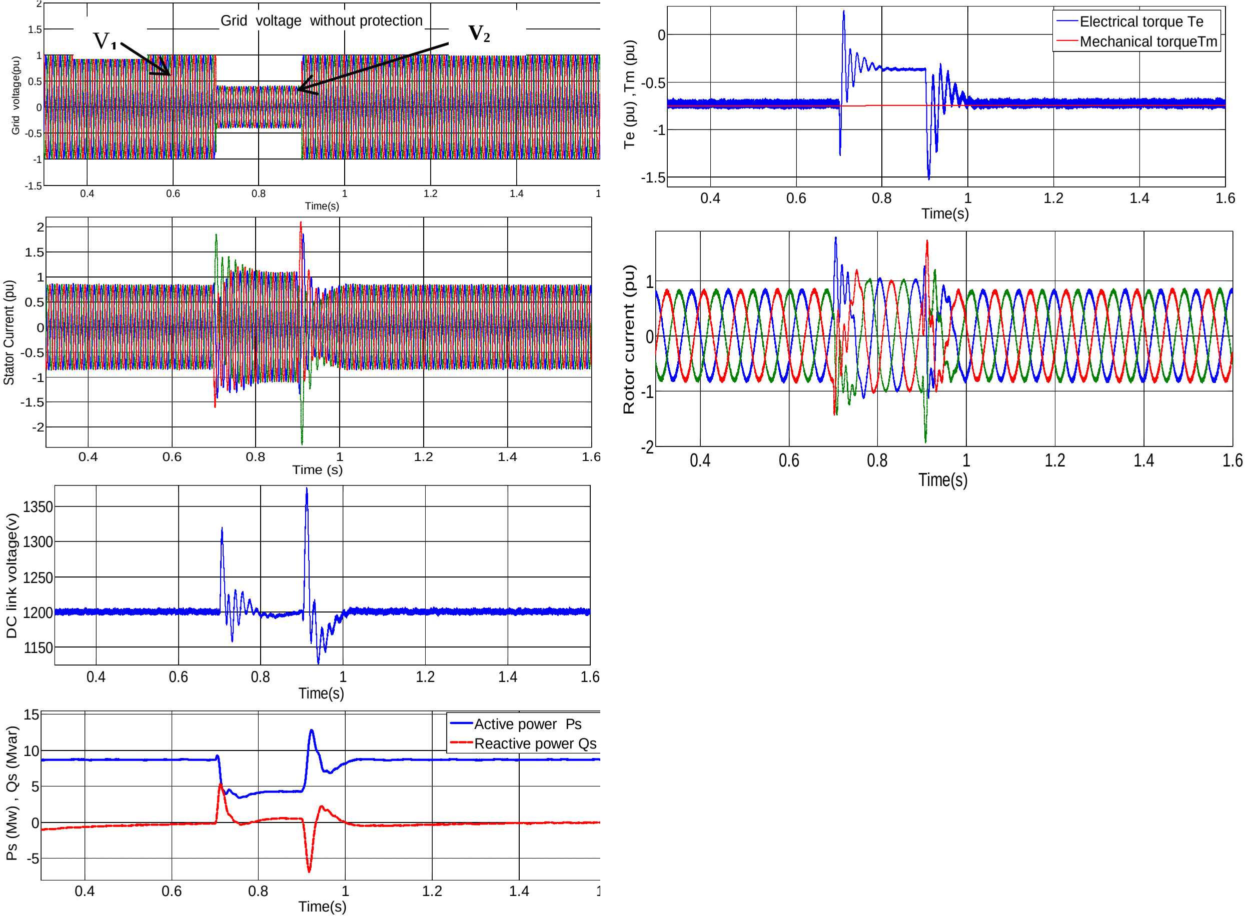
Quantity	Quantity
Base power	10 MVA
Base voltage at generator terminals	575V
Base frequency	60 Hz
Rotational speed base at generator side	1200 rpm
Rated generator rotational speed	1.2 pu
Rated wind speed	11 m/sec
Rated dc voltage	1200 V

Thus, this can be clarified by the simulation results of DFIG model when a fault occurs at the grid connection point as the fault starts at time (t = 0.7s) and cleared at t = 0.9s as follows:

3.1.2.1 Case study1: a three-phase voltage dips of 0.6pu

Fig.3 shows the system responses for grid voltage dip of 0.6pu for 0.2 s. When faults occur in the grid leads to a decrease in voltage on the stator winding from $V_1$to V_2, which leads to induced of voltage in the rotor winding and increase its current this results in rising DC-link voltage. The wind turbine shaft will experience oscillating torque, leading to severe stressing of the turbine shaft and fluctuations in both the active and reactive power.

Figure 3: *Three-phase 0.6pu voltages dip for 0.2s.*



3.2 Asymmetrical voltage dip

3.2.1 Analysis of the DFIG issues using mathematical representation

Asymmetrical dips aremore harmful to the generator than are symmetrical dips, since they induce higher voltages in the rotor. besides, the nature of these voltages is different; not only do they have transitory components, such as those originated in symmetrical dips, but they also have permanent components that remain throughout the whole dip[19]. According to this symmetrical components theory, a three-phase voltage system can be expressed as the sum of three components: positive, negative, and zero sequences. The stator voltage can be decomposed into three vectors, one for each component:

$$\vec{V_s} = \vec{V_{1.}} e^{i\omega st} + \vec{V_{2.}} e^{-i\omega st} + \vec{V_{0.}} \qquad (7)$$

The positive sequence V_1 creates a flux that rotates and the negative sequence V_2 creates a flux that rotates reversely. The zero sequence V_0 does not create any flux. These fluxes will be denoted by ψs_1 and ψs_2, respectively. They can be written as:

$$\vec{\psi_{s1}} = \frac{V_1}{i\omega_s}.e^{i\omega st}$$

$$\vec{\psi_{s2}} = \frac{V_2}{-i\omega_s}.e^{-i\omega st} \qquad (8)$$

Each flux induces a voltage in the rotor according to its amplitude the rotor voltage is then the sum of the three terms:

$$\vec{V_{ro}} = \vec{V_{r1}} + \vec{V_{r2}} + \vec{V_{rn}} \qquad (9)$$

The voltages induced by the forced fluxes can be achieved. Expressing them in the rotor reference frame:

$$\vec{V_{r1}} = V_1 \frac{Lm}{Ls} \ .S.e^{-i\omega s.t}$$

$$\vec{V_{r2}} = V_2 \frac{Lm}{Ls} \ .(S-2).e^{-i(2-s)\omega s.t} \qquad (10)$$

The V_{r1} is small. The V_{r2}, however, includes a factor close to 2, and therefore, its amplitude can be important if the asymmetrical ratio of the dip is big. Since the slip is usually small, its frequency is approximately twice the grid frequency. The voltage due to the natural flux depends on its initial value:

$$\vec{V_{rn}} = -\frac{Lm}{Ls}\left(\frac{1}{\tau_s} + J\omega\right).\vec{\psi_{no}}.e^{-t/\tau s}e^{-i\omega t} \qquad (11)$$

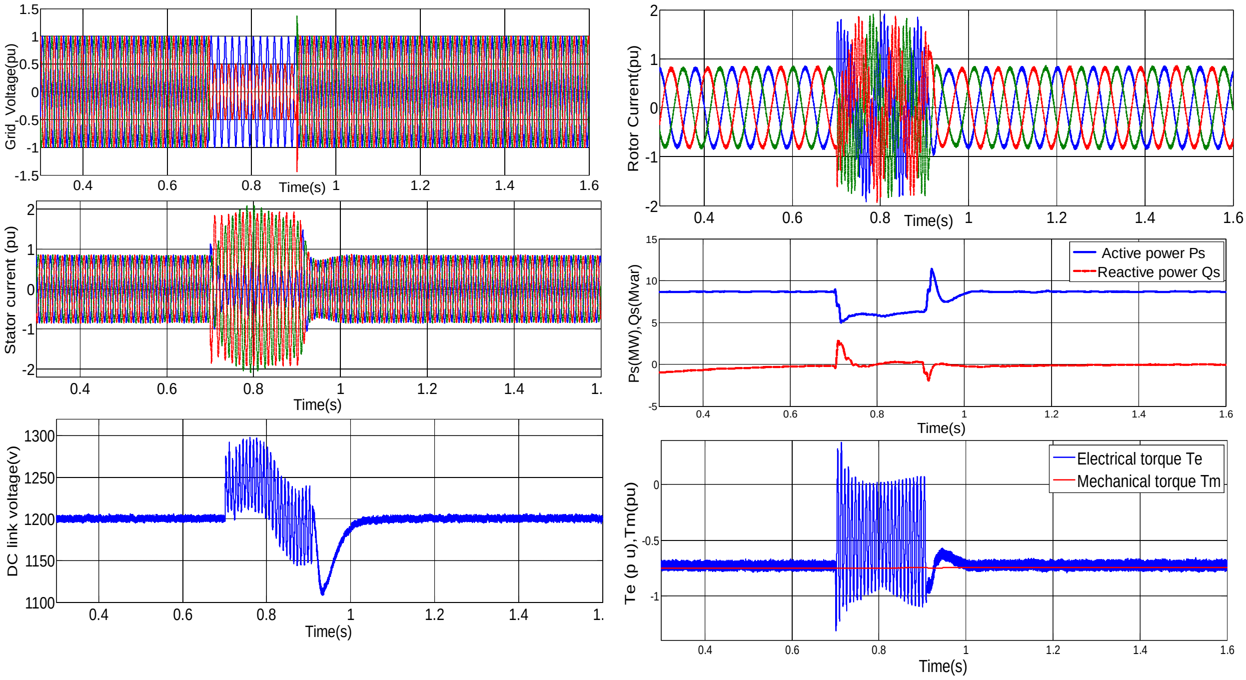
They induce voltages in the rotor that are much greater than those appearing under normal operation. If the rotor converter does not compensate these voltages, control of the current is lost even permanently. In this situation, overcurrent's appear that can damage the converter.

3.2.2 Analysis of the DFIG issues using simulation

3.2.2.1 Case study1: a three-phase voltage dips of 0.6pu

Fig. 4 shows the system responses. The phase's b and c are shorted together for 0.2 s, leading to a voltage dip at the stator terminals. As described in the simulation results, voltages are induced in the rotor. The nature of the rotor induced voltages is different as they have permanent components that remain throughout the whole dip. There is an increase in the stator and rotor currents that remain throughout the whole dip as shown in **Fig. 4**. For the most serious phase, and increase in the rotor currents. Thus, the higher rotor currents lead also to rising DC-link voltage. Large electrical torque fluctuations occur. Also, large fluctuations occur in both the active and reactive power.

Figure 4: *Phase b to c short circuit for 0.2 s*



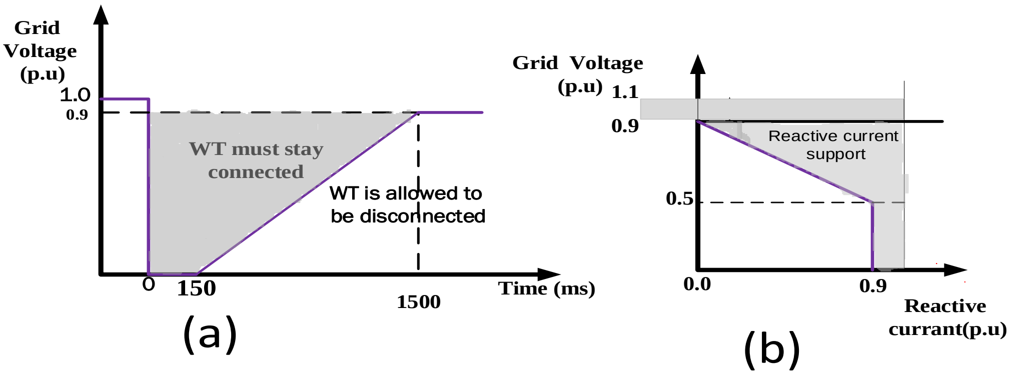
Due to the analysis of the DFIG issues that have caused differences in on both magnetic and electric variables to the generator during a voltage dip (such as stator and rotor currents, DC-link voltage, electromagnetic torque, active and reactive power fluctuations at the grid connection point). in other words, this difference on both magnetic and electric variables that could even destroy the converter if no protection elements are included and disconnect the turbine from the grid .With this solution, the wind turbines are not able to collaborate in resuming normal operation of the grid. Even worse they contribute to increase the dip as they stop generating electric power. As it happened the European outage on November4, 2006, caused the disconnection of 2800 MW of wind-origin power in Spain, is mentioned in [20-22].With the increase in the production of electric power from these turbines and their widespread spread, grid codes began to demand that the wind turbines remain connected to the grid.

IV. GRID CODES' LVRT REQUIREMENTS

It is noteworthy that renewable generators unlike conventional power plants will not be able to support the voltage and frequency of the grid during and immediately following the grid failure. This would cause major problems for the systems stability. It is therefore worldwide recognized that to enable large-scale application of wind energy without compromising system stability, the turbines should stay connected to the grid in case of a failure. They should be similar to conventional power plants [23].Currently, many countries have revised their grid code in order to maintain safe and reliable operation of power system by defining grid code requirements for the wind farms that refer to that wind turbines remain connected to the grid during the grid faults [24].

A brief review on LVRT requirements for DFIG presented in [24],the grid codes requirements for the LVRT capability of WTs are shown in **Fig. 5.** As shown in **Fig. 5(a),** the WTs must keep connection to the grid if the system voltage and fault duration remain in the shadow area. Because the voltage drop of the WT terminal causes over voltages and over currents in the rotor windings that could even destroy the converter, the additional protection devices should be installed. Moreover, WTs must deliver the reactive current during the voltage dips to maintain the grid voltage. This voltage control must be activated within 20ms after the voltage sag is detected. The required amount of the reactive current relies on the voltage dip, as indicated in **Fig. 5(b).** The reactive current output of a WT should be within the shadow area. After the fault is cleared, WTs must continue to deliver the active power immediately with the gradient of at least 20% of the rated power per second.

Figure 5: *The grid code requirements that consist of (a) ride-through curve and (b) support curve of reactive current [24].*



LVRT requirements of grid codes could be summarized as follows:

Wind turbines should remain connected to the grid during certain level of voltage dips at point of common coupling (PCC) for predetermined time periods [25].

- Standard IEC 61400-21 also defines voltage drop tests for wind turbines for verifying their response to grid voltage dips.
- Different kinds of symmetrical and asymmetrical voltage drops are specified with different voltage magnitudes and fault duration times.
- Wind turbines should produce certain amount of reactive current during the voltage dips to support grid voltage stability.
- Wind turbines should generate active power immediately after fault clearance to support grid frequency.

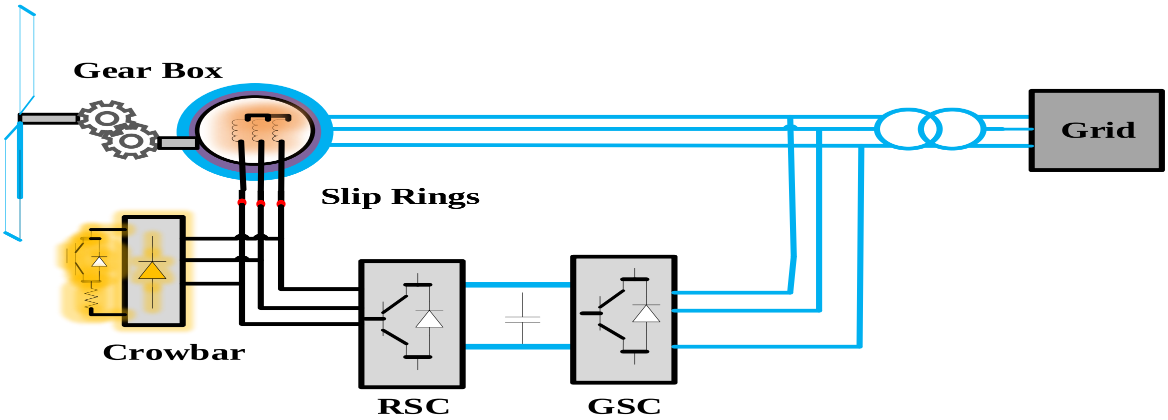
V. LVRT IMPROVEMENT METHODS FOR DFIG BASED WTS

In this section, we will provide the scientific solutions by researchers to DFIG issues, improved methods for these issues. Initially were the first steps to solve the problem by wind turbine manufacturers to protect the rotor and converter by short circuit the rotor windings with the so-called crowbar. This can be discussed in detail as follows:

- The Crowbar protection scheme

The mainstream scheme adopted by manufacturers to ride through grid faults as shown in **Fig. 6**[26, 27].Note from this figure that the crowbar protection scheme is a set of resistors that are connected in parallel with the rotor winding terminals .coupled via the slip rings to the generator rotor. The purpose of the crowbar is to limit the rotor current at the fault time so that it can protect the power converterto reduce the rotor voltage by means of providing an additional path to the rotor current. Its overall operating principle is that during voltage sag the gating signals of the rotor-side converter (RSC) are turned off and the rotor slip-rings are short-circuited through the crowbar resistance[28,29]. However, during crowbar operation the control of the active and reactive powers of the WT which is originally performed by the RSC is temporally lost upon its activation. So, the DFIG starts acting as a squirrel-cage induction generator (SCIG) characterized by the reactive power absorption from the grid which increases the voltage dip and delays the grid recovery after a fault [30,31,32].However, it reduces of the over-currents in rotor and stator.

Figure 6: *The Crowbar Protection Scheme [27].*



Manufacturers have implemented this solution without considerations and requirements for the network system, as mentioned in the Refs.[33, 34].With this solution is also not able to control the DFIG based WTs during gridfaults. Additionally, the generator consumes reactive power leading to further deterioration of grid voltage and the probability of disconnecting the turbine form grid, the probability of other turbines outages increase which will cause to grid insatiability [34].However, as the number of grid-connected turbines grows, this influence has become more important. keep to stability and security of the grid are two vital aspects of energy supply so, DFIG based wind turbines are requested to meet the LVRT requirements issued in grid codes during grid faults and WTs must have the LVRT capability to avoid system blackouts.

Therefore, the researchers began to work on assessing the effectiveness of this solution and develop and find other solutions, the results of their research presented several solutions can be presented as follows:

5.1 Energydissipatingbased methods

These methods include (Crowbar, SDR, Chopper Circuit, etc.), which will be described as follows:

5.1.1The Crowbar protection scheme

Considering the aforementioned drawbacks of the crowbar operation, but more research on improving the crowbar operation has been conducted which can guarantee the active/reactive power control and increase the performance of the DFIG based WTs [35]and active crowbar is then proposed which could be disconnected at the right instant to enable the RSC [36,37]. The reactive power injection could be realized according to grid codes requirements by disconnecting crowbar after few milliseconds [38]. Also, single phase crowbars are designed and compared to commonly use three phase crowbar in [39]. When crowbar is on, the DFIG is converted to an induction generator. In [40], the GSC is controlled to act as reactive power source. Also there are different methods to crowbar protection namely passive crowbar, active crowbar and stator crowbar as mentioned in[41].A discussion on the crowbar optimum resistance and switching strategy is also carried out in [42] as the crowbar resistance (R_{crw}) value can affect the current control behavior during transient-state [43]. Large crowbar resistances result in a better damping of the over-currents in rotor and stator and the torque overshoot. It also minimizes the reactive power consumption. However, very large crowbar resistances can cause current spikes upon deactivation and a high voltage at the rotor slip rings, resulting in voltage stress on the rotor windings.Ref.[44] suggested a crowbar resistance of 0.3p.u,if themaximum rotor voltage is limited to 1.2p.u. Also, the author derived the optimal crowbar resistance ($R_{\mathbf{crw\text{-}opt}}$) as follows:

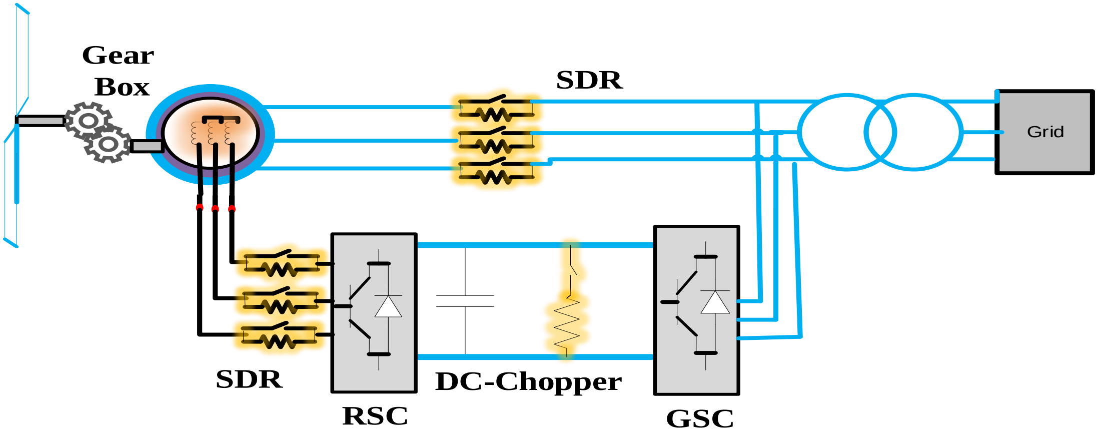
$$R_{crw-opt} = \frac{\sqrt{2}(V_{rmax}\,\omega_s l_s)}{\sqrt{(3.2V_s^2 - 2V_{rmax}^2)}} \qquad (12)$$

Although the crowbar is a cost-effective method able to protect the generator and the converter during the faults, it has some disadvantages that cannot be overlooked. Its major disadvantage is that, the DFIG loses its controllability once the crowbar is triggered, due to the rotor-side converter deactivating. In such a situation, the DFIG absorbs a large amount of reactive power from the grid, leading to further grid voltage degradation. In addition, the crowbar resistance should also be carefully calculated in order to provide sufficient damping and minimum energy consumption [45], because it thevalue dependent on the generator data, and hence, in case of another generator, a new resistance value of the crowbar protection has to be chosen.

5.1.2 The Series Dynamic Resistor protection scheme

The Series Dynamic Resistor (SDR) is consists of a set of resistors are the connected in series with the rotor or stator winding as shown in **Fig. 7** It controls the insertion of the resistance inside the rotor or stator circuit by the power electronic switches [46].It is bypassed by power electronic switches during normal operation and becomes active when a voltage dip is sensed. Hence it increases the stator or rotor equivalent resistance during the voltage dips, thereby limiting the over-currents. It also dissipates active power and mitigates DC link over-voltage as well as torque oscillations. SDR is proposed in many papers to enable the DFIG to ride through severe faults including the use of dynamic resistors in series with the rotor is proposed for symmetrical and asymmetrical voltage dips in [43]the use of SDR besides proper reference values for the rotor currents is proposed in [47]. A rotor current controller and dynamic resistors in series with the stator is also suggested in [48] for unbalanced voltagedips. A passive resistive network consisting of shunt and serieselements is proposed in [49]. Series passive resistive network atthe stator side is also discussed in [50].It is shown that this method has more effective performance.

Figure7: *DFIG-based wind turbine with some protective schemes*



5.1.3DC link chopper protection scheme

The detailed diagram of the chopper circuit with DC-link capacitor as shown in **Fig.7**a braking resistor (DC-chopper) consists of a switch and a resistor connected in parallel with the DC-link in a normal operation.The switch is open to bypass the resistor. When a grid fault is detected, the switch is close and the resistor is parallel to the DC-link capacitor to limit the overcharge during low grid voltage.This protects the IGBTs from overvoltage and can dissipate energy, but this has no effect on the rotor current. The surplus active power will be dissipated in its resistor under fault conditions. InRef. [33] control-delay method and minimum threshold type controller are examined during the voltage dips. First method is simple and maintains the DC link voltage within the safe limit, but it cannot effectively prevent dangerous rotor currents. The second method is more sophisticated. In this method, application of the chopper is released by a predefined rotor current threshold and feedback control restores to lower rectification period. But the performance of this complicated approach was not satisfactory. This is also a cost effective approach to improve the LVRT capability because it is a without energy storage based system. But this method dissipates the energy instead of storing it, and sometimes the resistor of the chopper circuit can be over-heated for dissipating energy [4].

5.1.4 Other protection scheme

Table 2 summarizes other hardware based DFIG LVRT solution schemes. Effectiveness of the proposed solutions is verified via experiments or time domain simulations. However, all of them increase the system overall cost and add the complexity.

Table 2: *protection schemes to enhance DFIG LVRT*

Solution	Reference(s)
A series converter on the rotor side	[51]
A nine switch converter instead of conventional six switch grid side converters	[52]
IGBT modules with high current rating and anti-parallel thyristors at the stator	[53]
A protective structure composed of an uncontrolled rectifier, an inductor, two sets of IGBT switches and a diode	[54,55]
Superconducting fault current limiter	[56,57]

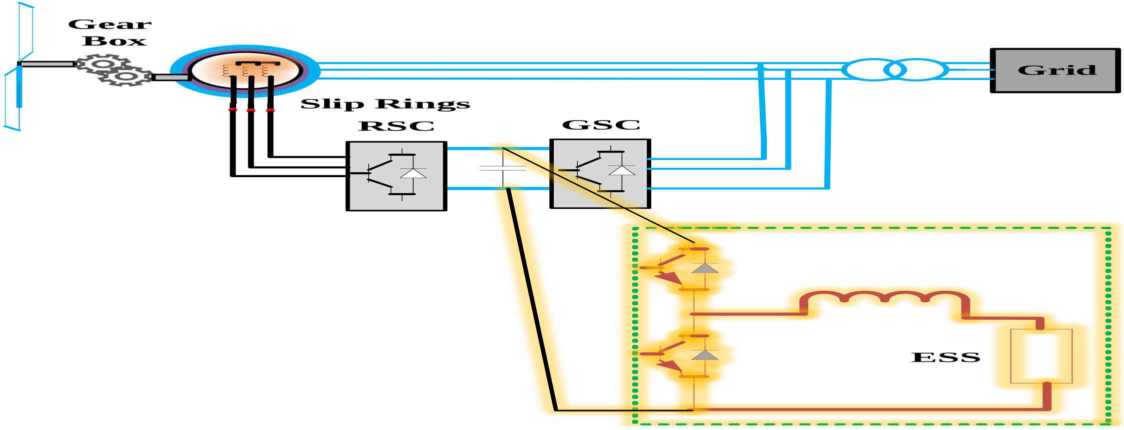
5.2 Energy storage based methods

These methods have different examples e.g. battery, electric double layer capacitor (EDLC), super- conducting magnetic energy storage (SMES), energy capacitor system (ECS)etc. That can be readily integrated into the design of the DFIG.

5.2.1 Energystorage system(ESS)

This method also mentioned in [58] that is used a bidirectional dc/dc converter coupled with the dc busas illustrated by **Fig.8.** For this topology, either theline-side converter or the storage converter controls the dc bus voltage. The power flows from the rotor windingsto the converter. For this case, some energy is stored while theremainder is exported onto the grid via the line-side converterthat has also the ability to control the generator during the fault. However, the rotor-side converter must be sized accordingly in order to allow fault currents to flow through the DFIG rotor circuit. Although an ESS can help stabilize the DC link voltage and smooth the output power simultaneously, it is very difficult to eliminate the overcurrent and electromagnetic torque oscillations but, additional energy storage devices are requiredleading to the system Increased cost and complexity[59-61].

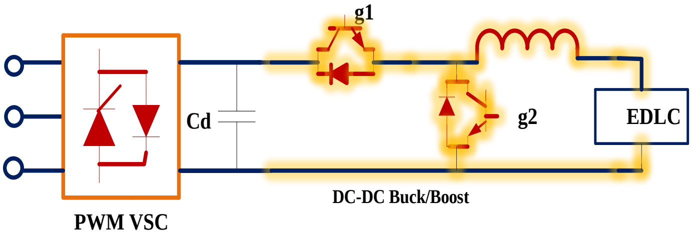
***Figure 8**: DFIG-based WT equipped with ESS.*



5.2.2 Energy capacitor system (ECS)

ECS or DC capacitor sizing that mentioned in [62] is similar to some extent to a crowbar configuration and consists of a voltage converter, a DC link, a DC-DC buck/boost regulator connected to an electrical double layer capacitor (EDLC) as shown in**Fig. 9**. Except that this method protects the IGBTs from overvoltage. However, this has no effect on the rotor currents.

***Figure 9:** ECS configure ration.*



Complementing energy storage based methods has been considered in various cases such as Short term super capacitor energy storage for reinforce the DC link which is mentioned in [58] and super-conducting magnetic energy storage system in [63]. Although storage comes at a greater cost therefore has yet to be adopted by the industry, it possesses a number of advantages: it can be accessed at any operating condition, the operation of the machine need not be modified, and it can also enhance LVRT, potentially resulting in transient stability improvements.

5.3 Reactive power injecting-device based methods

Power injecting-device is used to improve the PCC voltage; flexible AC transmission system (FACTS) devices are composed of static synchronous compensator (STATCOM), static var compensator (SVC), dynamic voltage restorer (DVR), static synchronous series compensator (SSSC), and thyristorcontrolled series compensator (TCSC) and unified power flow controller (UPFC). During the fault condition, the transient state stability of the wind turbine is possible through the FACTSdevices. Among the various FACTS devices, the

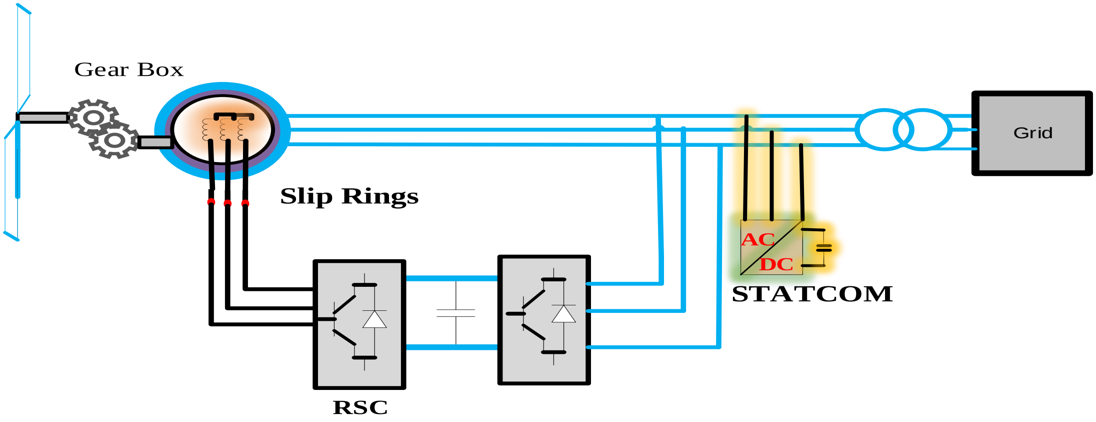
STATCOM and STATCOM with ESS (STATCOM/ESS) have been a popular approach to enhance the LVRT capability for the WECS. Several literatures have been proposed the STATCOM or STATCOM/ESS based approaches to improve the LVRT capability[4].

5.3.1 The static synchronous compensator scheme

The STATCOM is a shunt-connected device using power electronics which can regulate the voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When the power system voltage becomes low, the STATCOM generates the reactive power (i.e. STATCOM capacitive) for adjusting the system voltage. Besides, when the power system voltage becomes high, it absorbs the reactive power have been widely used to provide high-performance voltage control during steady-state and transient-state at the PCC [64]. As shown in **Fig. 10,** STATCOM is connected in the PCC through a coupling transformer a voltage source converter (VSC), and a DC-link capacitor, an ESS consists of battery storage and a bidirectional buck/boost DC–DC converter in order to control the charging and discharging operations of the battery. The STATCOM/ESS can store energy in the battery and then deliver that energy to the grid via the DC-link capacitor. The DC–DC converter operates in buck mode or boost mode to recharge or discharge the battery, respectively.

Though the STATCOM or STATCOM/ESS is very popular approach to improve the LVRT capability but the installation and maintenance of this FACTS device in a wind farm will be increased the system overall cost.

Figure10: *DFIG-based wind turbine with STATCOM*

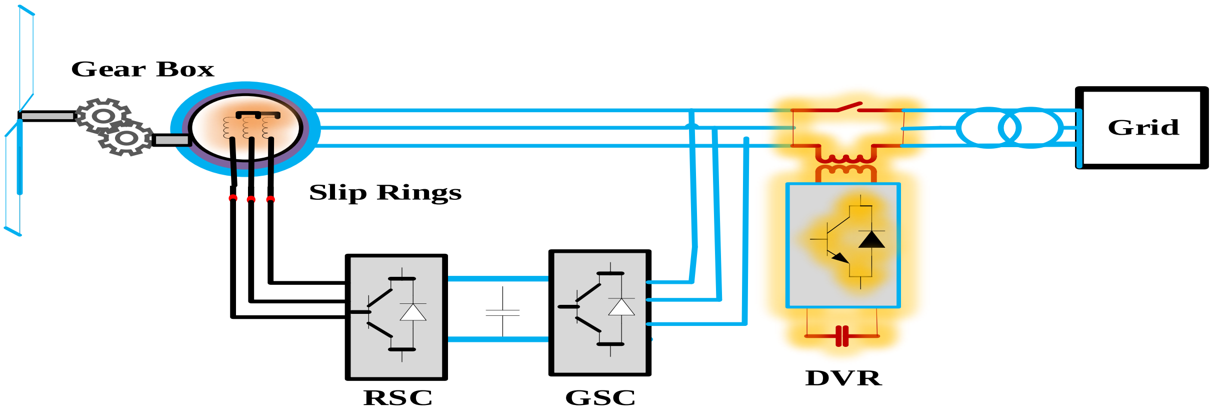


5.3.2The Dynamic voltage restorer (DVR)

DVR is composed of the voltage source converter (VSC), LC filters and coupling transformers connected in series with the grid to compensate for the voltage dip in the grid line during the faults as show in **Fig. 11.** Indeed, it produces a series voltage to correct the voltage at the terminals of electrical loads. Different system topologies of DVR are analyzed in [65]. But it can effectively enable DFIG to ride through severe voltage dips. It is proposed to be used in series with the generator to increase the stator voltage. Thus, the rotor current can be maintained below the maximum permissible value. In order to maximize the generator injected reactive power, the DVR voltage can be so regulated that in addition to terminal voltage enhancing, it absorbs all – or most – the active power generated by the generator. But it has several disadvantages:

- The rating of the DVR should be the same as the rated output of the WT.
- DVRs are very expensive due to many ancillary components and relatively complex.

Figure11: *DFIG-based wind turbine with DVR*



5.4 Modifiedconverters control structures based methods

These methods have drawn more attention in recent days. As most of the installed DFIG based WTs utilize the vector control (VC) to regulate the power generated by the DFIG. In order to cope with the increasing demand of integrating large capacity of wind power into the current power grid, grid operators require that the WTs should ride-through grid faults and support grid stability. However, the VCs are not capable of providing satisfied FRT capability as they are usually designed for the steady-state operation of the DFIG based WT. So, the modified VC must be applied to fulfill the FRT requirements from the distribution or transmission operators.The researchers suggested a lot of modifications from several points of perspectives. For instance

- A feed-forward transient current control scheme incorporated inthe RSC controller to enhance the FRT capability of the DFIG isproposed by Liang et al. [41], which introduces feed-forwardtransient compensators (Vσd and Vσq) to a conventional RSCcurrent regulator . When a fault occurs, the control scheme correctly aligns the RSC ac-side outputvoltage with the transient-induced voltage, resulting in minimumoccurrence of crowbar interruptions. As per the authors of [66],the stator currents as the references rotor current during the gridfaults which can cause the stator and rotor over currents todecrease is implemented. To decrease the rotor over-currentsand increase the flux attenuation, the gains of the PI currentcontrollers of the RSC are adjusted optimally as in [67]. Thecontrollers are designed for both the RSC and GSC using a linearquadratic output feedback decentralized control strategy to limitthe oscillations and peak value of the rotor current and the dc-linkvoltage [68]. Also, the adaptive internal model controller with thevariable gain adjustment mechanism is proposed to improve theFRT capability of the DFIG [69].

- Advanced control based strategies have been proposed and preferred to enhance the FRT capability of the WTduring voltage dips without risking the system stability. Recognizing the limitations of hardware based FRT schemes and thereactive power injecting devices, advanced control methods have been widely researched to enhance the FRT capability of the DFIGbased WTs. Most of them describe the different ways of achievingthe target e.g. using the advanced intelligent control and nonlinearcontrol of the DFIG system. As per [70, 51], a nonlinear behaviorunder classical control during various voltage sag conditions isdemonstrated, which leads to unstable system operations. So, itproposes the use of nonlinear controllers to improve the performance of the DFIG based WT during transient-state. Also, a robustcontrol technique presented in [71] and a hysteresis-based currentregulator in [72, 73] demonstrated the ability to positively improvethe transient response of the DFIG system. More advanced controlapproaches have been demonstrated and have shown theimprovements of the transient response of the DFIG based WTsat the expense of high computational burden. For instance, amodel predictive control is applied to improve the system stabilityin [74], and the flux tracking control based on improved vectorcontrol approach and the internal model control are also suggested to enhance the FRT capability of the DFIG based WT [67].Alternatively, as the wind turbines may be installed in remoterural areas, where weak grids with unbalanced voltages arecommon, the DFIGs based WTs can feed unbalanced and islandedloads. Therefore, the induction machines are particularly sensitiveto an unbalanced operation since localized heating can occur inthe stator, and the lifetime of the machine can be severely affected.Furthermore, negative-sequence current components in themachine produce pulsations in the electrical torque, which in turnincrease the acoustic noise and deteriorate the life span of thegearbox, blade assembly and other components of the typical WTs[76]. For the nonlinear control of the DFIGs operating in unbalanced systems, the control algorithms based on resonant control[41], predictive control [74] and sliding mode control [75] havebeen investigated and applied to improve the response of the DFIGbased WT. The central idea is to algebraically transform thenonlinear system dynamics into an equivalent (fully or partly)linear one through an appropriate coordinate transformation and anonlinear control input before applying the linear control techniques. Conversely, the control based FRT schemes may be difficultto realize in practical applications, and also they involve highcomputational burden during their design process.

-With these considerations, the implementation of classical flux-oriented vector control techniques (PI controllers) has been proven to work well for the accomplishment of the initial grid code requirements [77, 78]. But, this kind of control could be easily saturated when dealing with substantial sag. Moreover, it is sensitive to the generator parameters and other phenomena such as disturbances and unmolded dynamics [79, 80]. Recent network operator requirements seem to lead to more robust control techniques [81]. Indeed, the above classical control techniques main drawback is their linear nature that lacks robustness when facing a worst-case operation scenario. In this context, it should be mentioned that there are few publication addressing the nonlinear control of DFIGs during grid faults [82-85]. For instance, the work presented in [85] proposes a robust nonlinear controller based on the sliding mode. This controller is designed in a stationary reference frame. The behavior of this controller is investigated and tested under unbalanced voltage dip conditions. Some experimental results are given to confirm the proposed controller efficiency. The main limitation of this solution is the chattering problem.

Nevertheless, some of these algorithms are too complicated to be implemented for the industrial applications and depend strongly on the proper design of the control parameters or the estimation of certain parameters, which may have adverse effects on its robustness. Specifically, the existence of negative-sequence voltage during the asymmetrical fault brings double grid frequency oscillations on the active and reactive powers, as well as on the electromagnetic torque [86]. To eliminate such oscillations, several control schemes with sequence decomposition and advanced algorithms have been proposed to address small voltage unbalanced conditions [51, 87].

5.5 The integration of hardware and software based methods

The merging methods based on combining the methods are described in Section 5.1 with each other and the crowbar with the control strategy, etc. All the integrated schemes aim at minimizing the crowbar operating time and reducing the chances of transforming the DFIG based WT into the SCIG based WT.This can be illustrated as follows:

5.5.1 The crowbar integrated with the series R–L circuit

This method reported in [30]. Crowbar combined with dc-link chopper [88, 89] and/or the crowbar in coordination with series dynamic resistor [43], respectively. The crowbar integrated with series R–L circuit confines both the rotor inrush current and dc-link over-voltage to within their Pre-defined range. It also maintains the RSC connection to the rotor windings and hence the generator control is not lost. As per Pannel et al. [90], a timer controlled crowbar scheme is reported to improve the DFIG fault response by reducing the crowbar application periods to within 11–16 ms. The authors reported a successful management technique to divert the transient rotor current while restoring the generator power control within 45 ms during the low voltage sustaining period and thus enabling the DFIG based WT to meet grid-code requirements.

5.5.2 TheCrowbar integrated with the series dynamic resistor (SDR)

This is indicated inRef.[43].The circuitoperates by first connecting the RSC to rotor winding via the SDRwhich means that the generator power control is maintainedexcept during severe grid disturbances whereby the crowbar isengaged. The activation of crowbar, however, leads to the sameconflicts which may harm the converter and the dc-link capacitor.

5.5.3 TheSeries dynamic resistor, crowbar and the dc-link chopper

Ref.[44] significantly improve the responses of the DFIG based WTs during both symmetrical and asymmetrical faults.

All the three integrated schemes aim atminimizing the crowbar operating time and reducing the chancesof transforming the DFIG based WT into the SCIG based WT.

-The LVRT capability method for the DFIG using feed forward transient current control (FFTCC) and minimum occurrence of crowbar interruptions and direct transient current control (DTCC) methods have been proposed in Refs.[91,92]. In these methods require an availability of the crowbar protection. A pitch angle controller based LVRT capability scheme has been proposed in Ref. [93]. In this system, the pitch angle control system is required to modify in the short response time but still it may difficult for controlling the over voltage and current in the fault condition. A robust control method using the H1 and μ-analysis for the LVRT capability approach has been proposed in Ref. [94]. This method analyzed in a weak power network and does not improve the low voltage dip significantly in the fault condition. The FACTS devices, SVC, DVR, and UPFC based LVRT capability approaches has been proposed in Refs.[95−97]. Previously, it was mentioned that installation and maintenance costs of FACTS are very high.

5.6 Technologiesto the LVRTissues

Newer turbine models from industry leaders come with LVRTas integral (e.g. Full converter wind turbines have the greatestability to meet the most restrictive grid codes, ENERCON has a full converter turbine, as does VESTAS in its V112 3MW model) .However, Technology suppliers have therefore been working withtransmission grid operators and turbine manufacturers tointroduce technological solutions to the LVRT issue. Companies such as ELSPEC have introduced systems toinject reactive power, while AMSC and ZIGOR havedeveloped uninterruptible supply solutions. W2PS has developed a solution that works as a parallel solution,connected in series, protecting thewind turbine.Such solutions are proposed in some papers including [99,100].

VI. CONCLUSION

This paper deals review on the modeling, analysis and improvement of DFIG wind turbine LVRTwhich is still an active research area. DifferentLVRT methods have been described elaborately in this paper.The advantages and disadvantages of the different approaches are also described in this paper. Generally, all methods of the LVRT capability can be separated in two categories i.e.External Devices based methods and modified controller based methods, are comprehensively introduced. Based upon the analysis and test results reported in literature, Table 3 summarizesthe advantages and disadvantages of LVRT improvement methods discussed in previous sections.

Table 3: *Comparison between LVRT methods for DFIG based WTs.*

Methods	Advantages	Disadvantages
External Devices based Methods	1. Decrease rotor over current, DC-link over voltage and torque oscillations. 2. Useful under symmetrical and asymmetrical grid faults 3. Useful under deep voltage sags	1. Require extra hardware 2. Increase cost of system 3. Decrease reliability of system
Modified Controller Based Methods	1. Decrease rotor over current, DC-link over voltage and torque oscillations. 2. Do not require extra hardware. 3. Do not increase cost 4. Do not decrease reliability of system	1. Often useful under symmetrical grid faults 2. Only useful under moderate voltage sags 3.Increase complexity of system Difficult to design and implement in practical applications

Based upon the advantages and disadvantages of improvement methods we find that there are many challenges must be available in these methods:

- Simple design; low cost; effective protection; meet grid codes requirements.

Biography

Montaser Abd El Sattar Mohammedwas born in Abu-Tisht, Qena - Egypt, on August 23, 1983. He received B.Sc. Degree from Faculty of Engineering, Department of Electrical Engineering, Al Azhar University, Egypt, in 2006. He received the M.Sc., and Ph.D. Degrees from Faculty of Engineering, Department of Electrical Engineering, Minia University, Egypt, in 2011 and 2015 respectively. He is a lecture in El-Minia High Institute of Engineering and Technology, El-Minia, Egypt since 2015 until now. His research interests are in the area of renewable energy sources, power electronics, power quality, power system and control.

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