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Review on FRT solutions for improving transient stability in DFIG-WTs

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Abstract: Fault-ride-through (FRT) is an imperative capability in wind turbines (WTs) to ensure grid security and transient stability. However, doubly fed induction generator-based WTs (DFIG-WTs) are susceptible to disturbances in grid voltage, and therefore require supplementary protection to ensure nominal operation. The recent amendments in grid code requirements to ensure FRT capability has compelled this study of various FRT solutions. Therefore, for improving FRT capability in pre-installed WTs, re-configuration using external retrofit-based solutions is more suitable and generally adapted. The most relevant external solutions based on retrofitting available are classified as (a) protection circuit and storage-based methods and (b) flexible alternating current transmission system-based reactive power injection methods. However, for new DFIG-WT installations, internal control modification of rotor-side converter (RSC) and grid-side converter (GSC) controls are generally preferred. The solutions based on modifications in RSC and GSC control of DFIG-WT are classified as (a) traditional control techniques and (b) advanced control techniques. This study ensures to curate and compare the FRT solutions available based on external retrofitting-based solutions and internal control modifications. Also, the future trends in FRT augmentation of DFIG-WTs are discussed in this study.

1 Introduction

The drastic climate changes induced by global warming and escalating energy demands have compelled the growth of renewable energy worldwide. Wind energy is a pioneer among other renewable sources and has grown both in terms of capacity and technology adopted. Wind energy has advanced by adding another 54 GW in 2016 and reached a total global capacity of 486.8 GW. With the current trend, it is anticipated to reach a cumulative installed wind capacity of over 800 GW by 2021 [1]. Tremendous changes in the past 30 years of wind power generation include changes in its electrical and mechanical technologies, control techniques utilised and in the power system integration requirements.

Doubly fed induction generator-based wind turbines (DFIG-WTs) are a dominant WT technology. DFIG is an ingenious type of variable speed wind generator; however, DFIG-WTs are sensitive to grid-voltage disturbances. It utilises both rotor-side converter (RSC) control and grid-side converter (GSC) control for grid support [2]. RSC controls the maximum power capture through rotor speed control and GSC controls the active and reactive powers delivered, and also maintains constant DC-link voltage. During a fault incident, the voltage drops even up to zero and the active power generation is reduced leading to a rapid increase in the rotor current in an attempt to compensate the active power by the RSC. Hence, the converter increases the rotor voltage which leads to an overvoltage in the DC link and DFIG quickly loses internal magnetisation in proportion to the lost voltage. The demagnetisation produces large outrush currents/overcurrents on both stator and rotor circuits greater than the ratings of the converter. This may lead to tripping of the WT connected to the grid. Therefore, fault-ride-through (FRT) capability is proposed in grid code requirement (GCR) to ensure continuous operation and to avoid high loss of power caused by faults. Also to promote grid recovery during fault and to minimise re-synchronisation problems after fault clearing through reactive power support.

The increasing penetration of wind power has imposed critical challenges to grid security and stability, and therefore FRT capability in WTs has become mandatory. The former GCR had allowed the disconnection of wind energy conversion systems (WECSs) during fault or low-voltage conditions to avoid the flow of large overcurrents [3]. Owing to the large penetration of WECS, such sudden disconnection could cause voltage and rotor angle instability that may endanger the grid security. Hence, updated GCR requires constant active and reactive power regulation without tripping during a fault. FRT capability in WTs installed even before the inception of FRT requirements has become mandatory. The limits imposed for FRT in each country may vary with respect to its GCR. Generally, FRT scheme protects the rotor windings from overcurrents and DC-link capacitors from overvoltages. However, the reduced converter size of DFIG has made FRT capability more competitive compared with full-scale converter topologies [4]. Therefore, FRT has become an active research line within the DFIG topic.

The GCR for FRT determines the fault time (T_{fault}), fault voltage permitted (V_{fault}), recovery time (T_{rec}) and voltage to be recovered within recovery time (V_{rec}) and the prescribed sustaining period or settling time (T_{set}) as shown in Fig. 1. After fault clearance, the voltage recovery to the pre-fault condition of nominal voltage (V_{nom}) is indicated by T_{set}. This capability to come back to the typical condition of operation of the wind generators will decide the resoluteness of the power system during transient conditions. Also, FRT requirement requires increased reactive current injection during voltage sags as shown in Fig. 2. The reactive current support in response to severe voltage dip must be achieved within 20 ms after fault detection [5].

Conventionally, shunt resistors known as crowbar are short circuited to the rotor windings during a fault. It disconnects the RSC to protect the flow of overcurrents into rotor windings. During crowbar operation, the active and reactive power controls of DFIG are lost temporarily. DFIG acts as a squirrel cage motor resulting in consuming reactive power [6]. Also, the generator is able to inject reactive current only after disconnecting the crowbar. This exacerbates the grid fault condition and does not promote grid recovery. A sustained period of crowbar application will amplify

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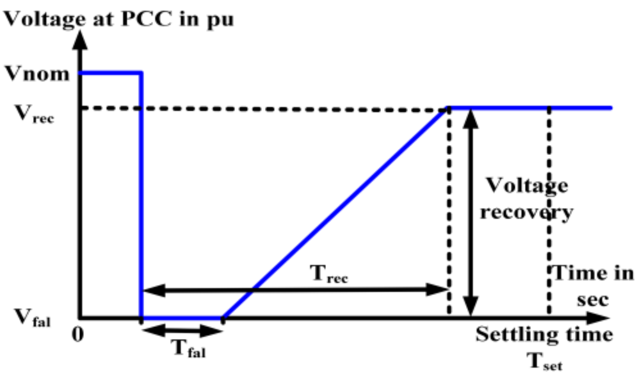

Fig. 1 *General FRT capability curve*

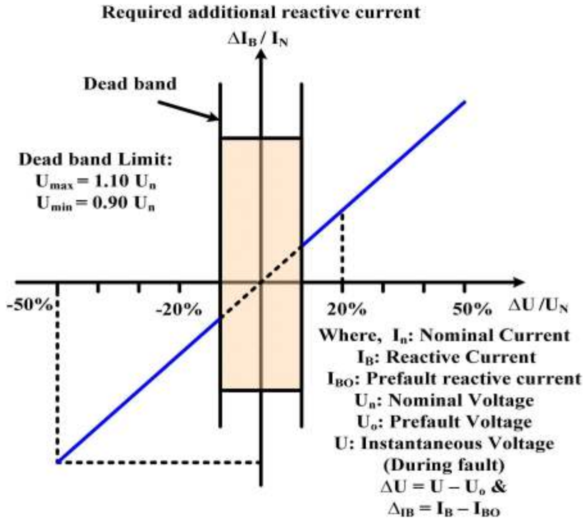

Fig. 2 *Reactive power requirement as per E.ON grid code*

this problem, so the threshold for crowbar application should be chosen carefully [7].

Choice of crowbar resistance is vital, as lower value causes higher electromagnetic torque and higher value may lead to an increase in DC-link voltage [4]. To reduce the cost of FRT solutions in high-power DFIG applications, a new single-phase DC crowbar has been proposed to substitute three-phase crowbars [4]. This method is attempted to simplify the available crowbar solution and to mitigate the overvoltage problem of three-phase DC crowbar. Also, crowbar in combination with DC-link chopper [5], series braking resistor (SBR) [6], a series *R*–*L* circuit and static synchronous compensator (STATCOM) are discussed. Complex control algorithms are introduced to improve the reactive current injection while enabling crowbar [7, 8].

An external FRT solution has various advantages, DC-link chopper braking resistor ensures that DC-link voltage remains under control during a fault [9, 10]. Series GSC regulates the output voltage to control the stator terminal voltage flexibly; thereby, it can effectively cope with various deep voltage sag conditions by suppressing or eliminating the transient DC and negative-sequence flux components [11]. Superconducting fault current limiter (SFCL) is considered as a self-healing method since it does not need any control action to be changed from superconducting to non-superconducting states [12]. Flexible alternating current transmission system (FACTS) devices based solutions provide FRT capability through reactive power injection. Series compensation based on dynamic voltage restorer (DVR) is most popularly adopted for FRT in DFIG-WT [13, 14].

Internal control modification-based FRT solutions are preferred for new installation of WTs. They are more economical and do not include additional hardware components. It increases the complexity of the DFIG control. The internal control is classified as traditional control techniques which include pitch control, modified vector control (VC), hysteresis control and feed-forward transient current control (FFTCC). The advanced control techniques include sliding-mode control, fuzzy-based control, model predictive control (MPC) and other recently proposed control techniques.

Although external control and internal control-based solutions are, new solutions are still evolving to provide a more efficient solution for the FRT capability of DFIG and to improve the seamless operation of the system during faults. This review of FRT solutions can serve as a reference to evaluate the strategies implemented so far and to identify the prospects for further improvement of the control techniques. The organisation of this paper is as follows: Section 2 is about the classification of FRT solutions based on the external and internal modifications, Section 3 discusses the protection circuit and storage-based external solutions and Section 4 discusses the FACTS devices based external solutions and Section 5 discusses the internal control modifications and Section 6 discusses the future trends and conclusion.

2 Classification of FRT solutions

During steady-state operating condition, RSC controls the generator speed and reactive power exchange with grid through the stator side, whereas the GSC regulates DC-link voltage (V_{dc}) and active/reactive power exchange with grid through the rotor side. Maintaining V_{dc} as constant ensures the active power flow through the rotor side and guarantees that both RSC and GSC work properly [15].

During transient operating condition, the voltage drop in the stator, stator current oscillations, pulsations in electromagnetic torque and stator-side active/reactive power changes occur. The oscillatory electromagnetic field (EMF) in the rotor circuit is produced by the DC component of the stator flux. The oscillation in stator current produces high rotor inrush current, due to stator and rotor coupling. This affects the DFIG's transient operation, leading to converter overloading. However, the GCR demands grid connection of the generator, even during the faulty conditions [15].

External solutions are considered as device installations retrofitted to modify the converter architecture. They are classified as shown in Fig. 3: (a) protection circuit and storage-based methods and (b) FACTS-based reactive power injection methods. The internal control modifications are classified into traditional and advanced control.

3 Protection circuit and storage-based external solutions

The retrofitting-based solutions using protection circuit and storage-based methods such as a crowbar, DC-link chopper, SBR, energy storage system (ESS), series GSC (SGSC) and FCL are discussed in this section.

3.1 Crowbar method

Crowbar is the most well-established protection circuit-based technique, connected across the power electronic switching devices of RSC and slip rings. It is operated only during a fault to protect the RSC. It creates a low resistance path during fault conditions, thereby isolating the RSC and preventing it from overcurrents. However, the drawback of this scheme is that the DFIG-WT will start acting as an induction machine and starts consuming reactive power resulting in deteriorating the grid voltage.

The conventional topology of crowbars includes anti-parallel thyristor-based crowbar and diode bridge crowbar [4]. Owing to only one switching device, the diode bridge crowbar is less expensive. The advancements in crowbar have led to active crowbar topology which eliminates the short-circuit current at any instant. For a successful ride through, the short circuit made by the crowbar has to be removed before the RSC could start. Premature removal of crowbar does not serve the purpose of converter protection and late removal leads to higher absorption of reactive power from the grid [4]. The appropriate value of the crowbar resistance is generally chosen as a compromise between certain objectives based on the performance of DFIG and the compliance

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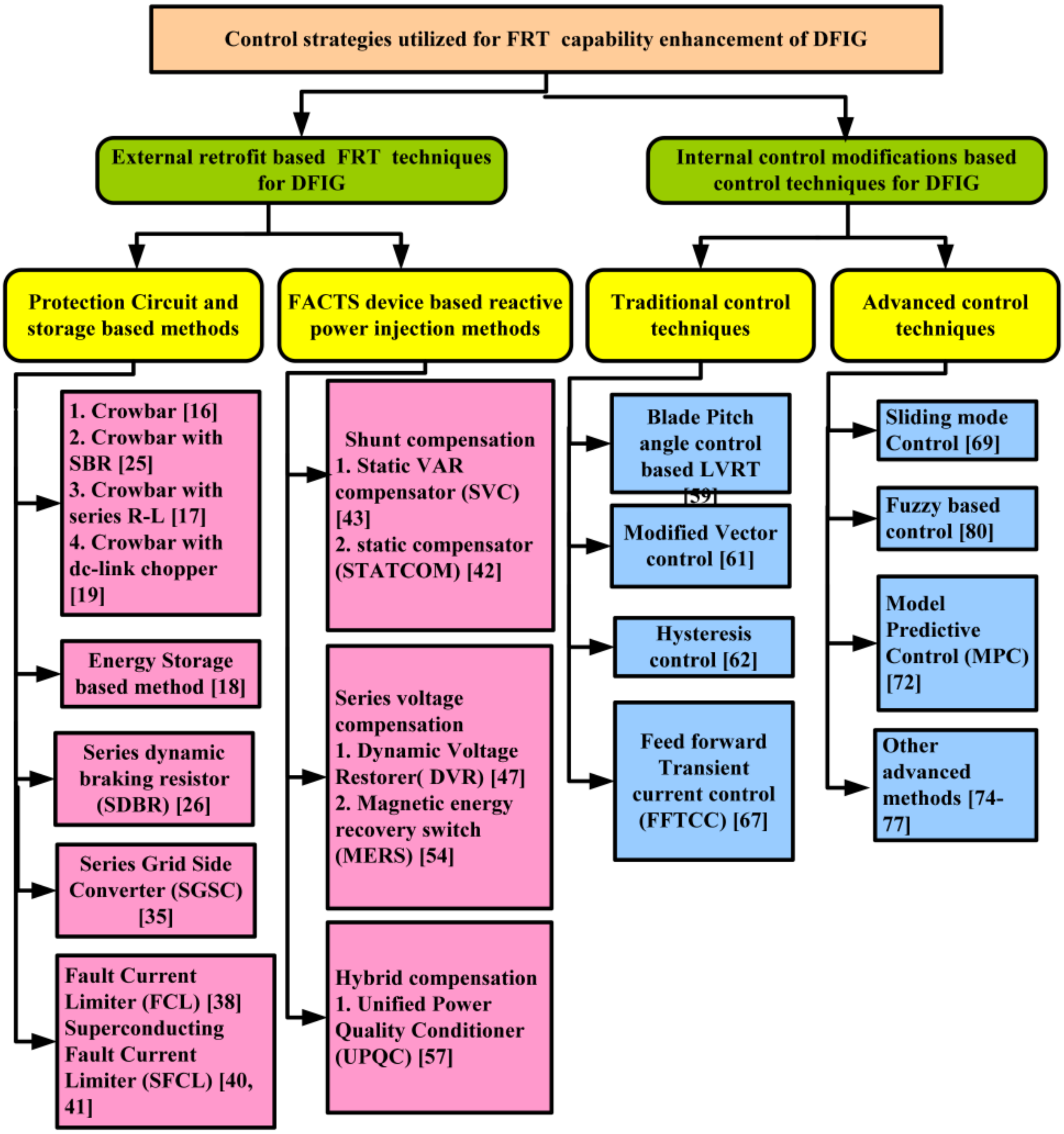

Fig. 3 *Classification of FRT capability enhancement techniques for DFIG*

of GCR. Low resistance value leads to large currents during the voltage dip and a large value causes a big peak in electromagnetic torque. Higher resistance reduces the rotor current but cannot reduce rotor voltage. Therefore, to increase the DC-bus voltage, the rotor current circulates even when inactive via the freewheeling diodes [16]. The ripples in the DC-link capacitor due to the fault are augmented using a crowbar with battery ESS [17].

Single-phase DC crowbars are used as an alternative to three-phase DC crowbars to overcome the overvoltage problem and to eliminate its complex and expensive clamping circuitry [4]. Unfortunately, sustained application of rotor crowbar causes loss of control and DFIG starts operating such as an induction machine and draws stator-side magnetisation. This produces a high-slip reactive power demand that would degrade the stator voltage. Therefore, it is clear that the fault inception and clearance instances impose arduous disturbance on a standard feedback control scheme. This accelerates the instability of the system combined with a temporary loss of VC orientation. This is the worst combination of poor torque output and very high reactive current demand.

Therefore, the crowbar must be capable of restoring the active and reactive power controls swiftly after the fault inception and clearance for system frequency stability and to improve the transient response of other locally connected equipment. Owing to the temporary loss of RSC control, reactive power absorption escalates the voltage dip and postpones grid recovery. Also, the crowbar is proposed in combination with a series *R*–*L* circuit [16], series dynamic braking resistor (SDBR) [18] and DC-link chopper [19] classified in Table 1. The different combinations of crowbar-based schemes are illustrated in Figs. 4–6.

3.2 DC-link chopper method

A chopper circuit acts similar to rotor-side crowbar to mitigate the DC-link overvoltage. It is a shunt resistance added to the DC link. The chopper dissipates the excessive energy to maintain the DC-link voltage within acceptable operating voltage. It is also used in combination with other devices such as SBR, superconducting magnet [26] and SFCL [27].

The chopper employed as a sole protection device is discussed in [11]. A simple delayed control method utilised for resuming

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Table 1 FACTS-based FRT capability improvement in DFIG

Reference	Method utilised		Advantages	Disadvantages
[20]	shunt voltage compensation	SVC	simple structure with reactive power compensation capability. Reactive current injection, voltage stability in the weak grid and continuous voltage control	voltage-dependent reactive control
[21]		STATCOM	contributes higher transient margin and overloading capability for short period during severe voltage dip.Faster control response compared with SVC, reactive current control. Rapid response to disturbances and negative-sequence voltage and current compensation	higher investment and operational costs. Unable to supply active power.Injecting current limitation
[22]	series voltage compensation	DVR	capable of eliminating transients in the generator currents and power at grid fault conditions.Decreases stator power reference. Fast voltage recovery and controllable reactive power supply	DVR needs the extra active power generated by wind generator during fault to be absorbed, to V_{dc} at the desired level. Requires sufficient energy storage capacity to mitigate voltage sags
[23]		MERS	eliminates reverse blocking switch. Effective for large-scale application. Low switching losses	less robust control and has a mechanical by-pass switch
[24, 25]	hybrid compensation	UPQC	both active and reactive controls and fast reactive power compensation. Long critical clearance time	active power absorption and requires a large DC-link capacitor

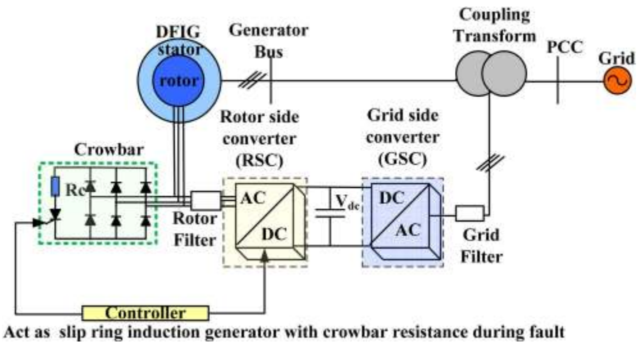

Fig. 4 *FRT capability using crowbar-based methods. Scheme 1 – diode bridge crowbar*

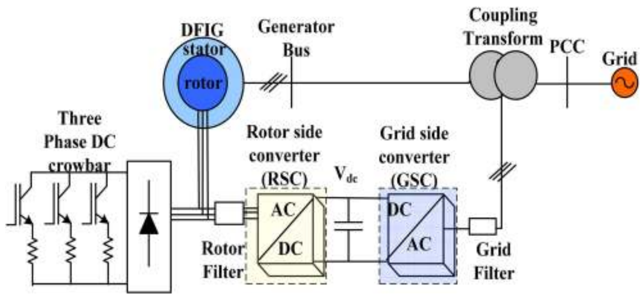

Fig. 6 *FRT capability using crowbar-based methods. Scheme 3 – three-phase DC crowbar*

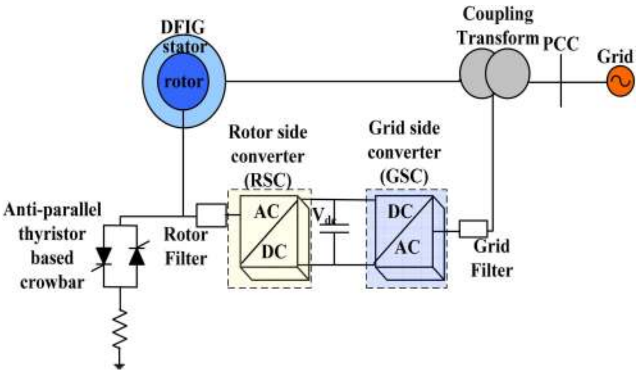

Fig. 5 *FRT capability using crowbar-based methods. Scheme 2 – anti-parallel thyristor-based crowbar*

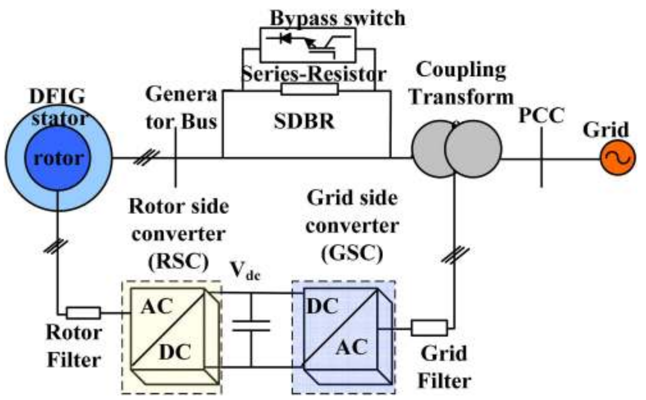

Fig. 7 *DFIG-WT equipped with SDBR*

pulse-width modulation (PWM) control helps to maintain the DC-link voltage within safe limits. However, this allows the rotor overcurrents to flow through the rotor converter diodes. However, the time taken for converter disengagement and restoration was longer than the crowbar control because the chopper does not assist demagnetisation of the electrical machine post-fault. Therefore, the electrical performance of a DC-link chopper is quite inferior when compared with crowbar [28].

3.3 Series DBR

Series dynamic resistors series are implemented with by-pass power electronic switches connected in series to the rotor terminal. Series topology connected to the stator terminal is called the SDBRs, this can handle severe fault conditions with low residual voltage and high-power generation and is illustrated in Fig. 7 [29].

Modulated series DBR (MSDBR) technique in [30] introduces a new modulating braking resistor, which is compared with single-step and multiple-step braking resistors. This scheme eliminates the use of crowbar as well as DC chopper. The MSDBR module is implemented with two anti-series insulated gate bipolar transistors connected in parallel with a braking resistor in each phase is as shown in Fig. 8. PWM signals generated from the stator voltage controller controls the stator phase voltage independently. Stator voltage restored aids the GSC and RSC to remain controllability of mitigating DC-link overvoltage, short-circuit currents and overcharging phenomena in the DC-link capacitor.

3.4 Energy storage-based methods

An ESS provides reactive power support to the grid and protects DC-link from overvoltages to improve the transient response of DFIG-WT by controlling the rotor current, and power system transient stability (measured through critical clearing time of the fault). ESS regulates the steady-state active power output of DFIG. Transient stability addresses the intermittency of renewable resources and load levelling by focusing on the loss of generation

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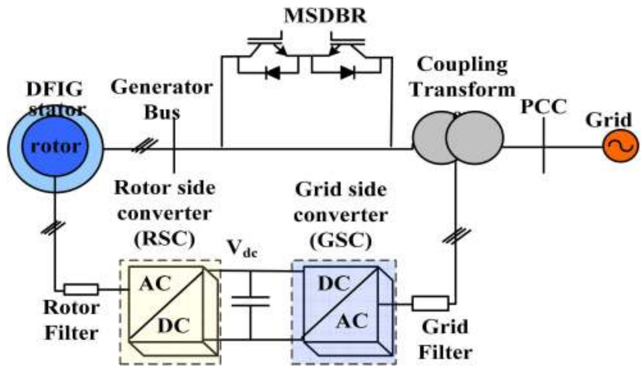

Fig. 8 *DFIG-WT equipped with MSDBR*

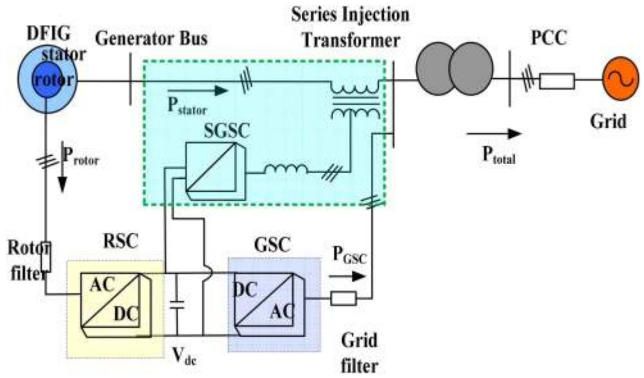

Fig. 9 *Schematic representation of DFIG with SGSC*

and huge sudden changes in loads to maintain a steady post-fault balance after the fault is cleared from the system [31].

In [32], ESS enhances transient support capability. The transient EMF is reduced by injecting the demagnetising current from the converters to the rotor circuit. Among the several types of ESS devices, batteries and super-capacitors react faster during transients. The DC-link capacitors complemented by super-capacitors provide effective FRT support.

In [33], fuzzy control in conjunction with hysteresis current control is used for superconducting magnetic energy storage (SMES). Control system with series and parallel compensation, using SMES is proposed to avoid power oscillations and terminal voltage fluctuations of a wind farm. Vanadium redox-flow battery-based batteries are also used to improve the generator capability during a ride-through conditions [34].

Batteries are used to limit fluctuations due to wind speed changes and the excess power via RSC through DC-link during a fault. In [35], a new flywheel-based approach utilising flux magnitude and angle control-based architecture is introduced. This approach effectively mitigates oscillations, reduces stress on protective devices and increases wind energy penetration. ESS received a major recognition in the year 2015. Hence, there are probabilities for further development of ESS-based solutions.

3.5 Series GSC

SGSC is an additional voltage-source converter (VSC) connected across the DC link as shown in Fig. 5. The output voltage of SGSC is regulated to control the stator terminal voltage. The unbalance due to negative-sequence voltage causes stator and rotor unbalances, electromagnetic torque and power pulsations. SGSC aids DFIG to overcome deep voltage sags and to reduce/eliminate the negative-sequence flux and transient DC.

A series compensation voltage vector is generated by the SGSC and injected to balance the stator voltage, to counteract the effect of negative-sequence grid voltage. Owing to the series transformer impedance, there is a difference between positive-sequence voltage and the DFIG voltage. Therefore, a positive-sequence voltage vector is injected to balance the impedance voltage drop. SGSC is capable of coping with long-term steady-state grid-voltage unbalances. The schematic representation of the SGSC connected to DFIG is shown in Fig. 9.

A unified architecture of SGSC with parallel grid-side rectifier is used to overcome the power processing shortcomings [36]. A passive impedance network connected in series with the stator windings is used to reduce synchronous frame stator flux oscillations [37]. The passive impedance consists of series impedance that limits short-circuit current and feeds current into the grid without interruption during fault and a shunt impedance that balances the energy of the WT during a grid fault. It allows direct handling capability of the stator flux state variables. However, based on practicality and cost, an optimised passive impedance network in series with the stator side, works well for both balanced and unbalanced faults [38].

The schematic representation of the configuration presented in [39] is shown in Fig. 10, where a new grid-connected converter with shunt and series compensation capability for normal and transient operation, respectively, is developed for improving FRT. The combination of shunt and series interfaces demonstrates a low component count, simple protection structure and improved performance of FRT with effective compensation to the electric grid. The power requirement of GSC is based on the depth of voltage sag during fault [40].

3.6 Fault CLs

FCLs were traditionally utilised in large interconnections of power systems to limit the fault currents [41]. These have now become popular for limiting the overcurrents in DFIG converters. However, control of RSC during severe faults is difficult. Hence, advanced control strategies to control GSC along with RSC were proposed in [42].

SFCLs can limit the fault currents based on its quenching state of operation which transits from the superconducting state to the quenching state of operation. This device introduces unique properties which cannot be achieved through conventional current limitations. The main advantage is that they do not add any impedance to the system during normal operations. SFCL is illustrated in Fig. 11.

The advancements have led to the utilisation of solid-state FCL (SSFCL) as shown in [13]. These SSFCL can be categorised as a bridge, resonant and switch type that are illustrated in Fig. 12. The cost of switch-type FCL (STFCL) is higher when compared with a crowbar but has negligible on-state losses of semiconductor devices. STFCL can limit fault current, rotor back-EMF voltage and also has enhanced RSC controllability. Therefore, it provides superior FRT capability.

Modified flux coupling-type SFCL was proposed in [43], which demonstrates an effective fault current limitation across DFIG's stator and rotor sides. When the stator side is chosen for installation of SFCL, the terminal voltage of DFIG can be improved to prevent the disconnection during a fault. SFCL with magnetic energy storage (SFCL-magnetic energy storage(MES)) utilises a superconducting coil as energy storage device and a fault current limiting inductor concurrently balances the output power fluctuations. A schematic representation of DFIG-WT using SFCL for FRT capability is shown in Fig. 7.

Hybrid high-temperature SFCLs (HTS-FCL) provides fast quench phenomena of HTS materials to ensure fast current limiting action and the multistep braking resistors to provide adaptive voltage compensation during voltage dips as proposed in [44]. They have very fast quenching, high limiting capability, resistive nature, controls faults and enhancing system stability. Integrated control of resistive-type FCL in [21] helps to limit the peak values of the fault rotor current, DC-link voltage and electromagnetic torque oscillations.

4 FACTS-based external FRT solutions

When DFIG is connected to the weak power network, the GSC cannot provide sufficient reactive power and voltage support during a grid fault. This is due to its reduced rating, which causes a risk of voltage instability. To overcome this issue, FACTS devices based on reactive power injection are used to augment FRT.

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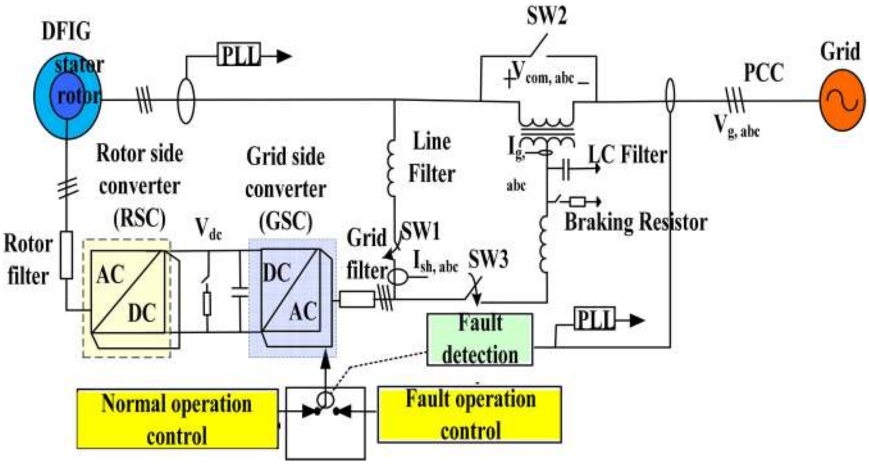

Fig. 10 *Schematic representation of DFIG with shunt SGSC*

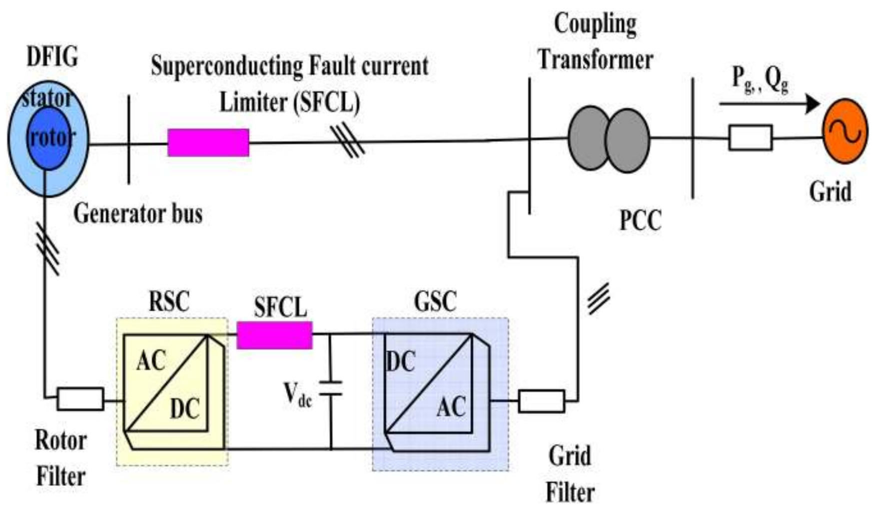

Fig. 11 *DFIG with FRT capability using modified flux coupling-type SFCL*

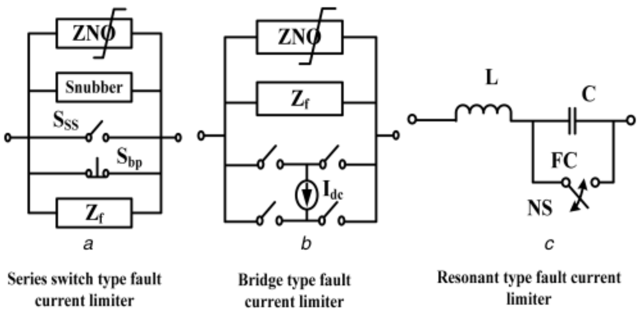

Fig. 12 *Generic topologies of SSFCL topologies*
(a) Series STFCL, ***(b)*** Bridge-type FCL, ***(c)*** Resonant-type FCL

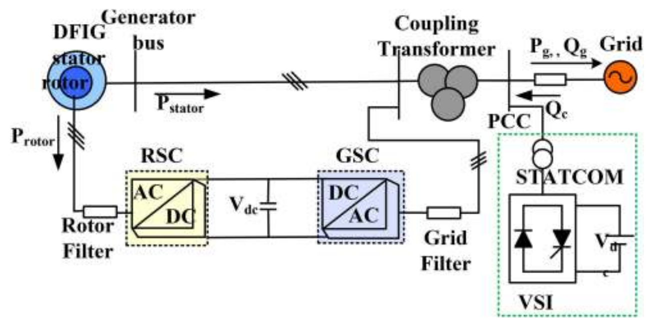

Fig. 13 *Placement of STATCOM with DFIG-WT*

Reactive power support provided by FACTS devices helps to uphold the transient stability. Shunt compensation, series compensation and both shunt and series compensation together (hybrid compensation) techniques are discussed and compared in Table 1.

4.1 Shunt voltage compensation

4.1.1 Static VAR compensator: Static VAR compensator (SVC) is a combination of thyristor-controlled reactor (TCR) and thyristor switched capacitor (TSC). TSC is switched in groups and TCR is controlled smoothly by a thyristor. By dynamically changing the reactive power that is exported by SVC, the bus voltage which is connected to SVC is controlled. SVC with DFIG is shown in Fig. 13.

SVCs are being used in power systems for voltage support and voltage stability improvement due to their simple structure and reactive power compensation capability. They are connected at the point of common coupling to improve the transient and steady-state performances. The SVC improves the voltage stability by providing fast dynamic reactive power compensation that maintains the terminal voltage regulation and the desired transient response.

STATCOM and SVC are both shunt compensation-based devices generally used for wind farms based on an induction generator to increase the reactive power control ability. SVC has one TCR to achieve continuous regulation along with TSC (step-wise controller). The capability of SVC can be extended by installing mechanically switching capacitor banks and mechanically switching reactor.

For SVC, switching between capacitor and inductor banks on the secondary side of the coupling transformer varies the reactive power. Each capacitor bank switching is done by the TSC and the reactor switching is done by TCRs. Therefore, SVC offers a controlled reactive compensation in the electric power system. The

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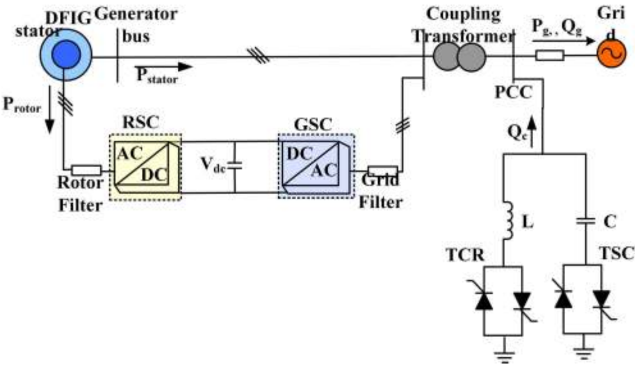

Fig. 14 *Placement of SVC with DFIG-WT*

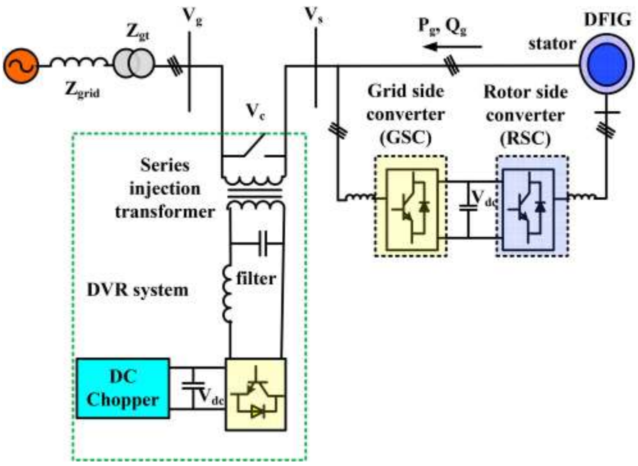

Fig. 15 *DVR connected to DFIG*

output of the compensator is controlled in steps by sequential switching of TCRs and TSCs. The step-wise switching instead of continuous control eliminates the need for harmonic filtering [20].

4.1.2 Static synchronous compensator: STATCOM was introduced for induction generators to stabilise and recover faults in a large-scale wind farm. During steady state, STATCOM will inject/absorb reactive power to preserve the bus voltage and avert fluctuations. During transients, in order to accelerate voltage recovery and restore the voltage stability, the STATCOM will inject maximum reactive current to support the electric grid. Comparing to SVC, STATCOM contributes higher transient margin with the possibility to implement overloading capability as shown in [20]. However, it includes the drawbacks of higher investment cost.

In DFIG, the STATCOM has a different topology and control structures and is shown in Fig. 14. The GSC of DFIG behaves like STATCOM and supplies the reactive power support to ride through the fault condition, while RSC is disabled by a crowbar. STATCOM has a faster control response compared with SVC. Since this is not applicable to prevent the faults occurring within the wind farm, it does not assure complete protection. The different topologies of the converter, its control algorithms and switching techniques are given in detail in [45].

Real-time implementation of STATCOM in a DFIG-based wind farm shows that STATCOM provides dynamic voltage support and improves the transient response at point of common coupling (PCC) shortly after grid fault. The RSC is blocked during grid fault and is restarted after the fault is cleared and PCC voltage is vastly recovered. Real-time digital simulator is used as a real-time tool for testing the STATCOM as an FRT tool [46].

Impact of DFIG control on rotor angle stability utilising the GSC as STATCOM to provide reactive power support and an additional power system stabiliser in the RSC reactive power control loop is studied in [47]. The study reveals the fact that the high penetration of DFIG-based wind farms degrades the rotor angle stability. The utilisation of GSC of DFIG as STATCOM will become a cost-effective solution to support the local voltage of the wind farms without an external STATCOM.

4.2 Series voltage compensation

4.2.1 Dynamic voltage restorer: DVR consists of a VSC for voltage injection, connected between the WT and grid through a coupling transformer, which has an energy source and includes filters for harmonic elimination. This avoids any need for further complication in the DFIG converter controls. DVR has a similar configuration of a static synchronous series compensator with direct control over the terminal voltage using capacitor bank or energy storage device, which has become familiar for FRT application [22]. Even though the application of DVR for FRT is expensive, it is capable of eliminating the transients in generator currents and power at grid fault conditions effectively.

DVR, in general, requires a higher-power rating of the converter since it aims to absorb all the power supplied by DFIG. In this case, the DFIG continues on normal operation and the rotor speed is maintained as a pre-fault condition [48]. Therefore, it can supply reactive power to the grid as per the grid code suggestion by utilising the remaining capability of the DVR. To make the system economical, DVR is preferred to perform full voltage restoration during partial voltage dips and limited restoration during serious conditions [49].

Decreasing the stator power reference for abnormal grid voltages reduces the DVR power ratings significantly. The schematic representation of the DVR connected to DFIG and grid is shown in Fig. 15. The positive-sequence voltage injection for compensating the line voltage depends on the type of compensation scheme employed. The difference between the compensation schemes is based on the angle between the load current and the injected voltage. Generally, the compensation schemes are classified as in-phase, pre-sag, minimum energy and zero-active power injection-based compensation [50].

Series compensators with reduced power capacity are observed to be much more effective in restoring voltage when compared with the parallel reactive power compensator in strong grid utility. A series compensator in DFIG stator side is shown in [51], where a ramp function injection voltage-based control is proposed to reduce the energy storage required by the compensator. DVR with fault current limiting action in collaboration with a multilevel inverter is shown in [52] (Table 2).

4.2.2 Magnetic energy recovery switch: Series compensation using magnetic energy recovery switch (MERS) consists of four power electronic switches and a capacitor similar to single-phase full bridge converter. The arrangement has two of the converter terminals connected in series. MERS was first developed in Tokyo Institute of Technology's Shimada Laboratory [53]. MERS as an FRT capability solution for squirrel-cage induction generator (SCIG)-WTs is proposed in [23]. The device creates some harmonics in line current whose effects are not severe but causes interference with the resonance frequency of the system to which it is applied and further study is required to avoid this disturbance. Even though MERS is classified as a viable FACTS controller for FRT capability of induction generators [24], it is still not studied widely for DFIG application and is shown in Fig. 16.

By controlling the current path through the device, it is possible to inject voltage for all currents within the device rating, thereby making MERS a series compensator. Also, MERS is a reactive power compensation device that acts like SVC with continuous controllable capacitive power compensation using easy control. This model is compared with other existing SVC technologies and is found to be an attractive alternative shunt compensator. Therefore, further studies are required to explore the viability of MERS solution for FRT capability enhancement of DFIG-WTs.

4.3 Unified power quality conditioner

Active power filter family-based unified power quality conditioners (UPQCs) having both shunt and series compensation (hybrid compensation) has superior performance [54]. It is more

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Table 2 Protection circuit and energy storage methods

Reference	Method utilised	Advantages	Disadvantages
[4]	crowbar method	activated during faults and prevents RSC from overcurrents	RSC control is lost when crowbar is applied
[29]	crowbar with SDBR	avoids frequent use of a crowbar.Maximises the operation time of RSC, reduces torque fluctuations	voltage quality may not be satisfactory, depends on SBR switching scheme
[16]	crowbar with series *R*–*L*	stator active and reactive power dynamic control is not lost	if small series impedance is used with a high crowbar resistance, rotor inrush current may pass through *R*–*L* circuit to the converter and cause destruction
[18]	crowbar with DC-link chopper	avoids DC-link voltage fluctuations and increases the normal range of DFIG operation	time taken for converter disengagement and restoration was longer than a crowbar
[17]	active crowbar with battery	extended operation leading to reactive power absorption is avoided by the battery. Also, it maintains constant DC-link voltage	additional battery-side converter and battery are required
[30]	MSDBR	this scheme eliminates the use of crowbar as well as DC chopper.Series compensation scheme and provides power evacuation	reactive power injection ability is not yet studied.Compared to the above techniques is a fairly higher cost
[32]	energy storage-based method (ESS)	improves transient dynamics of DFIG and the transient stability of power systems.Regulates steady-state active power output of DFIG	operation and maintenance issues in battery systems. Loss of stored energy when it is not in use in form of self-discharges
[39]	SGSC	damping synchronous frame stator flux oscillations and allows direct handling of the stator flux state variable	shortcomings in maintaining DC-link power balance
[42–44]	FCL SFCL	limits fault current, rotor back-EMF voltage and strengthen RSC controllability.Provides better reactive power support, fast quenching	cost of STFCL is high

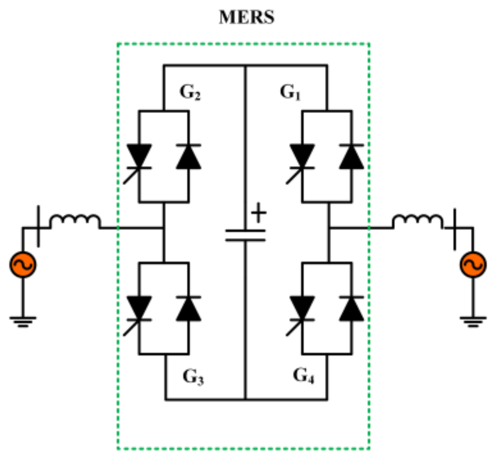

Fig. 16 *Configuration of an MERS as a series FACTS controller device*

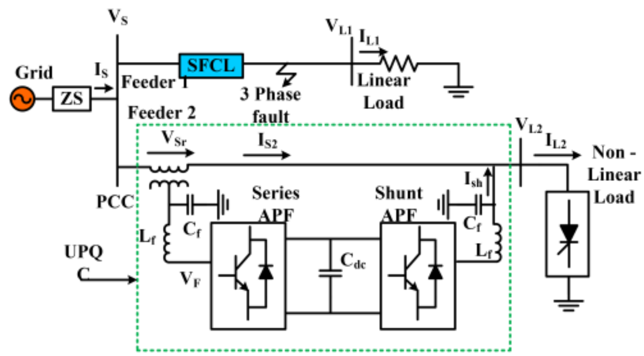

Fig. 17 *Combinatorial UPQC and SFCL topologies*

versatile as it can mitigate several power quality problems. The back-to-back inverter system configuration was popularised as UPQC after the implementation of this topology with a 20 kVA system by Fujita and Akagi [25]. Unified power flow conditioner (UPFC) is similar to UPQC with the same back-to-back VSC configuration connected to a common DC-link energy storage element, where the UPFC is employed in power transmission system and UPQC for distribution systems. FRT capability of fixed speed induction generator (FSIG)-WT per Irish grid codes is investigated in [25]. Fault current limiting is a major concern in the power system as large fault current will cause a voltage drop at PCC which will affect the load in other parallel feeders. Current source UPQC with fault current limiting function with good voltage sag clearance with very small voltage spikes in the load voltage is demonstrated in [55]. The short-circuit current decreases in the process and provides active power for voltage restoration. UPQC working in combination with SFCL is shown in Fig. 17.

5 Internal control modification-based FRT solutions

The dynamic performance of DFIG depends on control parameters and rotor voltage that controls the low voltage ride through (LVRT) capability. Internal control modifications in the RSC and GSC based on the control parameters are further subdivided into traditional control techniques (explained through the control structures shown in Figs. 18 and 19) and advanced control techniques. A detailed comparison of these control techniques is explained further. The basic configurations of RSC and GSC control configuration in DFIG are shown in Fig. 20.

5.1 Traditional control techniques

5.1.1 Blade pitch angle control: A change in pitch angle of the blade with changes in wind speed in order to adjust the rotor speed, thereby limiting the wind power extracted from wind, is done through pitch angle controller. The output torque of the WT is used to control the angular speed, which controls the mechanical output power. The turbines with high-rated generator are integrated with pitch angle so as to protect the wind generator from sudden wind gusts. This control is also capable of responding to the frequency deviations and mitigates them in order to contribute to the power stabilisation [56].

Conventional pitch control used during normal operation compares the output power of the wind generator with rated value and adjusts the pitch angle when the wind speed exceeds the rated wind speed. The controller is responsible for determining the desired pitch angle (β) reference, by comparing the measured rotor speed with the desired rotor speed. During pre-fault condition, pitch controller avoids the runaway condition by keeping the rotational speed at its rated value. During a fault, the generator itself contributes to the fault, as the drop in terminal voltage reduces the output power automatically.

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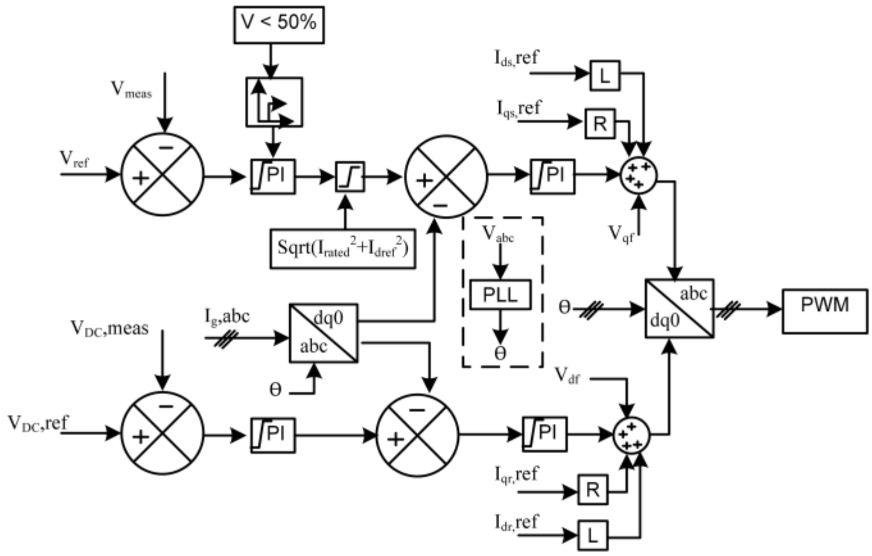

Fig. 18 *Configuration of a GSC control configuration in DFIG wind generator*

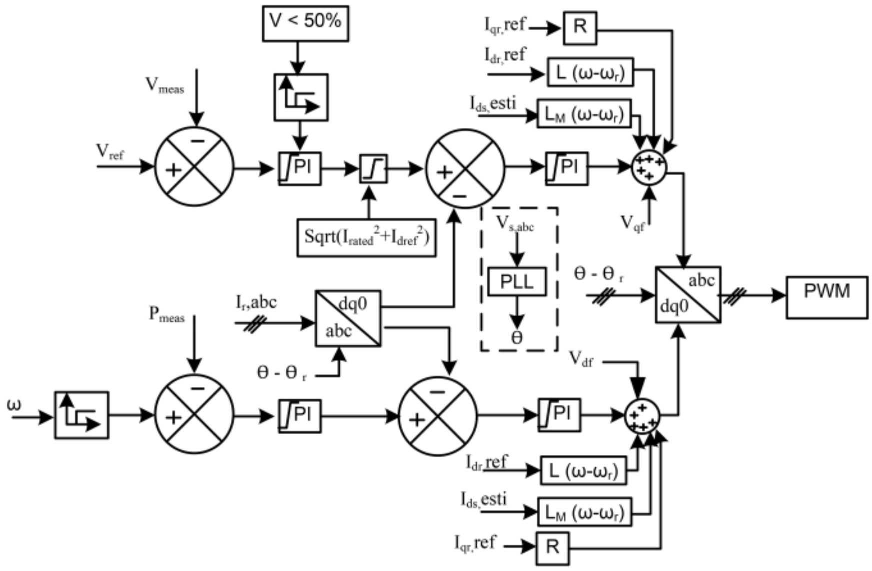

Fig. 19 *Configuration of an RSC control configuration in DFIG wind generator*

An advanced control strategy for LVRT in DFIG instead of the conventional crowbar control is executed through modified RSC and GSC controls. The modified RSC control of DFIG can convert the additional power into WT kinetic energy instead of dissipating through the crowbar resistance. This temporarily increases the generator rotor speed during grid faults to reduce the oscillations in currents. The pitch control will be triggered if the generator rotor speed exceeds the rated speed. Thus, limits rotor speed and prevents the mechanical stress overload to the turbine system. Yet, pitch control is a mechanical FRT technique which requires a longer time to restore the system steady state. It is reported in [57] that it takes 13 s to restore wind generation system stability, which is quite longer to sustain the stability of the electrical system. Hence, active methods which involve modified RSC and GSC control with a combined effort of pitch control is explored for the FRT capability enhancement.

5.1.2 Modified VC: The power converters of DFIG are usually controlled using VC based on stator flux orientation. The RSC independently controls the stator reactive power and the electromagnetic torque. The stator flux is generally considered to be constant and oriented along the *d*-axis of the synchronous reference frame to simplify the current controller design. At the same time, the VC approach enables independent active and reactive power flow control between GSC and grid with a reference frame oriented along the grid-voltage vector. The objective of GSC is to maintain a constant DC-link voltage. However, stator flux drops because of direct grid connection and the quadrature stator flux oscillates instead of equalling to zero during voltage dip. Therefore, it is important to consider the dynamics of stator flux during current controller design [58]. The hysteresis control, feed-forward and transient current control, and MPC are current control-based techniques and are closely related to the current compensation control schemes as explained in modified VC.

Although the control structures are closely related and similar, the control techniques have been discussed individually to improve clarity. Also, most of the control techniques are discussed in detail individually in most of the literature. Also, many hybrid control techniques are adopted in a combination with the above techniques as well. The control architecture of DFIG is in itself complicated, and therefore it is an essential requirement to reduce the complexity of the control when adopting FRT capability.

5.1.3 Hysteresis control: Hysteresis control consists of a non-linear feedback loop with two-level hysteresis comparators. This can produce switching signals directly when the error exceeds the assigned tolerance band. Vector-based hysteresis current regulator (VBHCR) can generate an optimal switching pattern similar to the popular support vector machine technique. Thereby, notably reduces average switching frequency of RSC and the oscillations in output current vector. This control utilises instantaneous

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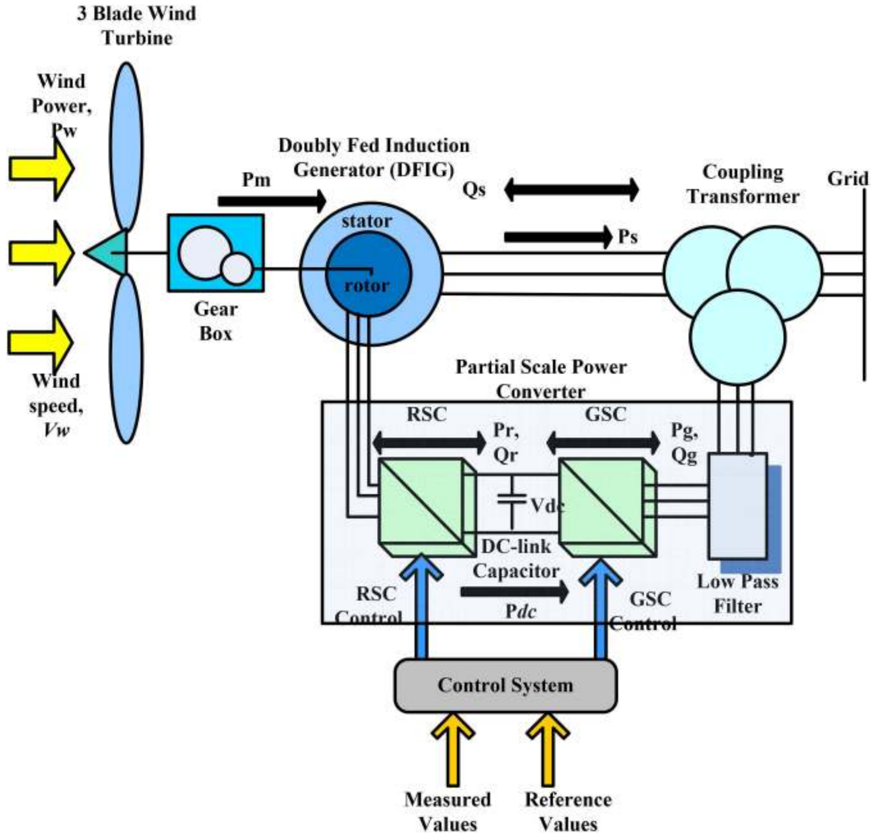

Fig. 20 *Configuration of an RSC and GSC control configuration in DFIG wind generator*

measurements of rotor current; therefore, is robust to voltage distortions and system parameter variations [59].

VBHCR obtains the RSC switching on detecting a grid fault. This current control is better than predictive current controllers due to the simpler control structure and inherent peak current limiting characteristic [60]. However, due to variable switching frequency and low-order current harmonic distortions, long operating time of VBHCR is not desirable [61]. A continuous supply of active and reactive powers to the grid and operation of WTs using VBHCR-based control is shown in [62]. Voltage sag and swell mitigation to aid LVRT and high voltage ride through (HVRT), respectively, using VBHCR are shown in [63]. Even though the voltage sag transients are dealt with using hysteresis controllers, the complexity of implementation is overlooked.

5.1.4 Feed-forward and transient current control: Feed-forward term added to the conventional current regulator gives the FFTC controller in RSC of DFIG. It aligns the RSC AC-side output voltage with transient-induced voltage reduces the rotor current during transients and minimises the crowbar interruptions. Feed-forward transient compensation control with proportional–integral (PI)– a resonant controller that improves LVRT. The LVRT capability of DFIG improves in RSC of DFIG with an FFTCC [64]. Transient compensation terms of feed-forward are injected into both the current and power control loops to improve the transient current control capability and reduce the torque ripple resulting from grid faults. Generally, the feed-forward compensation employed reduces the torque pulsation caused by negative-sequence current [65].

5.2 Advanced control techniques

5.2.1 Sliding-mode control: Sliding-mode control is a discontinuous control signal-based non-linear control method; this alters the dynamics of the system [66]. This controls the system to slide within a cross-section of the system's normal behaviour. Advantages such as robustness against faults and no extra mechanical stress on the drive train are the main reasons for utilising higher-order sliding-mode-based control for FRT in DFIG. With the growing need for a robust and non-linear controller, sliding-mode control is suggested as a pertinent choice to solve FRT problem in DFIG [67].

The sliding-mode control proposed can command the RSC during grid fault to prevent the fluctuations in electromagnetic torque and stator reactive power and GSC to ensure constant DC-link voltage and steady active power output from the overall system. A new gain scheduled continuous higher-order sliding-mode control is the future trend of this control. This approach proves the effectiveness of control utilised and the scenario with unknown control direction is yet to be explored.

5.2.2 Fuzzy logic-based control: Fuzzy control can control the power flows in DFIG. It consists of linguistic rules which can be designed without knowing the exact system parameters as required in the conventional PI design method. Fuzzy control is applied to the stator of DFIG to control real and reactive powers independently. Comparison of the fuzzy logic controller with sliding-mode control shows satisfactory performance in smoothing active and reactive power outputs and damping of DC-bus overvoltage under grid faults. Also, it shows a negligible transient overshoot using fuzzy logic control compared with sliding-mode control [67].

RSC control based on type-2 fuzzy logic control considering the non-linear relationship between generator speed and DC-link voltage to maintain the constant DC-link voltage in permanent magnet synchronous generator-based turbines is verified for symmetrical and asymmetrical grid faults in [68]. The surplus energy created by the difference between the generated active power and grid delivered the active power is stored in generator inertia to keep the DC-link voltage constant through this control. Therefore, these ideas pose a new arena for the utilisation of fuzzy control for the FRT capability in DFIG in both active and passive methods.

5.2.3 Model predictive control: An exponential development of the digital signal processors for processing power has led to the utilisation of predictive control. A cost function is defined and the voltage vector which minimises the cost function is MPC. Finite

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Table 3 Internal control modification based on traditional control techniques

Reference	Control	Advantages	Disadvantages
[56]	blade pitch angle control	regulates rotor speed	mechanical control, therefore, the response is slow.Modified pitch control is based on wind generator speed rather than generator power
[59]	hysteresis control	simpler control structure and inherent peak current limiting characteristic.Helps power converters to remain connected to grid, avoids reactive power consumption during fault and maintains grid stability	long-time operation is not desirable because of its variable switching frequency and low-order current harmonic distortions.Complexity of implementation
[64]	FFTCC	improves transient current control capability.reduces the torque pulsation caused by negative-sequence current	complicated control.Sensor is needed for sensing input voltage and slow response
[66]	sliding-mode control	robust against external disturbances.No extra mechanical stress on the WT drive train	chattering phenomenon causes oscillation.Over estimation of control gain, model complexity and saturation of control input signals
[67, 71]	fuzzy-based control	negligible transient overshoot using fuzzy compared with sliding-mode control	cost, complexity, power consumption and time response
[69]	MPC	fast dynamic response.Also includes the non-linearities and constraints of the system	complex and costly implementation.Requires experimental validations

Table 4 Internal control modification based on advanced control techniques

Reference	Year	Control	Inference
[51]	2016	coordinated control strategy using a genetic algorithm for LVRT	two controllers are using a fuzzy controller tuned by genetic algorithms
[72]	2016	modified rotor current limiter and equivalent stator power limiter	overall performance improvement under unbalanced grid-voltage conditions due to the limiters
[21]	2016	analysis tool based on optimisation theory	Pontryagin's minimum principle is employed to solve this optimisation problem. The tool estimates the theoretical control limit of RSC and to suppress the short-circuit rotor currents during grid faults
[73]	2015	FFRT strategy	fault condition categorised into slight, moderate and severe faults. Increased FRT capability of wind farm clusters and reduced wind power curtailment during faults
[10]	2011	virtual resistance in combination with demagnetisation control to limit rotor overcurrents	though demagnetisation control handles stator flux variations, under deeper fault it requires crowbar activation

control set-based MPC utilises limited switching states of the converter for solving optimisation problem from the discrete model of the system. The switching action minimises a given quality function and is directly applied to the power converter, and therefore does not require any modulator. It also includes the non-linearities and constraints of the system.

Direct drive WTs with neutral-point clamped inverters controlled by MPC to meet the LVRT requirement are proposed in [69]. Balanced grid voltage under fault conditions, proper active and reactive power regulations and DC-link voltage balance are achieved by using this method. Further possibilities of MPC-based control and evolution of finite control set MPC is elaborated in [70]. Thus, MPC-based control offers many advantages as it can effectively handle the non-linear conditions during grid disturbances. Furthermore, research based on MPC for LVRT capability in DFIG is yet to be explored. The different active control methods discussed so far are compared and analysed in Table 3.

5.2.4 Other advanced controls: There are several new control strategies and modelling approaches introduced to analyse and tackle the LVRT capability of DFIG. DVR with fault current limiting action [52] and genetic algorithm-based control [51] methods are newly proposed. The flux-linkage tracking-based control strategy is shown in [72], suppresses the short-circuit rotor current.

A coordinated control strategy of the DFIG converters using auxiliary hardware during a fault is proposed in [21]. Here, the two controllers are using a fuzzy controller tuned by genetic algorithms. The RSC eliminates the oscillations electromagnetic torque oscillations and stator reactive power.

The feasibility regions of DFIG are determined for different fault types. On the basis of the outcome, a modified rotor current limiter and equivalent stator power limiter are developed. The overall performance of the system is considerably enhanced under unbalanced grid-voltage conditions due to the limiters introduced.

A new approach to achieve FRT capability by considering a flexible FRT (FFRT) strategy is studied through simulated results considering power systems of China with high-wind power penetration as in [73]. The fault condition is categorised into slight fault, moderate fault and severe fault. The main defending objective of the strategy is the slight faults and moderate faults with a high probability of occurrence. Temporary overloading capability of DFIG is considered to enhance the capability to defend slight faults and avoid tripping when crowbar is disconnected after clearing moderate faults. The simulation studies show an increased FRT capability of wind farm clusters and reduced wind power curtailment during faults. Such an alternative strategy coupled with advanced control strategies further enhances the FRT capability of DFIGs.

An analysis tool to estimate the theoretical control limit of RSC and to suppress the short-circuit rotor currents during grid faults is developed in [10]. The tool is based on optimisation theory employing Pontryagin's minimum principle *o* and takes into account the practical constraints of RSC.

The operation of these control strategies require testing before certification, and therefore the various testing tools available to ensure the reliability of LVRT solutions are discussed in [74]. These control strategies are listed in Table 4. The impacts of FRT improvement techniques due to grid faults or low-voltage condition for the major FRT techniques discussed is given in Table 5.

6 Case study – 2016 South Australian Blackout

The South Australian Blackout occurred in 2016, highlights some of the hard truth behind the high share of the renewable energy mix in the power grid. The growing penetration of wind energy has impacted the system inertia during fault conditions. The blackout is

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Table 5 Impacts of FRT improvement techniques due to grid faults or low-voltage condition

FRT capability technique	High stator current (PV)	High rotor current (PV)	High rotor voltage (PV)	Oscillations of stator current	Oscillations of rotor current	Oscillations of stator voltage	Oscillations of rotor voltage	High DC-link voltage (PV)	Oscillations of DC-link voltage	Reactive power support	Active power support
rotor crowbar [4]	NA	yes	NA	NA	yes	NA	no	yes	yes	no	NA
DC-link chopper with crowbar [18]	yes	yes	NA	NA	yes	NA	NA	yes	yes	no	NA
DC-link chopper [75]	no	no	NA	NA	NA	NA	NA	yes	yes	NA	NA
SDBR [30]	NA	no	NA	NA	NA	NA	NA	yes	yes	NA	NA
energy storage [32]	no	no	no	no	no	no	no	no	yes	yes	no
SGSC [39]	no	no	NA	no	no	NA	NA	yes	yes	no	yes
SFCL [44]	no	no	yes	no	no	yes	yes	no	no	yes	yes
DVR [48–50]	no	no	no	no	no	no	no	no	yes	yes	yes
static compensator (STATCOM) [45–47]	no	no	no	no	no	no	no	no	yes	yes	no
traditional RSC and GSC control [19], [57, 58]	NA	yes	NA	yes	yes	NA	NA	yes	yes	NA	NA
pitch angle control [56]	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	no
current compensation control [59, 64, 67, 69]	NA	NA	yes	yes	NA	yes	yes	yes	yes	no	no
sliding-mode control [66]	NA	NA	NA	NA	NA	NA	NA	yes	yes	no	no

PV – peak value and NA – not applicable.

predominantly due to the 35% wind powered system in the region. This is blamed on the 'overly sensitive' safety settings of the WTs. However, the more essential problem is the 'lack of inertia' and the complexity. Therefore, this phenomenon forces us to include more studies on improving the inertial response of the WTs which is caused by the lack of synchronous generators [76, 77]. The severity lies in the 1895 MW supply interrupted due to this particular blackout, which has cost extensive losses to the entire country.

7 Conclusion with discussion on future trends

A comprehensive review of the operation of DFIG-WT with the proposed FRT solutions during fault conditions is covered in this paper. The external device installations are done to modify the converter architecture and are most preferred for pre-installed WTs. The retrofitting-based solutions using protection circuit and storage-based methods and FACTS-based reactive power injection-based methods are presented. Cost factor stands as a major barrier for pre-installed WTs, which have already started nearing their end of life time. Strategically analysed solution to convince the WT owners to install a particular FRT solution is required. The observation in Table 5 gives suitable proof for justifying the below conclusion and future trends.

The internal control modifications are preferred in a new installation of WTs. They are classified as traditional and advanced control solutions. These solutions are discussed in detail and the various advantages and disadvantages are analysed. This review is considered to be useful for understanding the various aspects to be focused to enhance the FRT capability of a DFIG-WTs. This review aims to provoke the research focus in improving the FRT capability further with respect to the real-time implementation challenges.

In summary, the conclusion and future trends are discussed as follows:

- Conventional crowbar protection provides successful FRT operation but late removal will lead to higher reactive power absorption from the grid. Crowbar can shorten the rotor decay time with appropriate rotor resistance selection, which will also assist faster recovery of control. The future trends should focus investigation of hybrid crowbar-based techniques to improve the FRT capabilities.
- FCL-based topologies have improved significantly in recent past. HTS-FCL-based technique acts as a voltage booster scheme which has smaller size and lower cost. Future trends should focus on new materials for hybrid HTS-FCL to improve the performance and reduce the cost.
- DVR avoids the need for any other protection methods in combination to provide FRT. Reduced rating DVR-based topologies are economical and are capable to eliminate the need for complicated control strategies as well as to provide an efficient reactive power support during FRT in DFIG. Reduced rating DVR can be utilised as an effective FRT solution for pre-installed WTs. The future trend focuses on fault current limiting action of DVR to provide effective FRT solution.
- GSC-based STATCOM solutions also need to be focused for a cost-effective solution.
- Active methods based on modified control strategies in RSC or GSC controllers can be effectively utilised for new WTs. These methods are superior when compared with the passive methods as they reduce the cost of external device.
- Testing of WTs to study the FRT operation in weak grid scenario will help to check the reliability of these methods before installation. This will help to focus the research on the actual requirements and thereby improve the control strategies. The future trends in analysing the FRT solutions through testing also need to be focused.

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