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Grid Ancillary Services From Doubly Fed Induction Generator-Based Wind Energy Conversion System: A Review

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ABSTRACT Modern electrical grids face serious challenges to maintain healthy operational conditions. The nominal voltage and frequency, for instance, are affected by huge load changes and renewable energy integration. Renewable energy conversion systems are traditionally installed to provide active power. Fortunately, advanced renewable energy conversion systems have the ability to provide other facilities such as reactive power control and harmonic mitigation. In fact, recent grid codes obligate renewable energy systems to serve other duties such as generating reactive power rather than just simply supply active power, participate in fault ride through, for instance. This paper presents a comprehensive study on the doubly fed induction generator (DFIG)-based wind energy conversion system (WECS), which provides ancillary services to the grid along with performing its regular duties. These services include reactive power control, voltage ride through, power quality improvement, frequency control, and power oscillation damping. The literature survey and comparative studies show that the DFIG-based WECS has the ability to support electrical grid during normal and transient conditions, and it can also help in the large-scale renewable energy penetration to the power grid. The effect of different industrial and nonlinear controllers on DFIG performance in extracting grid ancillary services is highlighted.

INDEX TERMS Doubly fed induction generator (DFIG), frequency control, grid ancillary services, power oscillation damping, power quality improvement, reactive power control, voltage ride through, wind energy conversion system (WECS).

NOMENCLATURE

AVR	Automatic voltage regulation
CFCL	Controllable fault current limiter
DCCC	Dc-link capacitor crowbar
DFIG	Doubly fed induction generator
DPC	Direct power control
DSP	Digital signal processing
DTC	Direct torque control
ESS	Energy storage system
FACTs	Flexible AC transmission systems devices
FFT	Fast Fourier transform
GSC	Grid side converter
IG	Induction generator
IGBT	Insulated gate bipolar transistor
LVRT	Low voltage ride through
MOR	Model order reduction
MPPT	Maximum power point tracking
PMSG	Permanent magnet synchronous generator
PCC	Point of common coupling
PF	Power factor
POD	Power oscillation damper
PRSC	Parallel rotor side crowbar
PSS	Power systems stabilizers
PWM	Pulse width modulation
RCL	Rotor current limiter
RMS	Root mean square
RSC	Rotor side converter
SDBR	Series dynamic braking resistor
SDR	Stator damping resistor
SRC	Supplementary rotor current
SRSC	Series rotor side crowbar
SSI	Sub-synchronous interactions
SVC	Static var compensator
THD	Total harmonic distortion

VC Vector control
WECS Wind energy conversion system

I. INTRODUCTION

Energy production and use, mainly from fuel combustion, are the single most important man-made sources of air pollutant emissions. The International Energy Agency (IEA) stated in its special report [1], which for the first time links between energy, health, and air pollution, that around 6.5 million deaths are attributed each year to poor air quality. This ruinous toll on human life is set to rise if the way that the world produces and uses energy does not change. According to the International Renewable Energy Agency (IRENA), increasing renewable energy usage would rapidly reduce the pollution and climate impact and could save up to 4.2 trillion USD per year worldwide by 2030. In addition, doubling the renewable energy share in the global energy mix can result in significant savings of fossil fuels and save up to 4 million lives annually by 2030. Moreover, the reduced usage of fossil fuels decreases carbon dioxide emissions and saves external costs related to the use of fossil fuels which stem from many causes such as air pollution [2]. The global energy trends are seriously moving towards renewable energy sources. In fact, governments and leading companies are targeting to increase the renewable energy share in their portfolio and are investing considerably in renewable energy sectors [3]. In 2015, wind and solar power commanded about 90% of the renewable energy investments due to significant cost reduction in recent years. For instance, the cost of wind turbines has fallen by nearly a third since 2009. Currently, onshore wind power is competitive or cheaper that gas, oil, and coal power stations despite the low oil prices and even without financial support [4]. An increasing number of locations and new markets including Asia, Africa, and Latin America are considering wind energy for new power generating platform since it is the least cost option [5]. The increase of wind power generation installed capacity was nearly 54,000 MW in 2016. In the same year, wind power recorded a cumulative increase of 12.%, and its total installed capacity was 486,800 MW [6].

A. ARTICLE MOTIVATION

The electrical power grid complexity is increasing nowadays due to the massive expansion in the energy supply and demand. Stiff load variation and renewable energies integration with the existing grid rise critical penetrations. There are various methods to solve the grid problems such as voltage and frequency deviations, variability, and stability. The common practice is to use external devices like flexible alternating current (AC) transmission systems devices (FACTS) such as static var compensator (SVC) and static synchronous compensator (STATCOM) for voltage control or harmonic filters for power quality improvement. These devices or tools are specific which means that additional components should be added to the grid to perform only one specific task at the expense of additional cost. Nevertheless, the brilliant idea is to use renewable energy systems as a solution to the grid issues. In addition to their main purpose which is generating electrical power, renewable energy conversion systems can provide additional services such as voltage control, frequency control, and even power quality improvements. By utilizing these features, we can stop two gaps with one bush, power generation and grid issues without the need of external costly additional mitigation devices.

B. ARTICLE CONTRIBUTION

This article focuses on wind energy and specifically on doubly-fed induction generator based wind energy conversion system, one of the most popular wind energy conversion system nowadays, not only because it is the preferred solution in the global wind energy market in the last decade [7] but also because of its tremendous advantages. This article contributes to the following:

- It comprehensively discusses the significance of utilizing DFIG to meet modern grid cods expectations as well as elaborates on the capability of DFIG for meeting these expectations.
- It summarizes the benefits and challenges of utilizing DFIG to support the grid with ancillary services.
- To the best of authors' knowledge, there is no comprehensive literature survey paper that considers all major DFIG auxiliary services in a single paper.
- It spots the light on the effect of various control techniques in extracting additional services from DFIG and analyzes this effect through comparative studies.
- It identifies the latest needs and opportunities in many DFIG ancillary services research directions and gives remarks and future works recommendations.

C. ARTICLE ORGANIZATION

This article is divided into five sections. Section I highlights the current global trend towards renewable energy and the article motivation and contribution. Section II gives a background to common electric generators used in WECS and their control classifications, WECS grid connection requirements, DFIG-based WECS principals, and DFIG-based WECS effects on the power system. Section III is the heart of the article, and it includes detailed DFIG based WECS ancillary services to the grid. Section VI encloses a comparative study and validation to some of the DFIG-based WECS ancillary services. Section V contains the final conclusions and future research directions.

II. BACKGROUND

This section includes a brief background to common electric generators used in WECS and their control classifications, WECS grid connection requirements, and DFIG based WECS principals.

A. COMMON ELECTRICAL GENERATORS USED IN WIND TURBINES

Wind turbines can be divided into four main categories. The first category is fixed speed wind turbines. This type uses an asynchronous squirrel-cage induction generator (IG) directly connected to the grid via a transformer. Also, this type of wind turbines cannot be automatically regulated. The second category is partial speed wind turbine with variable rotor resistance. This type of wind turbine uses a wound rotor induction generator which is directly connected to the grid. The slip and output power of this type of wind turbines can be regulated by a series controlled resistance. The third category is variable speed wind turbine with partial-scale power converter. This type of wind turbines is also known as the doubly-fed induction generator (DFIG). It uses a variable speed controlled wind turbine. The rotor phase windings are connected to a back-to-back converter via slip rings whereas the stator phase windings are connected directly to the grid. The speed range of the double-fed induction generator is between -30% and $+20\%$ of the synchronous speed. This is due to power converters ability to control the rotor speed by controlling the rotor's frequency. The last category is variable speed wind turbine with full-scale power converter. This type of wind turbines uses a full-scale power converters and a permanent magnet synchronous generator (PMSG). The stator windings are connected to the grid through full scale converters [8].

The first two categories of the wind turbines are very simple and maintenance free. However, they have many drawbacks. First, they do not have reactive power compensation. Second their mechanical construction must support high mechanical stress. Third, they require a stiff grid. Finally, the most important disadvantage is that they do not support any speed control. DFIG based wind turbines, third category, have many advantages. Firstly, their construction is simple and cheaper compared to the fourth type. Secondly, by controlling the rotor terminal voltages, they can decouple the control of the active and reactive powers and control power factor as a result. Thirdly, the DFIG wind turbines power converters rating is 30% of the DFIG rated power. This reduces the switching losses, converters cost, filter volume, and harmonic injection into the grid [9]. However, double fed induction generators wind turbines have disadvantages such as the need of protection schemes, periodic maintenance of slip-rings and gearbox, complex power control schemes, and limited fault ride through. PMSG based wind turbines, forth category, have many advantages. First, they do not have mechanical stress problems because they can avoid gearbox. Second, they can achieve full speed regulation, and hence maximum power point tracking (MPPT) is possible. Third, they do not need slip-rings; thus, they are more stable than the doubly-fed induction generators turbines. Finally, their control schemes are easy to implement and simple. Despite the advantages fourth category of wind turbines, they also have disadvantages. Firstly, they are heavy and large. Secondly, their power converters have high cost, generate high harmonics, and have high power losses. Thirdly, they use permanent magnet which may demagnetize at high temperature and increase the wind turbine total cost. Table 1 summaries the features and limitations of the common electrical generators used in wind turbines. Further information related to different wind generators and their comparisons is available in [10].

TABLE 1. Common electrical generators used in wind turbines.

	Features	Limitations
IG	- Simple construction - Maintenance free - Lower price	- No speed and MPPT support - No reactive power compensation - Must support high stress
DFIG	- Simple manufacturing - Low cost - Reduced converter ratings - Support MPPT	- Need for protection scheme - Frequent maintenance - Complex control schemes - Need for gearbox
PMSG	- No need for gearbox - No slip-rings - Full speed regulation - Support MPPT	- Full-scale converters - Large and heavy - Magnet demagnetization - Rare and costly materials

B. ELECTRICAL GENERATORS CONTROL CLASSIFICATIONS

There are many control classifications for AC machines in general. The most common control methods are vector or field oriented control (VC) and direct control which is further divided to direct power and direct torque control [11]. In the vector control scheme, the machine is controlled in a synchronous rotating dq frame with the d-axis oriented with the flux. The current components can independently control the active and reactive powers. For example, if the reference frame is oriented with the stator flux, the d-axis and q-axis current components control the stator reactive and active powers respectively [12]. The direct power control (DPC) scheme is based on a direct control of active and reactive powers of the stator. It is performed by injecting directly current/voltage vectors. The direct torque control (DTC) scheme is established by direct control of two magnitudes of the doubly fed induction machine which are the rotor flux and the electromagnetic torque. It is based on a space vector representation of the achievable output of AC voltages of the converter. This space vector representation is used as a look-up table for the converter output voltage. The DTC directly creates the pulses for the converter without using modulation schemes such as pulse width modulation (PWM).

C. WECS GRID CONNECTION REQUIREMENTS

The grid codes for wind turbines are complicated rules that consider both transients and stationary operation conditions. The main goal of grid codes is to supply wind farms with the control abilities encounters in traditional sources which are essential for power systems reliability, economy, and safety. The development of wind turbine technologies is influenced by grid codes, and modern wind turbines should meet all of them. The grid requirements fall in two main categories: normal operation and operation under grid disturbances [13].

1) GRID CONNECTION REQUIREMENTS UNDER NORMAL CONDITIONS

The grid requirements under normal conditions include three parts which are frequency and voltage deviations, active power control, and reactive power control.

a: FREQUENCY AND VOLTAGE DEVIATIONS

Operation about nominal frequency and voltage at the point of common coupling (PCC) is a requirement to avoid disconnections. The three operation zones for frequency and voltage are:

- Continuous operation: limited bound above and under the rated point.
- Time-limited operation: possible output reduction in extended bounds.
- Immediate disconnection: wind turbine must be turned off.

The acceptable frequency range varies from a country to another. For example, the frequency limit in the British code is (47.5-52 Hz), and the voltage range according to the Danish code is (90-106%) from nominal voltage. Figure 1 shows a typical voltage/frequency operation window [14].

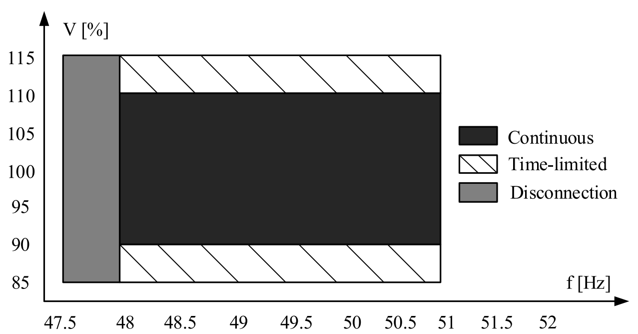

FIGURE 1. **Voltage/frequency operation ranges [14].**

b: ACTIVE POWER CONTROL

Active power control is the capability to regulate the generated power as recommended by the transmission system operators. The main objectives of active power control are power curtailments and frequency control. The power curtailment is the required ramp rate level per time. For instance, in Germany, the active power of the wind power plant should change with a ramp rate of at least 10% of the grid connection capacity per minute to any level required by the transmission system operator though no lower than 0.1 p.u. The frequency control objective is achieved when the active power output is changed during frequency variation, and this ensures smooth frequency control contribution of the wind power plant. The relationship between the generated active power and frequency is inversely proportional. For example, as per the Irish code, all generating units must reduce during operation if the frequency is more than 50.2 Hz with an active power gradient equal to 40% of available power of the wind power plant.

c: REACTIVE POWER CONTROL

The modern goal for using wind power plants is to make them act like conventional synchronous generator power plants, and this includes reactive power regulation. This option is known as automatic voltage regulation (AVR). The grid short-circuit power determines the voltage changing capability, and the reactive power requirements depend on the grid characteristics. This is given by three ways which are reactive power set point, power factor control, and voltage control. In the British code for instance, the reactive power requirement is 0.33 p.u., and this amount should be kept for active power down to 0.2 p.u. for lagging power factor and down to 0.5 p.u. for leading power factor.

2) GRID CONNECTION REQUIREMENTS UNDER GRID DISTURBANCES

Grid faults such as voltage swells and voltage sags can cause wind power plant disconnection, and this can lead to grid unbalance and even blackouts. Grid codes aim to avoid this phenomenon by setting three main conditions:

1) Keep connected even if the voltage drops to zero for up to 150 ms.
2) Inject reactive current to support voltage recovery.
3) Harmonize with the grid natural recovery by ramping up the active power after fault clearance with a limited ramp.

Grid codes generally define features for the behavior under grid disturbances. These features are stated below for Germany code as an example:

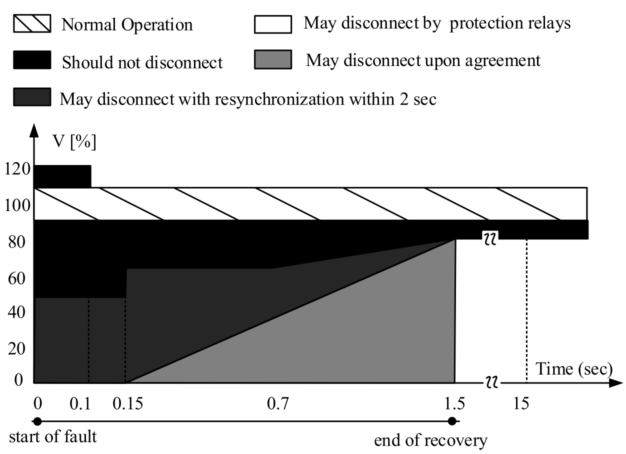

FIGURE 2. **Voltage ride through requirements for Germany [14].**

a: VOLTAGE RIDE THROUGH

The voltage ride through of Germany code is shown in Figure 2. The voltage value represents the maximum value of the three-phase grid voltages measured at the transformer's low-voltage side. No interruptions are permissible within the black area. The wind power plant must be connected even if the voltage at PCC reaches to zero.

The typical activation time of the protection relays is 150 ms. Short time interruptions with resynchronization for a maximum of 2 seconds are allowed in the dark gray area. After agreement with the transmission systems operator, short disconnections with resynchronization for more than 2 seconds are allowed, and this is shown in the light gray area. Stepwise interruptions are allowed for faults longer than 1.5 seconds.

b: ACTIVE AND REACTIVE POWER LIMITATION DURING FAULTS AND RECOVERY

The current can be decreased during faults to match the reactive current requirements after the fault. Important factors such as the power balance within the frequency and grid stability necessarily require fast return to normal active power generation.

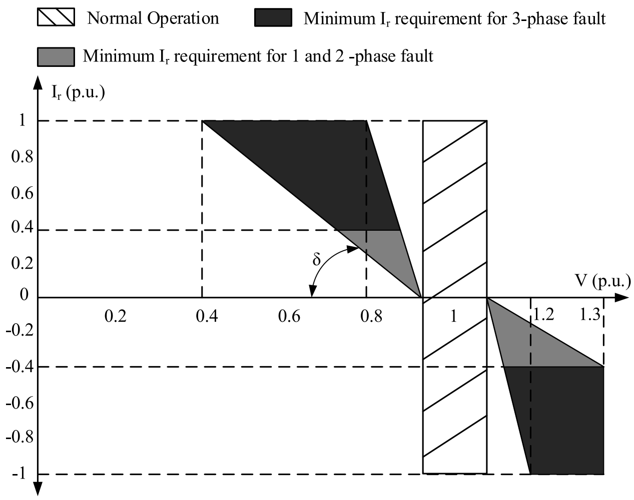

FIGURE 3. Reactive current requirements for Germany [14].

c: REACTIVE CURRENT INJECTION

Figure 3 shows the reactive current injection as per Germany grid code. In this figure, the reactive current requirements apply to the maximum value of the three phase voltages during faults within the black gray area. The highest reactive current can be bounded to 40% of the rated current in the case of single and double line faults. Proportional reactive current has to be absorbed or injected in the case of severe deviation in voltage. The smallest reactive current slope $K = tan(\delta) = \frac{\Delta I_r}{\Delta V}$ may vary between 0 and 10. In order to improve stability, a 10% dead-band of voltage shift is allowed. For high voltage transmission connection, the dead-band can be removed. In addition, the control range needs be between 10% and 20% of the rated current, and the controller response time of the reactive current may not exceed 30 ms. Moreover, the reactive current reference shall not change stepwise. This will prevent stability problems after fault clearance. In the case of voltages below 0.8 p.u. and if the power utility cannot provide the reactive power required voltage support, the system protection will trip the wind power plant at the PCC.

d: RESUMING LIMITED ACTIVE POWER RAMP

The generated active power must be continued directly after fault clearance with a minimum 10%/sec gradient in temporary disconnection. Similarly, the generated active power should be directly connected after fault clearance. Also, it should be amplified to the previous reference with a minimum 20%/sec gradient during fault clearance without disconnection.

D. DFIG-BASED WECS PRINCIPLES

The working principle of doubly-fed electric machines is not new, yet they have entered into common practice in the last decades because of their use in wind power technologies [15]. The DFIG based WECS system consists of a wound rotor induction generator connected to two back-to-back connected electric converters: the grid side converter (GSC) and the rotor side converter (RSC). Both converters are usually two-level six-switch voltage source converters.

1) GRID SIDE CONVERTER (GSC)

The GSC regulates the direct current (DC)-link capacitor voltage. The DC-link capacitor is used as an energy storage element which delivers the required energy between the generator and the grid. Furthermore, the GSC has the ability to absorb or generate reactive power for voltage support requirements. Usually, the reactive power reference is set to zero to obtain unity power factor operation.

2) ROTOR SIDE CONVERTER (RSC)

The voltage applied to the DFIG rotor is generated by the RSC. The main objective of the RSC is to control the rotor currents such that the rotor flux positions is optimally oriented with respect with the stator flux such that the required power is developed.

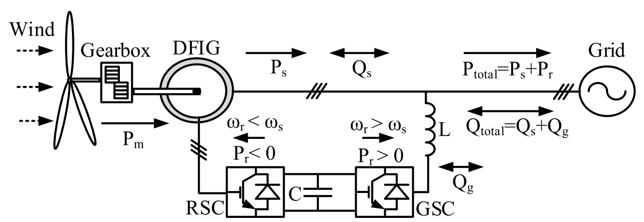

FIGURE 4. DFIG based WECS power flow diagram.

3) DFIG-BASED WECS POWER FLOW

The DFIG based WECS power flow is shown in Figure 4. This figure shows typical power flow for both active and reactive powers to and from the system.

Initially, the wind power rotates the wind turbine blades which are usually connected to the DFIG rotor via gearbox. Due to the rotor rotation, mechanical power P_m is generated. If a lossless DFIG system is assumed under steady-state (fixed turbine speed), the mechanical power is given by:

$$P_m = P_s + P_r \tag{1}$$

The total active power delivered to the grid depends on the stator and rotor powers P_s and P_r. The rotor active power depends on the rotor angular frequency ω_r. For example, if the rotor speed is less than the network or grid angular frequency ω_s, the rotor active power will be negative. The rotor active power magnitude range is between 0 and 30% of the total power and given by:

$$P_r = P_m - P_s = -sP_s \quad (2)$$

where s is the slip of the generator and represented by:

$$s = \frac{\omega_s - \omega_r}{\omega_s} \quad (3)$$

In DFIG based WECS, the maximum slip is limited to 0.3, and this clarifies the reduced electrical converters ratings (only 30% of the generator rated power). Furthermore, the total reactive power can be sent to and from the grid, and it depends on the grid side converter reactive power Q_g and the stator reactive power Q_s. The DFIG based WECS power is limited by the generator ratings as per the equation:

$$S_{total}^2 = P_{total}^2 + Q_{total}^2 \quad (4)$$

where S_{total}^2 is the total apparent power. The power factor (PF) is represented by:

$$PF = \frac{P_{total}}{S_{total}} \quad (5)$$

The power factor reference required by the WECS is unity power factor. However, if reactive power compensation is implemented, the power factor may change to leading or lagging depending on the system operator requirements.

E. DFIG-BASED WECS EFFECTS ON POWER SYSTEMS

The DFIG effect on power system dynamics is divided into four main categories which are voltage stability, small-signal stability, transient stability, and frequency stability [16]. Voltage stability is defined as the capability of power systems to maintain nominal voltages at all buses after disturbances. DFIG based WECS can improve voltage stability with its ability to supply or absorb reactive power. The DFIG based WECS voltage recovery performance is better compared to an induction generator IG-based WECS with the same rating. Small-signal stability is known as the ability of power systems to insure synchronism under minor disturbances. Small signal instability can cause critical oscillations and rotor angle increase due to damping and synchronizing torques shortage. Transient stability is similar to small-signal stability, but it is concerned with serious disturbances. In the case of a dangerous disturbance like short circuit, the power system inertia and synchronizing torque are affected because the DFIG based-WECS inertia is decoupled with the power system. As a result, the total angular deceleration or acceleration takes place in the power systems synchronous generators. Frequency stability is the power system capability to preserve system nominal frequency under serious generation load unbalance. The DFIG based WECS power fluctuations may lead to frequency perturbations and reduce system inertia.

Power system stability can be improved by wind WECSs which provide oscillation damping and temporary frequency

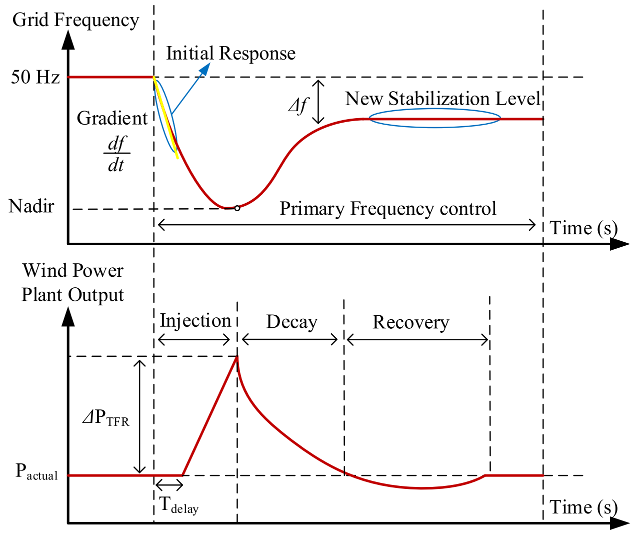

FIGURE 5. Power system and wind power transient frequency response [17].

response. However, coordination between them is necessary to avoid undesired stability degrade [17]. Figure 5 describes the power system and wind power plant transient frequency responses. The power system transient response can be seen from two intervals which are initial response and primary frequency control. The initial response illustrates the synchronous generators inertia response to the premier frequency variation. In the primary frequency control interval, the synchronous generators frequency droop controllers which have important effect on the final steady state frequency level and nadir are automatically enabled to settle down the system frequency to a new stabilization level.

The wind power plant response is divided into three sections which are injection, decay, and recovery. During the injection phase, the wind power plant temporary supplies power to compensate for the grid frequency nadir. Through the decay period, the wind power plant output power gradually returns to its initial power level. Finally, the wind power plant output power enters a recovery phase where it stabilizes to its first power reference.

TABLE 2. DFIG-based WECS ancillary services.

Ancillary Service	References
Reactive power control	[18]–[23]
Fault/voltage ride through	[24]–[38]
Power quality improvement	[39]–[50]
Frequency control	[51]–[61]
Power oscillation damping	[62]–[72]

III. DFIG-BASED WECS ANCILLARY SERVICES

Table 2 summarizes some of the research papers that are presented in this article and consider DFIG based WECS ancillary grid services like reactive power control, fault or voltage ride through, power quality improvement, frequency control, and power oscillation damping.

A. REACTIVE POWER CONTROL

The DFIG reactive power control can be classified into four methods which are unity power factor operation, reactive power control by GSC, reactive power control by RSC, and voltage control by using both GSC and RSC [19].

1) UNITY POWER FACTOR OPERATION

In this method, the DFIG reactive power reference Q_s^* is set to zero. This means that the DFIG will not supply or absorb reactive power and will only provide active power. The control diagram of the DFIG reactive power is shown in Figure 6.

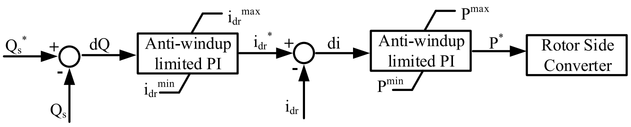

FIGURE 6. **DFIG reactive power control diagram [19].**

2) REACTIVE POWER CONTROL BY RSC

In this method, the reactive power is controlled by the RSC. The reactive power reference value is chosen to ensure that the nominal voltage reference is achieved. Figure 7 shows how Q_s^* is obtained. It can be noted from the same figure that the controller is limited so that the ratings are not exceeded.

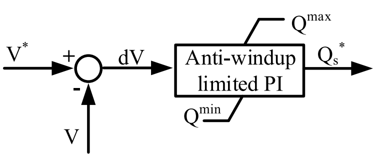

FIGURE 7. **Reactive power control by RSC [19].**

3) REACTIVE POWER CONTROL BY GSC

In this method, the reactive power is controlled by the GSC. The GSC ensures constant dc-link voltage, but it also has the ability to control reactive power. The GSC ratings are typically 30% of the generator ratings, and this limits the allowable reactive power generation.

4) REACTIVE POWER CONTROL USING GSC AND RSC

Reactive power control using both GSC and RSC can be further classified to uncoordinated and coordinated operation. During the uncoordinated operation, GSC and RSC reactive power controllers are operating independently to control the reactive power as shown in Figure 8. This method is not recommended because there is a possibility that the control actions of the two controllers overlap.

However, when coordinated operation is applied as shown in Figure 9, the controllers for two converters share the reactive power control duty. One possible sharing method is to set one converter as default reactive power source and the other converter supports it. Another method is to give a specific operation ration for the two converters.

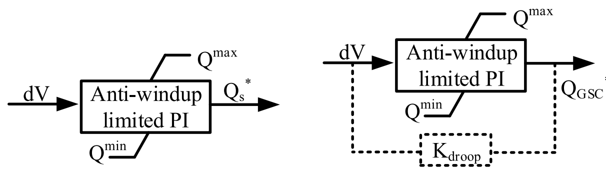

FIGURE 8. **Uncoordinated voltage control using RSC and GSC [19].**

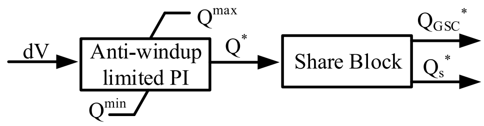

FIGURE 9. **Coordinated reactive power control using RSC and GSC [19].**

Considering the four reactive power control methods, it can be concluded that using RSC is more effective compared with GSC, yet the RSC may be disconnected by protection circuits in the case of sever disturbances. In addition, the coordinated reactive power control between GSC and RSC may be the best option, but it will increase the control scheme complexity [19].

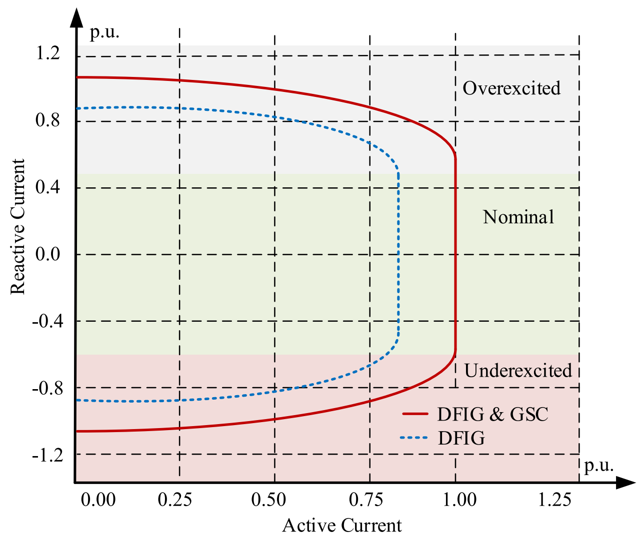

FIGURE 10. **Reactive current as a function of active current [21].**

a: COMBINED ACTIVE-REACTIVE CURRENT CAPABILITY

Figure 10 shows DFIG reactive current capability as a function of active current at nominal voltage. It can be seen from this figure that the reactive power capability of the DFIG alone is less compared to the GSC and DFIG capabilities combined. This is true in three operation regions, under-excited, nominal, and over-excited.

b: REACTIVE POWER CAPABILITY

Equations for power output can be expressed as [21]:

$$P = Re\{\underline{u}_S \underline{i}_S^*\} + Re\{\underline{u}_{GSC} \underline{i}_{GSC}^*\} \quad (6)$$

$$Q = Im\{\underline{u}_S \underline{i}_S^*\} + Im\{\underline{u}_{GSC} \underline{i}_{GSC}^*\} + q_{filter} \quad (7)$$

$$q_{filter} = \omega_s C_{filter} u_S^2 \quad (8)$$

The active power of the GSC can be calculated from the rotor power, considering the converter losses.

$$Re\{\underline{u}_{GSC}\underline{i}^{*}_{GSC}\} = Re\{\underline{u}_{R}\underline{i}^{*}_{R}\} + p_{loss} \tag{9}$$

Figure 11 shows the DFIG characteristics of reactive power against active power while considering active power and speed around the synchronous point at nominal voltage. It can be noted from this figure that a dynamic overload zone is allowed for a short period only in the nominal operation region and not in the overexcited and underexcited regions.

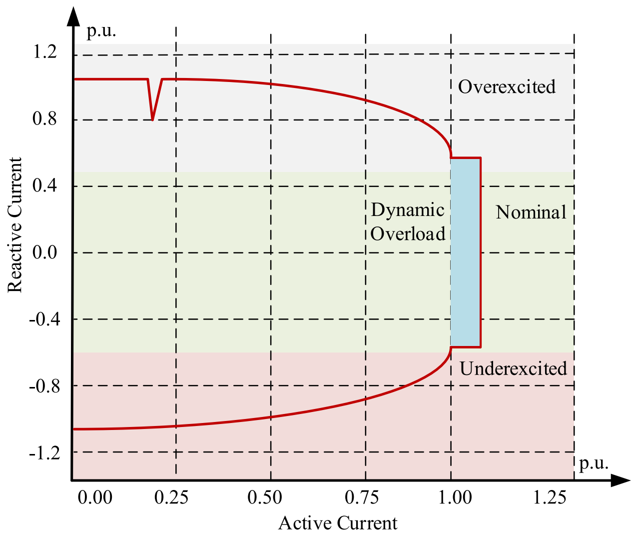

FIGURE 11. Reactive vs active power at nominal voltage [21].

B. VOLTAGE RIDE THROUGH

There are various voltage ride through techniques in literature. The most common voltage ride through techniques applied to wind energy conversation systems include energy storage system, crowbar protection, stator damping resistor and rotor current limiter, STATCOM, and dc-link copper. Figure 12 shows common voltage ride through techniques for the DFIG based WECS.

1) LVRT CAPABILITY USING ENERGY STORAGE SYSTEM

The energy storage system (ESS) is suitable for stand alone connection [25]. It is connected to the dc-link voltage. The advantage of this technique is the low cost since a simple buck/boost converter is required.

2) LVRT CAPABILITY USING CROWBAR PROTECTION

Crowbar protection is used to protect the power converters against high rotor current transients, in case of faults, by limiting the rotor current using short circuiting rotor using resistors [33]. The resistors ratings depend on the generator. The RSC is disabled when the crowbar protection is enabled. In other words, when the crowbar protection is enabled, the DFIG acts like squirrel cage induction generator and consumes reactive power.

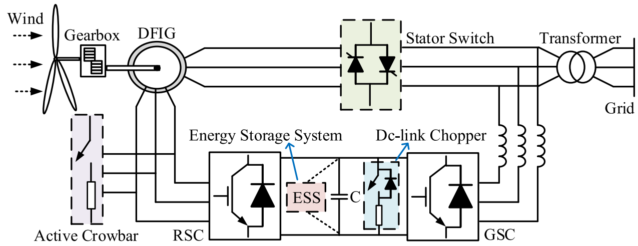

FIGURE 12. DFIG voltage ride through techniques.

3) LVRT CAPABILITY USING RCL AND SDR CIRCUIT

The rotor current limiter (RCL) and stator damping resistor (SDR) methods are used to limit the current by connecting a series resistor with the stator, in case of SDR, and the rotor, in case of RCL, and save the electric converters [33]. The main feature of RCL and SDR is that the DFIG system will not be disconnected like in the crowbar protection scheme, and it will still provide power during disturbances which will enhance the grid stability.

4) LVRT CAPABILITY USING CHOPPER CIRCUIT

LVRT using chopper circuit consists of a fast switching switch, usually Insulated Gate Bipolar Transistor (IGBT). The switching reference of the switch is determined from the dc-link voltage control. The main drawback of this technique is that it dissipates energy and does not store it like ESS, yet this method is cost effective compared with ESS.

5) OTHER LVRT METHODS

A consistent control method for parallel rotor side crowbar (PRSC) and series rotor side crowbar (SRSC) with the dc-link capacitor crowbar (DCCC) protections to the DFIG converters is presented in [26]. Another strategy that suggests connecting a set of resistors to the DFIG rotor in order to limit faults high current is presented in [27]. Reference [28] introduces improvement in the LVRT control by observing the stator-flux linkage components. The research article [29] investigates the application of a dynamic voltage restorer (DVR) which can be easily integrated with existing DFIG based WECSs. Reference [32] proposes that the DFIG should operate in a decoupled operation like an induction generator (IG) and as a reactive power source in the case of sever grid disturbances. Series dynamic braking resistor (SDBR) connected to the stator and dc-link chopper-controlled braking resistor with supplementary rotor current (SRC) control of RSC are discussed in [33]. Another interesting LVRT strategy which is DC-link controllable fault current limiter (CFCL) is presented in [35]. Another recent nonlinear scheme which aims to achieve a globally consistent power generation [73] and enhance LVRT is presented in [38]. More LVRT strategies for DFIG based WECS are available in [37].

C. POWER QUALITY IMPROVEMENT

The DFIG based WECS is traditionally used to generate active power, yet it can also operate as active power filter which can enhance power system quality by reducing the total harmonic distortion (THD) at the point of common coupling (PCC). Figure 13 shows how the DFIG system can act like an active power filter.

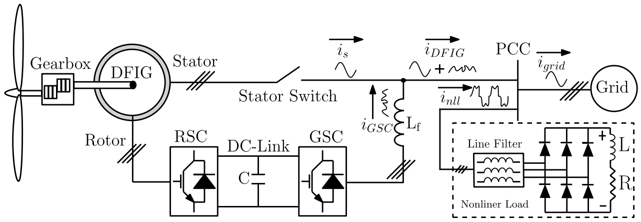

FIGURE 13. **DFIG system as active power filter.**

There are few research articles that address power quality improvement using DFIG based WECS. Reference [40] proposes a power compensation and a model predictive direct power control (MPDPC) technique to effectively eliminate distorted currents injected into the power grid by the DFIGs. Reference [41] applies feed-forward regulator instead of the resonant regulator to remove the DFIG stator current distortions rose by disfigured network voltage. Three schemes that can handle nonlinear unbalanced load current containing co-phasor components of a standalone DFIG are introduced in [42]. Reference [43] proposes a single resonant compensator tuned at six multiples of synchronous frequency in the rotor current controller to eliminate the DFIG stator voltage fifth and seventh harmonic. Reference [44] also proposes a 6n±1 harmonics resonant filter integrated to rotor current controller to reject both negative and positive stator voltage harmonics for stand-alone application. Reference [45] investigates voltage harmonics in DFIG caused by unbalance in stator and nonsinusoidal conditions in rotor. Reference [46] suggested to add a sixth-order resonant stator current harmonic controller to remove positive sequence seventh order and negative sequence fifth order DFIG system current harmonics. The effects of system harmonics and unbalanced voltages in DFIG connected to a network are explored in [47]. Other references such as [48] considered the power quality issues and improvements of DFIG wind farms. A detailed evaluation of advanced and recent active power filters that considers size, weight, and cost of electric converters used in wind energy conversion systems is presented in [49].

D. FREQUENCY CONTROL

Unlike the conventional synchronous generators, the increase in wind generators does not increase the system inertia. As a result, wind generation will have an impact on power systems frequency variations during disturbances. Therefore, wind turbines should adjust their inertial response characteristics to support system frequency variations [51].

1) INTEGRATING WTGS FOR FREQUENCY SUPPORT

Figure 14 shows a typical power system response after power loss. It can be inferred form this figure that larger systems

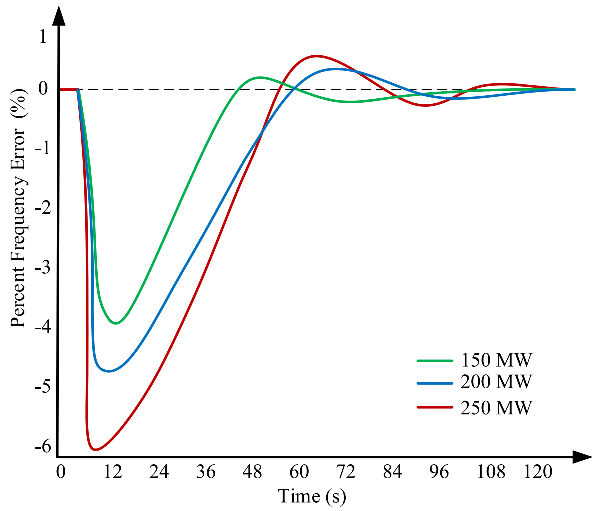

FIGURE 14. **Typical power system response after power loss [54].**

cause higher frequency error. Wind generators kinetic energy integration requires four aspects. First, in order to sense the kinetic energy variations, a frequency detector is needed. Second, a temporary huge kinetic energy discharge power pulse is also needed during governors delay. Third, a recovery period is required such that the wind generator returns to its nominal speed. Finally, pitch control support is desired.

2) ADDITIONAL FREQUENCY SUPPORT FROM DFIG SYSTEM

The DFIG system has the ability to support the system frequency variations by changing its inertial response by adjusting its rotational speed and electromagnetic torque. Since the DFIG has very small inertial response, the frequency nadir following a loss of generation can be significantly reduced. Important factors like current ratings limit the possible inertial response of DFIG. The response of a DFIG wind turbine for a frequency change can be explained using the torque-speed curves shown in Figure 15. When the generator speed is reduced due to frequency decreased, decelerating torque is induced. Also, the generator aerodynamic torque increases while the electromagnetic torque is reduced.

The DFIG system can be under loaded by changing the maximum power curve operating point. An increase in the rotor speed will increase the kinetic energy of the rotating mass. As a result, the frequency support provided to the network is decreased. A control strategy can be found in [52]. On the other hand, a decrease in the rotor speed will result in an increase in the kinetic energy given to the network which leads to a higher frequency support level. Factors such as the rotor maximum speed must not be exceeded in DFIG frequency support. Many research articles address the DFIG frequency control. For instance, [55] reports that long-term reset time can be countered using flux magnitude and angle controller (FMAC), and it is compared with classical synchronous generator control. Other study [56] proposes a control method that integrates energy storage system,

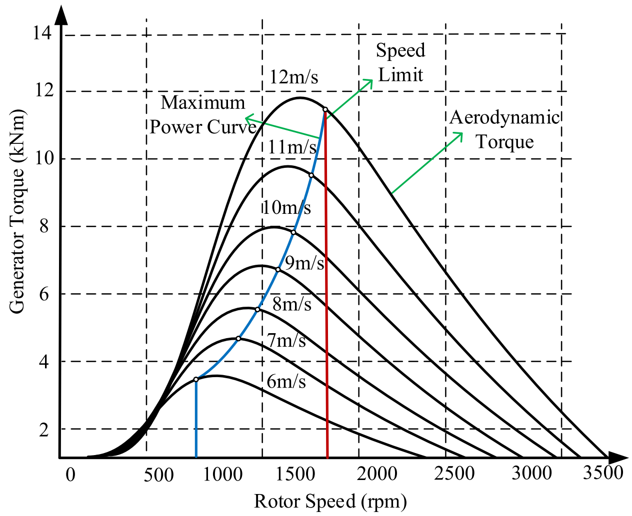

FIGURE 15. DFIG torque-speed curves [53].

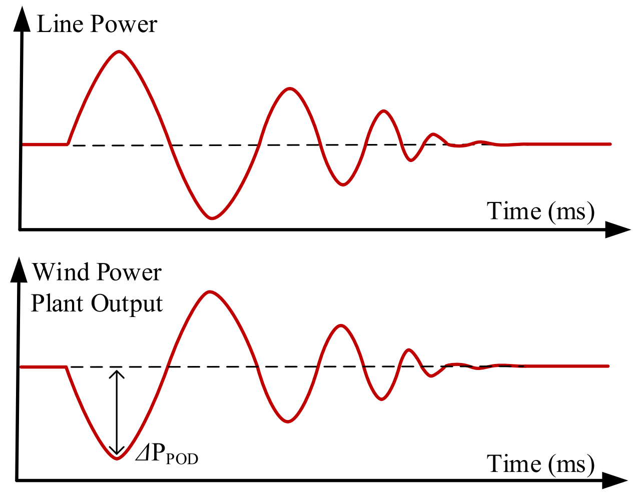

FIGURE 16. Wind power plant power oscillation damping [53].

approximately 10% of the generator ratings, with DFIG for frequency support. The paper [57] investigates the influence of DFIG penetration on frequency regulation in terms of artificial speed coupling, inertial response on the machine behavior, and impact of converter current limits and auxiliary loop parameters. A technique that is based on model order reduction (MOR) and subsequent online controller design for primary frequency and inertial responses is presented in [59]. A primary frequency control method based on using pitch angles is proposed in [60]. This method adjusts the mechanical power such that the power over frequency droop demand of the primary frequency response is contented. Another important aspect is tuning the controller gains. For instance, [61] considers tuning the PID controller gains using particle swarm optimization algorithm (PSO) to improve the frequency control by DFIG WECS. Additional optimization methods that can be used for turning the DFIG's controllers gains are presented in [74].

E. POWER OSCILLATION DAMPING

Power system oscillations can lead to instability and blackouts. WECS have the ability to damp inner wind turbine oscillations and power system oscillations [63]. Figure 16 shows the wind power plant oscillation damping concept. The wind power plant output power should be equal in magnitude but opposite direction compared with the system or network power.

Traditionally, oscillations are eliminated by power systems stabilizers (PSS). Power oscillations are either power system oscillations or machine oscillations. Power system oscillations are further classified into inter-area and local modes while machine oscillations are classified into drive-train and control modes. Oscillations categories are outlined in Table 3. In order to implement the suitable power damping control method, oscillation roots should be identified.

Fixed speed wind turbines have positive impact on power system oscillation damping. However, variable speed

TABLE 3. Oscillation classifications.

Oscillation	Mode
Power system oscillations	- Inter-area modes: 0.1-0.7 Hz - Local modes: 0.7-2 Hz
Machine oscillations >2 Hz	- Drive-train modes - Control modes

wind turbines behavior depends on the control algorithm. Frequency control has the ability to improve power system stability while voltage control affects the power damping. All in all, the power oscillation can be eliminated by mechanical elements like pitch control or by electrical elements such as converter control [63]. Various research studies consider DFIG to reduce the effect of power oscillation. For example, a control method, which is implemented to the RSC of DFIG for iner-area oscillation damping, is presented in [64]. Moreover, the article [65] investigates oscillation damping using GSC and RSC and proposes a multi-input multi-output state-space methodology to mitigate sub-synchronous interactions (SSI) for DFIG systems connected to series compensated lines. It is found that the power oscillation damping using RSC has better performance compared to RSC. In [66], a controller to damp inter-area oscillations is integrated to the DFIG classical control. Another [67] proposes a two-level hierarchical method for robust power oscillation damping. The method includes wide area centralized and local controls of the power oscillation damper (POD) installed with power system stabilizer (PSS) and DFIG based WECS. In addition, an inter-area power oscillation damping DFIG controller that is based on second-order sliding mode control is introduced in [68]. Reference [69] also proposes a prescribed convergence law algorithm, which is also a second order sliding mode strategy, for coordinated DFIG active and reactive powers oscillation damping control. Heuristic optimization control technique for coordinated power oscillation damping control of DFIG is proposed in [70]. The paper [71] considers an important aspect which is time varying signal latency when designing wide-area power oscillation damping controller. It is found that if signal latency occurs, the power oscillation damping controller will not be able to remove inter-area oscillations. As ideal communications can not be achieved in real world to solve this issue, latency issue is removed by an optimization strategy in the controller design stage. Finally, [72] proposes a specified structure mixed H_2/H_∞ control based on linear matrix inequality LMI technique for power oscillation damping using DFIG.

IV. COMPARATIVE STUDY AND VALIDATION

In this section, a comparative study is carried out for two specific ancillary services which are power quality improvement and reactive power control.

A. DFIG AS ACTIVE POWER FILTER

The configuration that is shown in Figure 13 is investigated in this subsection. Two harmonic mitigation control methods, classical PI control and method [75], are compared. Figure 17 shows the simulation results of the study. Figure 17(a) shows the nonlinear load phase-a current. It can be inferred from simulation results that both control methods achieve the main desired objective which is maintaining the dc-link voltage constant at specified reference. In addition, both methods help in reducing the current THD at PCC. However, the classical PI control method is not able to eliminate high current pulses in the grid current which is clearly seen in Figure 17(d). The second control method is able to remove the nonlinear load's high current pulses and obtain a clean grid current sinusoidal waveform as seen in Figure 17(f). This is a case when the PI classical control cannot achieve the control objective due to the fast change in the control variables. Even if the controller gains are increased or tuned very well and regardless of the tuning method, there will be an error between the reference and actual values.

The Fast Fourier Transform (FFT) results of the grid current using the two harmonic mitigation techniques are shown in Figure 18. In the normal operation case where no harmonic mitigation is used, the current THD is high (typically >20%), and the odd current harmonics are the most significant. On the other hand, when harmonic mitigation methods are used, the grid current THD is considerably reduced as shown in Figure 18(a) and Figure 18(b). The THD level reduction is related to the control technique, and it should comply with IEEE-519 standards [76] which states that the current THD should be <5%. Here, the second method meets the standards.

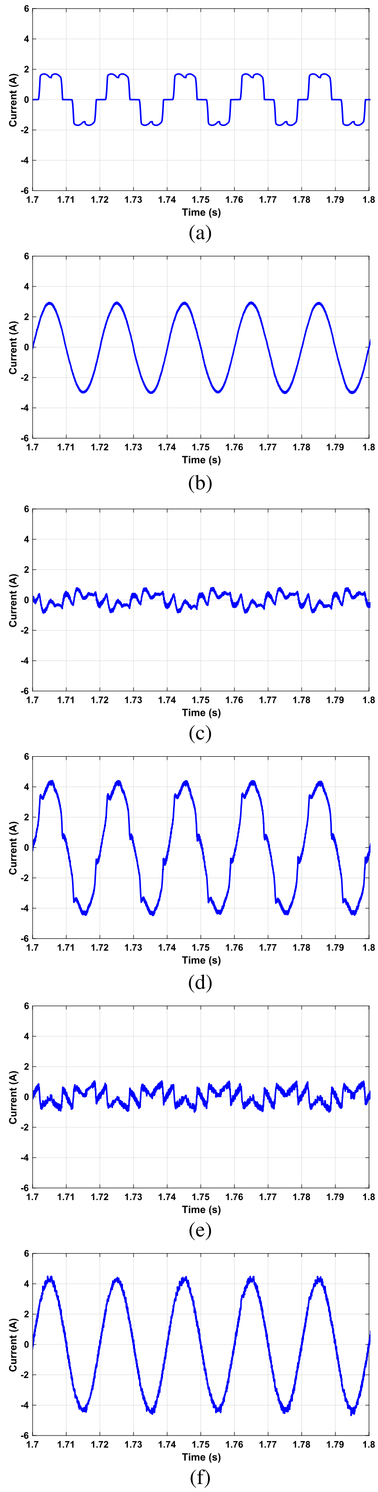

FIGURE 17. Simulation results: (a) Nonlinear load current phase-a (b) Stator current phase-a (c) Converter current phase-a method-1 (d) Grid current phase-a method-1 (e) Converter current phase-a method-2 (f) Grid current phase-a method-2.

B. REACTIVE POWER CONTROL

As discussed previously, the DFIG system is able to provide both active and reactive powers. In the following test, a step change in the DFIG stator reactive power is conducted. Five control methods, proportional integral (PI) control [11], H_∞ (Hinf) control [77], state-feedback with disturbance observer (SFDO) control [78], [79], state-feedback with high gain observer (SFHGO) control [80], and state-feedback with sliding mode perturbation observer (SFSMPO) control [23], are selected as examples and investigated in terms of transient

TABLE 4. Control techniques comparison.

Control Technique	PI	H∞	SFDO	SFHGO	SMPO
Design	Easy	Complicated	Easy	Moderate	Moderate
Implementation	Simple	Difficult	Simple	Moderate	Moderate
Performance	Good	Very good	Excellent	Very good	Excellent
Advantage	Simple	Performance Ensured	Performance Ensured	Estimated states	Less number of measurements
Limitation	Requires tuning	High computations effort	Requires model information	Estimation time	Chattering effect

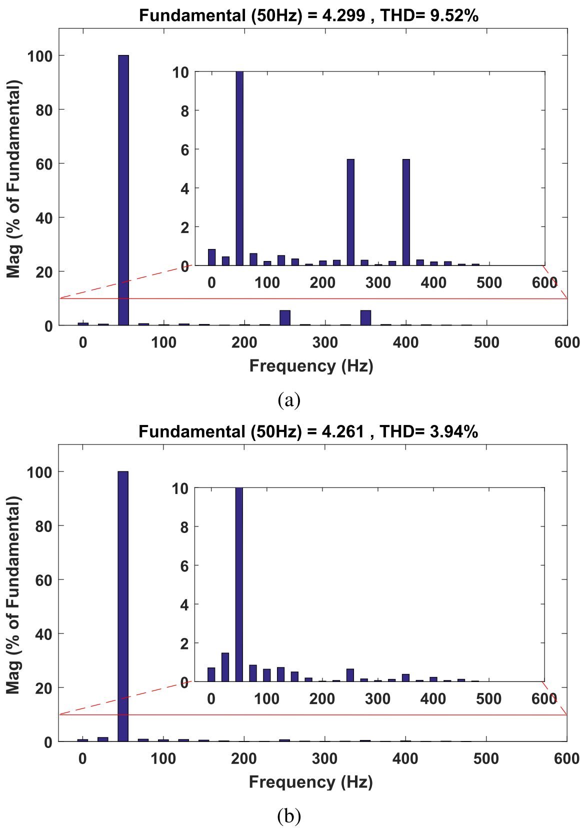

FIGURE 18. THD simulation results: (a) Grid current phase-a THD method-1 (b) Grid current phase-a THD method-2.

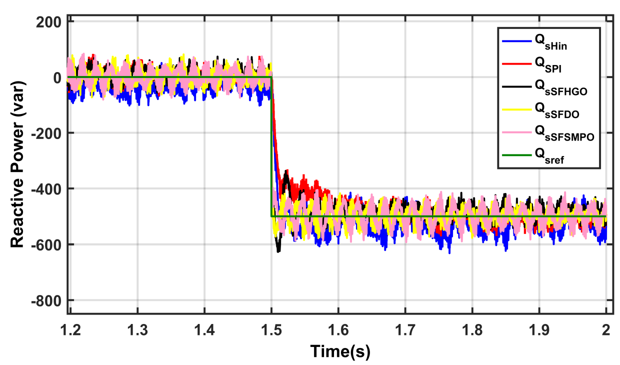

FIGURE 19. DFIG reactive power step change.

and steady-state performances. Figure 19 shows simulation results of the DFIG reactive power step change test.

The five control methods seem to have similar response in steady-state region. However, the transient performance can

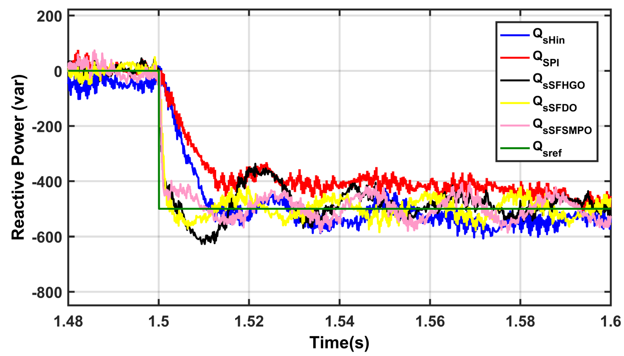

FIGURE 20. DFIG reactive power step change zoomed.

be further analyzed as shown in Figure 20. The PI control method requires more time to reach the reference reactive power value. The PI controller parameters are chosen using trial and error. The H_∞ control reaches to the reactive power reference faster than the PI controller. The H_∞ control has tradeoff between performance and robustness to uncertainties and disturbances. The controller weighting functions are choose to obtain a balanced performance in this test. The SFDO and SFSMPO have the best transient performance. The SFHGO control performance is similar to SFDO; however, during transients, the high gain observer needs time to force the estimated states to track their actual states. This will negatively affect the controller overall transient performance since the actual and estimated states do not match each others during transients. As a result, the state-feedback controller will see mismatched signal since it uses the state estimate as input. Table 4 summarizes the control methods performance in this DFIG reactive power test.

There are a lot of other novel control methods, and each method has its own advantages and disadvantages. However, conducting a fair comparison between them is a challenging task. Saying that one control method is better than the other is not necessarily correct. The controller effectiveness depends on the control objectives, requirements, and also on the system itself. In the end, all methods are used for one supreme purpose which is improving the DFIG base WECS services.

V. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The DFIG based WECSs have tremendous advantages. In addition to their main objective, providing real power, they can also assist power systems in terms of reactive power control, voltage ride through, power quality improvement, frequency control, and power oscillation damping. They may not completely replace the excising synchronous generators, but they can significantly enhance the power system operation. This can reduce the overall cost and eliminate the need for additional expensive correction devices. The simulation results indicate that improvements in control techniques can help DFIG to provide grid support in a better way. Future improvements can be brought to DFIG ancillary services in the following areas [81]:

- **Grid codes**: regulations are very important to manage the integration of renewable energies in general to the grid. Researchers should help in preparing standards which regulate and guide ancillary services usage.
- **Control methods**: investigating advanced control techniques shall improve the DFIG auxiliary services responses. The advanced control methods include but not limited to robust control methods, controller gains optimization, and composite control methods which include more than one control method. Control methods should focus on different levels such as device level, system level, and network level. For example, optimization techniques can be used to improve the coordination between GSC and RSC taking into account factors like power losses, lifetime, and converter limits.
- **Power electronics**: more efficient and reliable power converters will help to decrease the system overall cost and also improve the ancillary services performance. This topic include advanced power electronics devices and technologies. For example, higher capability power converters such as multilevel converters, H-bridge converter, and matrix converters are expected to replace the conventional power converters.
- **Energy storage systems**: as most of renewable energy technologies are unpredictable such as solar and wind, energy storage systems are an excellent solution to maintain constant power operation from renewable energy. This will certainly increase the reliability of the ancillary services provided by the renewable energy sources and make them available all the times even during power shortage periods.
- **Topologies**: hybrid topologies are among the most promising topics. Future hybrid topologies aim to include various techniques and utilize their advantages and overcome their drawbacks. For example, a solar energy conversion system can be integrated DFIG system to enhance the overall reliability of the system. The solar system may provide the ancillary services during day time and DFIG system may provide them during night or as per the system availability.
- **Ancillary services analysis**: the main objective of any energy conversion system is to provide power, and there should not be any compromises on the power system. Thus, future studies should further investigate the effect of ancillary services on DFIG complete reliability. For instance, the effect of components life time and effect of generated power properties can be investigated.
- **Other ancillary services**: other ancillary services include for example power system operation and security services. This contains for instance advanced communication techniques which maintain the power system reliability by the coordination between generation and transmission, and also between the existing network or grid support devices and DFIG ancillary services.

As wind power generation increases year after year, modern grid codes will force WECS to provide ancillary services in a better way and also include some services which are not currently obligatory such as power oscillation damping. At that time, utilizing the DFIG based WECS to provide ancillary services will not be just a feature; it will be a must.

APPENDIX

DFIG RATINGS AND PARAMETERS

Two DFIG practical ratings and parameters are summarized in Table 5.

TABLE 5. Practical DFIG ratings and parameters.

Parameters	Symbols	DFIG-1 [77]	DFIG-2 [19]
Rated power	P_r	2 kW	2 MW
Rated torque	T_r	13.3 Nm	12.7 kNm
Rated voltage (LL-rms)	V_s	415V	690V
Turn ratio	m	1/3	1/3
Stator resistance	R_s	2.26 Ω	2.6 mΩ
Rotor resistance	R_r	1.767 Ω	2.9 mΩ
Stator inductance	L_s	2.587 mH	20 mH
Rotor inductance	L_r	2.587 mH	20 mH
Magnetizing inductance	L_m	2.5 mH	325.3 mH
Number of pair poles	p	2	2
System frequency	f	50 Hz	50 Hz

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