Int J Syst Assur Eng Manag (December 2022) 13(6):2809–2832
https://doi.org/10.1007/s13198-022-01754-7

REVIEW PAPERS

Control of doubly fed induction generator for power quality improvement: an overview

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Received: 17 December 2021 / Revised: 10 July 2022 / Accepted: 29 July 2022 / Published online: 22 August 2022

Abstract Wind energy outweighs other kinds of renewable energy for endless harvestable potential. The integration of wind power into electric grids poses unique challenges because of its stochastic nature, causing a highly erratic generation of power. It affects the power quality and planning of power systems. This article outlines technical issues of wind power integration in the electric grid, providing the power quality interaction of the Doubly fed induction generator (DFIG) in the electric grid perspective. The prevalence of the DFIG in such large numbers necessitates this. An overview of different control strategies for power quality improvement of DFIG, application of energy storage schemes (ESS) and Wind power forecasting techniques, their requirements and advantages for facilitating increased penetration of DFIG in the electric grid is given. Robust integration and deeper penetration of wind power into the future electric grid necessitate balancing power quality improvement, energy storage technology, and wind power forecasting technique of the wind energy system.

Keywords Control strategies · Doubly fed induction generator (DFIG) · Power quality improvement · Electric grid · Wind power penetration

1 Introduction

Wind energy is mainly favored wind energy with respect to its technical and economical characteristics (Alam et al. 2020; Chen et al. 2019). Figure 1 depicts the various components of a wind energy system. However, the inherent variability of wind power, lack of control thereof and prediction complexity () make it difficult to store, posing a significant challenge in the proper operation of the electric grid. Employment of doubly fed induction generator (DFIG) in large variable-speed wind energy systems, as well as in stand-alone applications, is because of its ability to provide reactive power during grid faults and voltage support in low voltage conditions (Cardenas et al. 2013; Ren21 R 2016; Ahmed et al. 2020). DFIG configuration shown in Fig. 2 is a preferred choice in high-power grid-connected Wind energy conversion systems (WECS) due to the enormous economic gains (Ren21 R 2016). Nevertheless, the monetary gain is not considered in the case of stand-alone wind turbine systems, where the power level is relatively low (ranging from a few kilowatts to a few hundred kilowatts) (Carpinone et al. 2010).

DFIG can also extract the best wind power for extended wind speeds, reduced mechanical stress and four-quadrant operation. Table 1 summarize additional DFIG advantages over other wind turbine generator technologies (Failed 2021; Polinder et al. 2006; Datta and Ranganathan 2002; Zou et al. 2013). However, various power quality (PQ) issues persist due to DFIG's interaction with the electric grid. They vary under different conditions of wind and electric grid characteristics. Suitable Power quality improvement strategies are necessary to overcome this limitation for deeper penetration of wind power in the robust grid of the future. Improved power quality manages voltage compliance and eliminates pockets of mitigation of low voltage, while poor power

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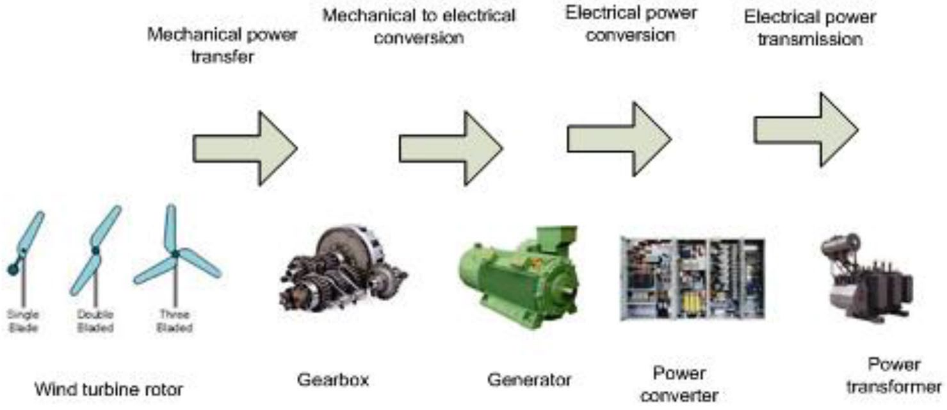


Fig. 1 Components of a wind energy system

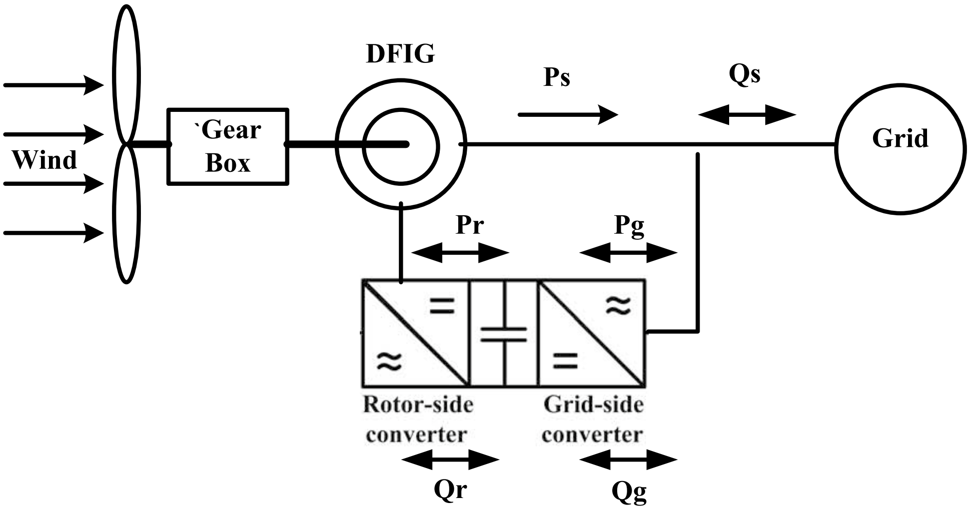


Fig. 2 Schematic of grid-connected DFIG

quality can cause various problems resulting in unstable utility systems and power disruption (Herbert et al. 2007). Poor grid power quality affects wind energy system generators' performance causing increased losses for the utilities and other consumers (Standard 2001).

Voltage unbalances, system harmonics and the harmonic grid introduces oscillations in the DFIG system output power, stator power, dc-link voltage and electromagnetic torque, resulting in unwarranted torque harmonics and inaccuracy in the active/reactive power generation, worsening the performance of DFIGs (Ackermann 2005; Nian et al. 2012).

In Fig. 3, the interaction between grid-connected DFIG and power quality phenomenon in correlation to the electric grid characteristics is established. IEC 61400-21 (Standard 2001) assesses the grid-connected wind energy systems regarding power quality. In addition, it describes the process for evaluating the wind turbine power quality features by analyzing flicker, wind turbine switching operation, and harmonics as illustrated in IEC 61000-4-7. This article attempts to provide an overview of different issues related to the interconnection of the DFIG wind energy systems in the electric grid. Additionally, categorization of control strategies for DFIG power quality improvement for increased wind power penetration in the electric grid was done.

In addition, technologies of ESS and methodologies of wind power forecasting were taken into consideration for an unprecedented number of options for energy production and consumption. This is due to the fact that in the not-too-distant future, the codes for the electric grid will take into account the possibility of microgrids, island grids, and ESS technologies qualifying for integration into the primary electric grid. This will enable the main grid to achieve optimal performance and provide grid resiliency to power quality issues.

The paper's organization is as follows: Sect. 2 evaluates various interconnection and power quality issues of grid-connected DFIG, paving the way to identify the most potential problems, followed by Sect. 3, where different control strategies for power quality improvement are discussed with respect to their advantages and drawbacks. Energy utilization of the DFIG wind energy system was outlined in the same section. It was accomplished using

Table 1 Comparison of Wind energy systems (*+ + is better than +, − is an undesirable aspect)

Parameters	Type A	Type B	Type C	Type D
Structure Complexity	+ +	+	+	−
Generator size, weight and cost	+ +, +, −	+, +, −	+, +, +	+, −, −
Generator maintenance cost	−	−	−	+
Investment cost	+	+ +	+	+
Cost	+ +	+ +	+	−
Grid connection	Direct	−	Partially via converter	Totally via converter
Power rating	−	+	+	+ +
kWh production	+ +	+ +	−	−
Converter type	Thyristor, low current	Thyristor, high current	IGBT, low current	IGBT, high current
Converter scale	−	−	30%	100%
Converter size	−	−	Excellent	Good
Size, Price, and maintenance of control module	Small, medium and Low	Small, medium and medium	Medium, medium and high	Large, high and low
Efficiency of control module	−	−	+	+ +
Torque density	−	+	+	+ +
Speed	Fixed	Limited Variable	Variable	Variable
Speed range	−	−	+	+
Short circuit (active)	Partly	Partly	Yes	Yes
Short circuit power	Contribute	Contribute	No	No
Standby function	Yes	No	Yes	Yes
Active-reactive control	Dependent	Separate	Separate	Separate
Operating current	Non-sinusoidal	Non-sinusoidal	Non-sinusoidal	Quasi-sinusoidal
Controllability	−	+	+	+
Grid friendly level	−	−	+	+
Cost of enhancing grid friendly capability	−	−	+	+
Grid support capability	−	+	+	+ +
Power factor	−	−	+	+
Power quality	−	−	+	+
Harmonic distortion control	−	−	+	+
Voltage fluctuation	High	Low	Low	Low
Endurable range of instant voltage fluctuations	−	−	+	+ +
Effect of grid voltage sag	−	−	+	+ +
Fault detection	−	−	+	+ +
Fault response duration	−	+	+	+ +
Maintenance	+	+ +	+	+
WT Suitability	Small	Small—medium	Medium—large	Small—medium
Efficiency	−	+	+	+ +
Reliability	+	+ +	+ +	+ +
Noise level	−	−	+	+

wind power forecasting tools and energy storage strategies (ESS). This was done to ensure the smooth functioning and continued development of DFIG wind energy systems, with the goals of achieving optimal performance and grid resilience in the face of power quality challenges. The conclusion is presented in Sect. 4, along with the future scope.

2 Grid connection issues for DFIG

Wind power penetration exceeding 10% affects the economic operation of a power system (Zou et al. 2013; Herbert et al. 2007). It involves voltage management, production efficiency, transmission and distribution efficiency, power reserves and wasteful energy (Ackermann 2005). Host

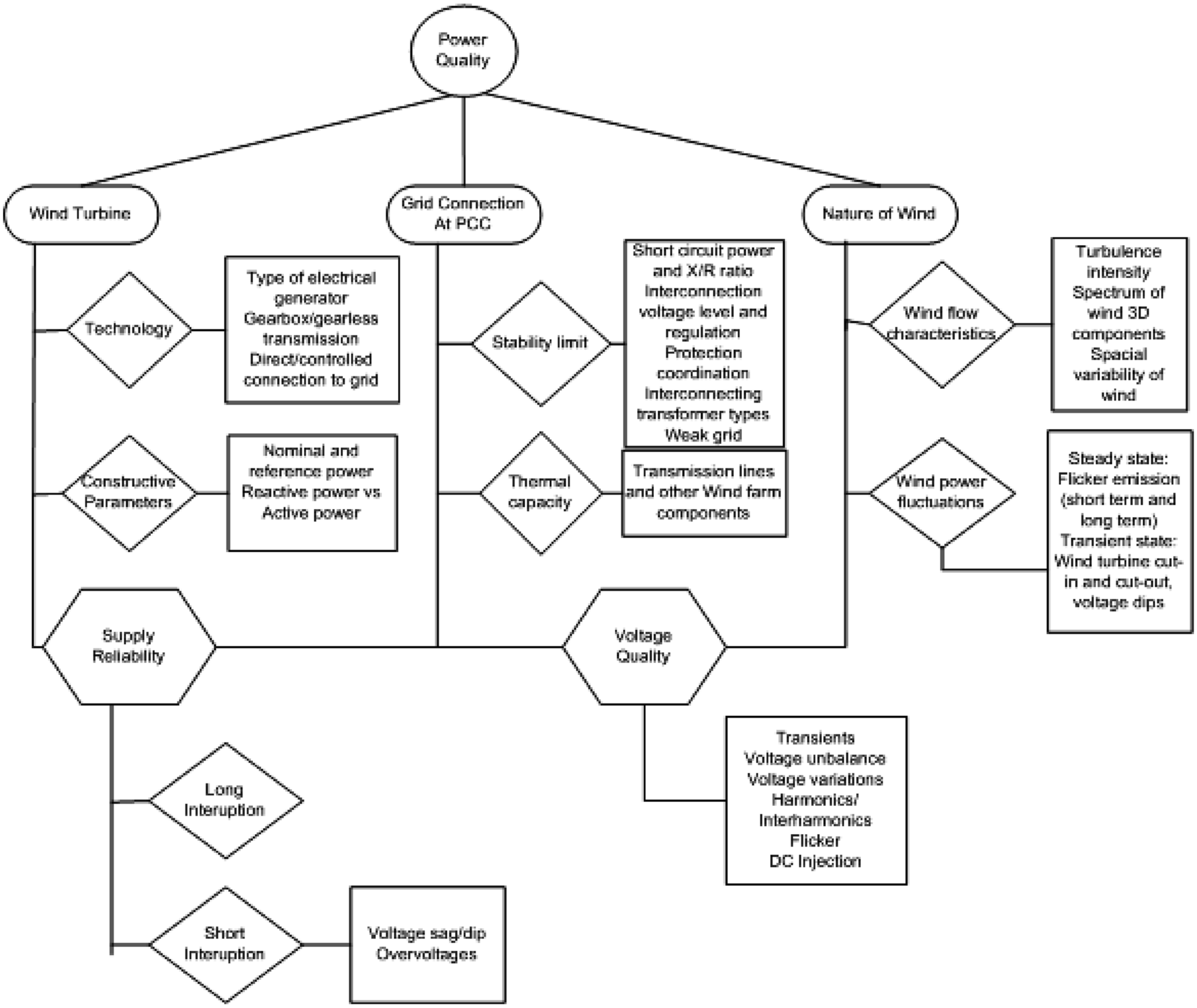


Fig. 3 Interaction of power quality phenomenon and DFIG wind energy system

utilities should tolerate system disturbances and maintain a smooth voltage profile at the interconnection point. In addition, protection against voltage flicker caused by wind gusts, along with stability for post-fault electromechanical swings in the electric grid, is necessary. Control is essential to eradicate torque and reactive power pulsations (Nian et al. 2012) under the unbalance in the stator currents for a DFIG-based wind energy system. This is because large oscillations occur because of disturbance in a weak system (Glover et al. 2012).

Interaction of the electric utility with the wind energy system influences power quality and is mitigated best at the point of interconnection of a wind energy system to the utility (Georgilakis 2008) since the wind energy power factor and active output power output influences reactive power, which in turn causes voltages variations at PCC of the wind energy system (Liu and Kong 2014a). The power quality of the WECS and how stiff or weak the electric grid is at the point of wind energy system connection influence the voltage quality of the electric grid (Glover et al. 2012; Etxegarai et al. 2015). In more substantial parts of the electric grid, the sensitivity of customers to the power quality issues resulting thereof wind power connection reduces. Grid strength is characterized by the Short-circuit power level, applicable to the point of common coupling (PCC) of the electric grid (Etxegarai et al. 2015). Short-circuit power level measures current passing in a network installed with a wind energy system under fault conditions. Its consideration is vital for power quality issues on the grid and is represented as,

$$S_{sc} = U_{grid} I_{sc}^{*} = U_{grid} U_{grid}^{*} / Z_{grid} = U_{grid}^{2} / Z_{grid} \quad (1)$$

S_{sc}—Short-circuit power level, U_{grid}—Grid voltage, I_{sc}^{*}—Short-circuit current, Z_{grid}—Grid impedance.

From above equation, the voltage at PCC under normal grid operation:

$$U_{PCC} = U_{grid} - \left(I_{load} - I_{turb}\right)Z_{grid} \quad (2)$$

UPCC—Voltage at PCC, I_{load}—Current through load, I_{turb}—Current through turbine.

The above equation implies that lower grid impedance causes load and turbines to have less impact on PCC voltage, and a more robust grid has a higher short-circuit power level related directly to the ability of the grid to withstand disturbances.

Short-circuit power level may be low at PCC in wide-area weak power grids as the AC system impedance may be high relative to AC power (Pepermans et al. 2005). However, Short-circuit ratio (SCR) is more convenient to justify generation connected to the PCC. The grid topology or size of each country or region decides the ratio between the grid short circuit capacity of the grid and the wind power installed. It represents the grid strength with respect to the amount of wind power interconnected (Farias et al. 2010) as,

$$SCR = S_{sc} / S_n \quad (3)$$

S_{sc}—Short circuit capacity, S_n—Rated power of wind turbine.

SCR values above 20 (Tande et al. 2007) to 25 (Feltes and Fernandes 2012) indicate a strong grid and weak for SCR values below 6–10, though these values vary in various literature. Low SCR is a concern for values of 5 or below (Farias et al. 2010). The system weakens with outages as reactance between the turbines and the system increase, resulting in lower levels of the SCR. DFIG interaction with the weak grid is accounted for by design parameters, nature of wind, and grid condition, as illustrated in Fig. 4.

DFIG wind energy systems are nonlinear and the presence of uncertainties results from wind speed causing electromagnetic torque to be a nonlinear function of the stator and rotor currents (Xiaodong et al. 2010). For a DFIG wind energy system, an unbalanced stator current could result from slight stator voltage imbalances that are unaccounted in the control system of DFIG. Unequal heating on the stator winding as well as torque and power pulsation in the generator results in unbalancing beyond a limit. Wind energy systems switch out of the network, further weakening the grid performance (Abo-Khalil et al. 2007). The various power quality issues of grid-connected DFIG discussed below:

2.1 Harmonics

Harmonics generated by DFIG wind energy systems are termed as higher-order fundamental frequency integer multiples. The back-to-back (B2B) configuration of DFIG introduces harmonics. Both stator and rotor of DFIG have harmonic components under different conditions:

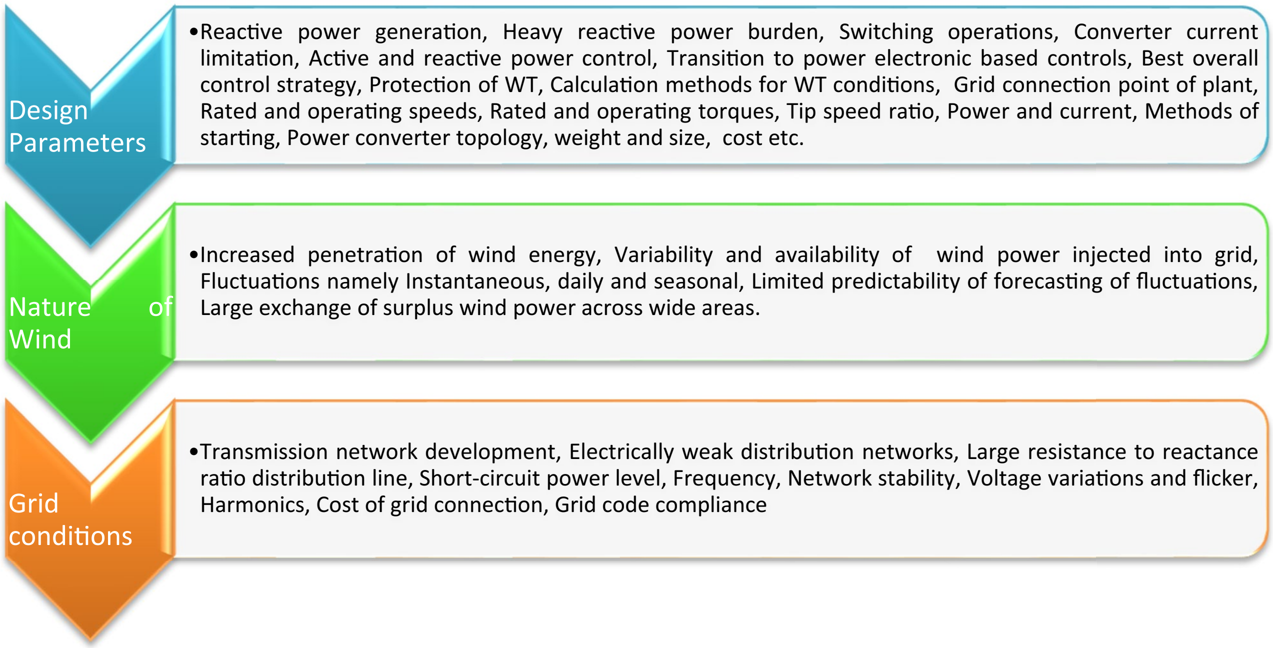


Fig. 4 Major contributors to power quality issues in weak grid

- Non-sinusoidal rotor voltage injection (Rotor harmonic components) (Xiaodong et al. 2010)
- Unbalanced grid voltage (Stator harmonic components) (Pepermans et al. 2005)
- Harmonically distorted grid voltage and its interaction with unbalanced grid voltage (Stator harmonic components) (Fathabadi 2014).

Harmonics due to the switching operation of the diode rectifier (mainly low order harmonics) and the rotating magnetic fields stemming from the rotor current harmonics induce rotor current and stator current harmonics. The dc-link voltage oscillations are less concerned as they are small (Yang et al. 2012). Limitations in control of rotor voltage and GSC current components cannot eliminate all the harmful effects caused by distorted grid voltage.

Variations in reactance due to slots generate harmonics in DFIG, whose magnitude and frequency depend on rotor speed and vary from balanced to unbalanced load conditions (Agrawal et al. 2015). 6 k ± 1 order harmonics generated by six-step switching cause quasi-sine wave rotor voltage. Machine design limitation creates non-sinusoidal air gap flux causing harmonics called MMF space harmonics. Mechanical design of the DFIG and RSC gives rise to stator harmonics and inter-harmonics. The design of stator, rotor windings, and slots generate MMF space harmonics and slot harmonics (Agrawal et al. 2015; Shafiullah et al. 2013).

2.2 Unbalanced voltages

- Asymmetrical and/or unbalanced grid voltage is the first abnormal condition that affects the operation of a DFIG.
- The distorted grid voltage is the second abnormal condition, which results in an effective decrease in the DFIG performances (Abo-Khalil et al. 2007).
- The third abnormal problem is non-sinusoidal rotor voltage injection that effectively reduces the performance of a DFIG (Tande et al. 2007).

Ample torque and stator oscillations, unbalanced stator and rotor currents due to unbalanced voltages result in increased machine losses (Rodríguez et al. 2012), and DC-link voltage pulsation affects its life. To understand the behavior of the output active and reactive powers of DFIG connected to an unbalanced grid, the symmetrical components theory is necessary (Georgilakis 2008; Fathabadi 2014). In order to achieve tracking of instantaneous active and reactive powers reference values for eliminating resulting oscillations, proper strategies applied, utilizing the DFIG's rotor voltage or rotor current, acting as control inputs (Farshadnia and Taher 2014).

2.3 Voltage dips

Voltage dips are brief reductions in voltage, lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds, usually calculated for each half-period and measured by the RMS value; The duration is defined by the length of time the voltage is less than 90% of the nominal value (Sun et al. 2005). Voltage dips at the PCC result in high current flow in DFIG stator winding propagating through the rotor due to the magnetic coupling. Assessment of sudden voltage reduction assumes that a voltage change factor, k_u (ψ_k) (Tande 2005) characterizes each wind turbine:

$$d = 100k_u(\psi_k)\,(S_n/S_k) \tag{4}$$

d—depth of voltage dip, $k_u(\psi_k)$—voltage change factor, S_n—rated apparent power of the wind turbine, S_k—short-circuit apparent power of the grid.

The above equation does not consider the number of wind energy systems as a simultaneous startup is unlikely in a wind farm at the exact same time (Xie et al. 2013).

Severe voltage dips induce emf in the rotor windings as the maximum value of induced rotor voltage during the dip, V_{r0} occurs at the instant of voltage dip and rotates in reverse with respect to rotor windings. Under rating of converter for a voltage lower than V_{r0}, cause rotor currents to be uncontrolled transitorily resulting in over-currents. The amplitude of these over-currents depends on the depth of the dip, maximum voltage of the converter, machine parameters and protection elements (Lopez et al. 2007). Stator flux cannot evolve to its final steady-state as quickly as stator voltage under sudden voltage dip.

In the steady-state operation of DFIG, for sudden voltage dip, sudden rotor voltage change should accompany a sudden change in stator voltage to avoid a significant increase in rotor current (Vidal et al. 2013). Supervising the rotor over current and dc-link overvoltage through PLL or synchronizing methods detects grid voltage dip (Abad and Iwanski 2014). During an asymmetric voltage dip, a voltage dc component or combination of dc and reverse-rotating ac components in air-gap flux, depending on the fault type, induces a high voltage in the rotor windings at rotational and/or double the rotational frequency, which causes the RSC to lose its ability to control the amount of current flowing through it (Kanjiya et al. 2014). This necessitates the consideration of stator flux dynamics. The design methodology necessary for DFIG to withstand voltage dips should have the following approach (Vidal et al. 2013):

- DFIG design: for rapid stator flux damping.
- B2B converter design: increased dc-bus voltage and current at maximum ratings.

2.4 Flicker

The visual fluctuations (frequency spectrum of 0.05–35 Hz (Tohidi and Behnam 2016; Ammar et al. 2011) in the light intensity (Saqib and Saleem 2015) because of periodic disturbances in the network voltage caused by grid power flow changes are termed as flicker. Continuous switching or start-up (at cut-in speed and rated speed) operations (Kasem et al. 2010) of wind energy systems cause flicker. IEC 61400-21 provides a calculation methodology for flicker emission of wind energy systems under both operation cases (Saqib and Saleem 2015). Specific frequencies cause small but persistent voltage fluctuations to be annoying. Flicker becomes a PQ issue at the PCC of a wind farm for short-circuit ratio (SCR) less than 10 and grid impedance ratio less than 2. Flicker emission levels reduction involves:

- Increase in distribution line voltage levels higher than 35 kV
- Higher inertia of large WTs
- Injection of net active power into the grid from energy storage
- Exchange of reactive power with grid (Díaz-González et al. 2012; Rodríguez Amenedo 2003).

Dynamic changes arising from wind speed fluctuations (causes flicker for frequencies lower than that of drive train), turbine mechanical design (flicker due to tower shadow effect), and rotational speed of the machine (3p torque oscillations between 0.5 and 1.5 Hz) are sources of flicker emission (Rodríguez Amenedo 2003; Bevrani et al. 2010). Other factors are power output of WT at connection point or PCC and type of WT technology. Flicker emission studies consider renewable energy generators' operation under the unity power factor accounting for its intermittency and grid impedance angle, operating power factor and short-circuit capacity (International Electrotechnical Commission 2008). The flicker level is quantified by the short-term flicker severity value P_{st}, and allowable voltage change as a function of frequency is $P_{\mathrm{st}} = 1$. The flicker emission from variable-speed turbines is low compared to flicker emission from fixed-speed turbines. A normalized measure of the flicker emission during wind turbine continuous operation is given as,

$$c\left(\psi_k\right) = P_{st}\left(S_k / S_n\right) \tag{5}$$

P_{st}—flicker emission of the wind turbine, S_n—rated apparent power of the wind turbine, S_k—short-circuit apparent power of the grid.

A normalized measure of the flicker emission due to a single switching operation:

$$k_f\left(\psi_k\right) = (1/130)\left(S_{k,fic} / S_n\right) P_{st,} T_p^{0.31} \tag{6}$$

T_p—voltage variation duration due to switching operation; P_{st}—flicker emission of the wind turbine; S_n—rated apparent power of the wind turbine; S_k—short-circuit apparent power of the grid.

IEC 61,000–3-7 (International Electrotechnical Commission 2008) has standards of 0.35 and 0.25 for short-term flicker severity index and long-term flicker severity at wind farm PCC. In Fig. 5, the performance evaluation of the grid-connected DFIG wind energy system concerning power quality disturbances is shown.

Similarly, Fig. 6 shows the impact of individual PQ disturbances on DFIG stator voltages and currents.

3 Power quality and utilization of grid connected DFIG

3.1 Control strategies for PQ improvement

The selection of control strategies for PQ improvement depends on the power quality issues and interconnection point of the DFIG in the electric grid. Usage of control strategy for power quality (PQ) improvement regulates active power and reactive power, also accounting for a proper level of Dc link voltage (Bevrani et al. 2010). Different control strategies for the same are discussed below.

3.1.1 Direct power control (DPC)

Conventional DPC methods utilize a predefined lookup table for voltage vector selection to take into account voltage unbalance and control the generator output quantities. For DPC, feedback variables constitute torque and active and reactive powers of the DFIG stator (Yan et al. 2021; Razali et al. 2015). Accurate and prompt calculation of the active and reactive power is detrimental to the performance of the direct power control (DPC) scheme. It does not depend on DFIG system parameters. It is a reasonable solution for sudden voltage disturbance and imbalance ride-through applications for DFIG wind energy systems (Gao et al. 2021a). However, this scheme is unsuitable for generator speed control, and the performance of maximum power point tracking (MPPT) can be degraded. It also requires high switching frequencies increasing the computational burden (Razali et al. 2015).

A modified DPC with sequence domain control (SDC) (Baggu et al. 2015) for the GSC of DFIG is suitable for both continuous and sudden disturbances like system faults. A VPI-based DPC strategy (Gao et al. 2021b) for DFIG successfully achieves the smooth, active and reactive power output of DFIG under the harmonic voltage. A Coordinated

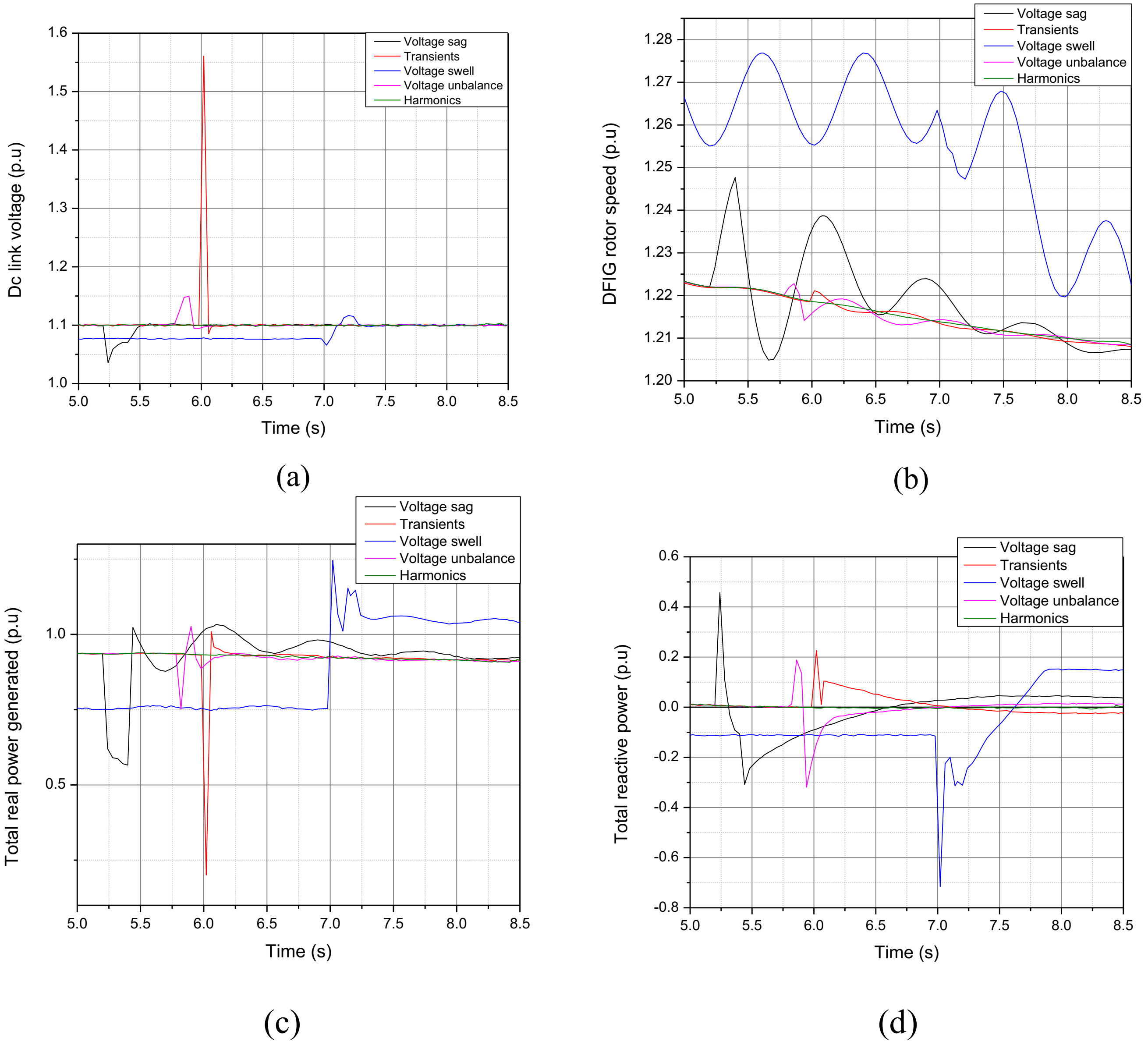
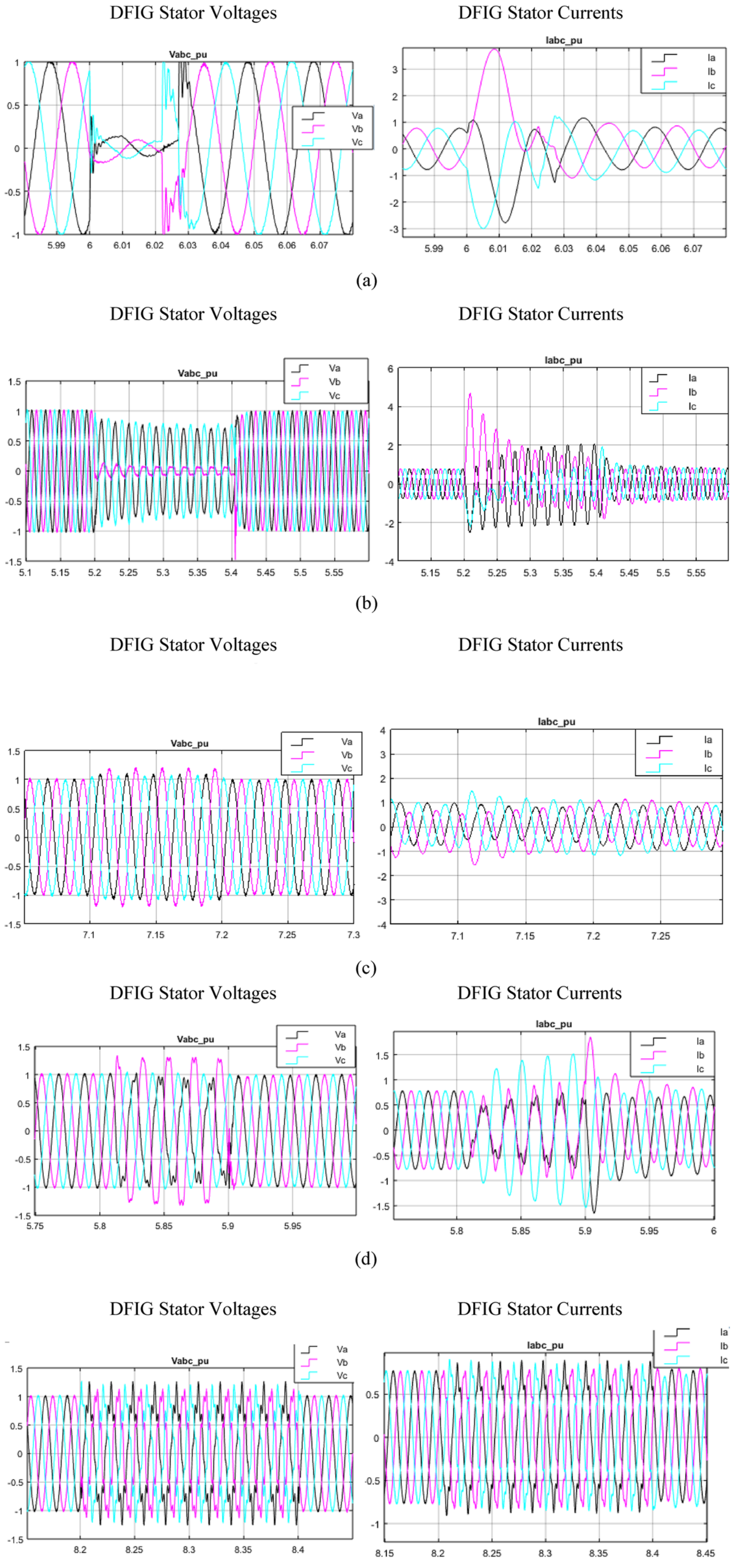


Fig. 5 Effect of PQ disturbances on **a** Dc link voltage **b** DFIG rotor speed **c** Total active power generated **d** Total reactive power

DPC scheme (Li et al. 2018) for RSC and GSC of DFIG uses a single-side resonant controller (reduced-order vector integrator (ROVI)) to avoid the complex calculations of the power compensating components. An SVM-DPC with a PI-R controller (Nian et al. 2015a) incorporates multiple complex coefficient filters (MCCF) for a grid-connected voltage-source inverter and compromises the fundamental negative sequence current and the output power ripples. An improved DPC with duty cycle control (Zhang et al. 2019a) for a PWM rectifier obtains Active and reactive power regulation, power ripple reduction and more sinusoidal grid current at a much lower sampling frequency achieving strong robustness against inductance variations.

The main DPC scheme with an auxiliary demagnetizing current control scheme (Nian et al. 2015b) for RSC of DFIG provides shorter and smoother dynamic responses of the DFIG under transient frequency variation along with damping of the natural flux linkages. In (Yan et al. 2019), the RSC control by a modified DPC scheme and GSC control with a PI-R controller tuned at sixth the network voltage frequency significantly improves DFIG performance connected to a harmonic network. In (Mohammadi et al. 2014), an innovative combined control considering the structure of VC (stator-voltage-oriented frame (SVOF)) and DPC has been presented for the RSC of the DFIG providing a compromise of the advantages of the two methods. Sliding mode control



(a)

(b)

(c)

(d)

(e)

Fig. 6 DFIG Stator voltages and currents in presence of **a** Transients **b** Voltage Sag **c** Voltage Swell **d** Voltage Unbalance **e** Harmonics based DPC (Shehata 2015) for RSC of DFIG provides low harmonics current in DFIG and minimal power oscillations.

A simple and robust integral sliding mode current-based (ISMC + CB-DPC) approach (Zhang et al. 2019b) for a DFIG-based wind energy system provides a better transient response and eliminates steady-state errors. In (Yongchang and Jiang 2021), the synchronous reference frame defines the oscillating terms of the B2B (back-to-back) converter of DFIG. This allows for simplified power terms extraction allowing for an improved DPC technique that achieves the control targets of reduction in unbalanced stator current, torque and power pulsations, and constant power output under network unbalance. Work (Xiong and Sun 2016) presents an improved DPC combined with a nonlinear backstepping-based algorithm for DFIG under harmonic grid voltage. It provides decoupling control of the active and reactive power of the DFIG in the absence of a PI controller. It achieves performance comparable to the resonant-based controller for harmonic current suppression. Research work (Zhang and Jiang 2021) proposes space vector modulated direct power control based on proportional-integral-resonant (PI-RES) controller for VSC under unbalanced network conditions. This strategy introduces a particular ac reactive power reference component to reduce dc-bus voltage ripple and active power harmonic components simultaneously.

3.1.2 Sliding mode control (SMC)

Sliding mode control has reduced reference values for maximum power tracking controller to obtain reduced induced torque oscillations. It has several advantages such as fast dynamic response, good disturbance rejection, and robustness against parameter variations or grid disturbances and easy implementation. However, the chattering phenomenon is the main drawback, causing low power quality and instability of systems (Zin et al. 2013).

For harmonic compensation, SMC combines with conventional control. The active and reactive power control using the SMC combined with the PI control is investigated in Zhang et al. (2020) for fast load-voltage regulation and unbalanced voltage compensation. Work (Babaei et al. 2010) proposed a combination of SMC and PR control strategies to regulate the load voltage rapidly under unbalanced and distorted voltage. To enhance the transient and steady-state responses in a stand-alone mode, the sliding mode repetitive control scheme eliminates periodic harmonic disturbance (Teodorescu et al. 2011). Multi-resonant SMC scheme (Shtessel et al. 2014) reduces tracking error and THD under grid-connected mode.

A novel SMHC scheme that is a non-selective harmonic compensation method (Kang and Kim 2015) enhances the power quality in a grid-connected inverter when non-linear loads pollute the grid. It eliminates mainly harmful low-order harmonics with robustness and fast dynamics. An ISMPC algorithm (Hemdani et al. 2015) operating with constant switching frequency for a three-phase grid-connected power converter provides a fast transient response, low current THD, and robustness against parameter variations and external disturbances. Under an unbalanced and harmonically distorted grid, an SMC-based control algorithm (Martinez et al. 2012) was proposed for DFIG converters.

A complete solution based on SMC controls the DFIG converters' average active and reactive powers with constant switching frequency (Martinez et al. 2013) and provides robustness against parameter deviations. Model reference adaptive system observer-based sliding-mode control (MRAS-SMC) (Susperregui et al. 2014) for DFIG achieves improved performance and fault detection mechanism for sudden or excessive parameter variations in grid-connected and islanded modes. A robust discrete sliding mode control (Pande et al. 2013) for DFIG under (1) parametric uncertainties, (2) system disturbances and (3) voltage sag in the grid voltage demonstrate the controller's effectiveness in providing a fast system transient response, with the real and reactive powers tracking their references smoothly even in the presence of speed variations. A robust ISMC (Kassem et al. 2013) controls the flow of active and reactive power between the DFIG and the grid for variations in machine parameters. This achieves reduced chattering with an appropriate finite gain and zero steady-state error.

Undesirable mechanical stresses and the chattering phenomena of SMC can be avoided using a higher-order sliding mode control (HOSMC) (Abdeddaim and Betka 2013) for controlling the RSC of DFIG and achieving flexibility between the ''Tracking mode'' and the ''Power regulation mode'' without the negative effects of synchronous speed overshoot. Research work (Djerioui et al. 2014) provides a technique of sliding mode observer for implementing sliding mode controller of PWM rectifier. This article presents the design of a sliding mode controller using a technique that aims to simplify the control procedure. This includes (1) control of virtual flux, (2) direct control of power switches, and (3) reducing the number of sensors required for robust control against load and line variations. Control of RSC and the GSC of the DFIG to overcome inter-area oscillation for a multi-machine network with a new fast adaptive FABTSMCPCS (Fast adaptive back-tracking sliding mode control) (Patnaik and Dash 2016) utilizes dynamic equations in terms of the active and reactive power components of the stator and GSC of DFIG. It also overcomes unpredictable wind speed variation and consequent power output fluctuation in the absence of PLL.

3.1.3 Repetitive control (RC)

Repetitive control is based on the internal mode principle (Wieland et al. 2011). Periodic disturbances are rejected, and references are tracked at the same time. The repetitive controller has significant gains for harmonics at integer multiples of the fundamental frequency (Wang et al. 2009). Conventional RC regulator modification is necessary for grid frequency deviation in order to compensate for deterioration in the capability of DFIG stator harmonic current suppression.

Odd-harmonic RC (Hornik and Zhong 2011; Escobar et al. 2008), which takes advantage of the fact that the frequency spectrums of the vast majority of AC systems only contain odd harmonics, has an inherent time delay equal to half the period of an entire cycle. As a result, its dynamic response is significantly faster than that of conventional RC. However, that may not be sufficient to deal with disturbances caused by the grid voltage, such as swell or sag. This could result in the inverter generating an output current much higher than the reference current. Relying on RC alone to deal with such disturbance could cause the current error to be too high during the RC convergence time, which could cause an overcurrent fault. Work in Chen et al. (2013) eliminates the $6n \pm 1$ harmonic components using RC. For a Dual mode-structure RC (Sha et al. 2011) convergence rate for error is improved.

A cascaded current–voltage control strategy for inverters using an $H\infty$ repetitive controller (Zhong and Hornik 2013). It simultaneously improves the power quality of the load voltage, and current exchanged with the grid. Sinusoidal current injected into the utility grid using a current control strategy (PI controller + RC) (Trinh and Lee 2014). Fast convergence and high tracking accuracy achieved with robust RC incorporating time-varying sampling periods (Kurniawan et al. 2014). Digital $nk \pm m$—order harmonic repetitive control ($nk \pm m$RC) scheme (Lu et al. 2014) efficiently mitigates $nk \pm m$—order harmonic frequencies in PWM converters. An improved RC regulator (Song and Nian 2015a) based on a conventional RC regulator for DFIG achieves good stator current harmonic suppression for the entire harmonic frequency spectrum. Research work (Abusara et al. 2015) implements a frequency adaptive odd-harmonic RC with a feed-forward loop at the fundamental frequency to ensure the current bounds for the convergence period of the RC. Authors in Song and Nian 2015b suppress stator current harmonic distortion of DFIG based on the BRC regulator.

3.1.4 Predictive control

The predictive control minimizes the forecast error to track the reference current without any error. It provides many benefits like reduction in torque and flux, active/ reactive power ripples, constant switching frequency, and excellent steady-state and transient responses. Nevertheless, it is sensitive to parameter changes due to the mathematical approach. The least-square method for parameter estimation improves the accuracy of control. A predictive dc-link voltage control (Yin et al. 2014) prevents Dc-link voltage fluctuation with the exact execution of the current reference. Work in Shi et al. (2020) implements a simple and robust Predictive Direct Virtual Torque and Power Control (PDVTC + PDPC) for RSC of DFIG to improve the power quality (Voltage and Frequency) in no-load mode; regulate active and reactive power in grid-connected mode.

Model predictive control (MPC) popularity is due to its flexible control scheme and accommodates system constraints and non-linearity easily. Depending on the application, the control objective varies (Cortes et al. 2012). It predicts the system behavior with the aid of a model to obtain the control signal by minimizing the objective function and selecting optimal switching states with a cost function as a criterion (Rojas et al. 2013). MPC performs an optimization procedure to calculate optimal control actions at each sampling interval. However, variable switching frequency achieves acceptable control results with relatively high sampling frequency and is unable to incorporate the modeling errors.

Research in Rahoui et al. (2021) proposes a model predictive control strategy for grid-connected inverters for renewable power generation to achieve islanded operation, grid synchronization and grid-connected operation. This done by changing the cost function appropriately to achieve different control objectives. Work in Liu and Kong 2014b presents an IOFL MPC for DFIG under normal and unbalanced grid conditions. Duty cycle control utilized in an improved low-complexity model predictive power control (MPPC) (Zhang et al. 2014a) for grid-connected power converters to reduce power ripples and current THD in conventional FCS-MPC. Model predictive current control (MPCC) has advantages, such as flexibility in controlling different variables, inherent decoupling behavior, fast dynamic response and easy inclusion of non-linearities and constraints (Pavlou et al. 2012). It is of some significance to achieve the source voltage sensorless control of the MPCC.

Unlike the traditional modulation-based algorithm, the MPCC needs the mathematical model of the converter to predict future currents. Hence, inaccuracy of the model parameters affects the control effect of the MPCC (Rodriguez et al. 2013). Because of this, the accuracy of the source voltage observation is further impacted. Owing to the above reasons, multivariable observation is necessary for the source voltage sensorless control of the MPCC. In the traditional current control strategy, multivariable observation has been widely studied. Some articles proposed parallel adaptive observation (Xiao et al. 2016), in which more than one observer estimates parameters and exchanges observation results. An improved MPCC (Liu et al. 2014) for a grid-connected converter with the newly designed HPO containing two parallel observers: linear extended-state observer (LESO) and adaptive filtering parameter observer (AFPO) is presented for wind energy system providing good stability, accuracy and reliability.

Authors in Song et al. (2013) introduce a robust model predictive current controller. Enhanced performance and disturbance compensation of the control obtained with an extended-state observer (ESO) with SVPWM. Work in Errouissi et al. (2017) utilizes a disturbance observer and predicts the stator current in the synchronous reference frame in the presence of model uncertainty and external perturbations. This achieved using Taylor series expansion over a finite time horizon. Simple design parameters aid the steady-state and transient performances.

3.1.5 Model predictive direct power control (MPDPC)

Model predictive DPC (MPDPC) effectively selects voltage vector and is more accurate (Ran et al. 2021; Camacho and Alba 2013; Xiao et al. 2021). Steady-state performance enhanced even in power ripples and current harmonics. It utilizes a cost minimization function for the selection of optimum voltage vectors. However, the possibility of applying of single voltage vector during the whole control period demands a high sampling frequency (Zhang and Qu 2015a). This can be avoided by introducing duty cycle control, achieving improved steady-state performance with lower sampling frequency (Zhang et al. 2013). An MPDPC strategy (Hu et al. 2015) for DFIGs considers the complete model of the DFIG and converter into account to respond quickly to grid conditions such as grid voltage unbalance.

Research work in Zhang and Qu 2015b uses APOE and proposes an MPDPC for PWM rectifiers to achieve sinusoidal grid currents and constant active power without modification to the original power references. MPDPC scheme with power compensation (Hu et al. 2015) for RSC of DFIG makes use of optimization cost function for selection of selects appropriate voltage vector. Authors in Arif et al. (2015) present a finite control set model predictive control (FS-MPDPC) for grid-connected converters. This is to address the uncertain grid parameters of a weak grid by integrating the estimation approach. However, neglecting the supply inductance reduces MPC performance and is detrimental to the grid voltage magnitude and phase.

MPDPC approach (Estrada et al. 2021; Aguilera and Quevedo 2011) avoids windup issues or linearization of the system for proper tuning of the PI controllers by eliminating the external PI-based dc-link voltage controller. However, MP-DPC is vulnerable to variations in model parameters. Work in Zhang et al. 2014b achieves a high control precision and error-free power control by eliminating steady-state errors and restrains power ripple, torque ripple and current harmonics of DFIG by using a three-vector based low-complexity model predictive direct power control (LC-MPDPC) strategy. DFIG operation under unbalanced grid conditions has to achieve the control targets of current harmonics and power and torque ripples. Research in Sun and Wang (2016) proposes a low-complexity model predictive direct power control (LC-MPDPC) strategy combined with power compensation. This provides a superior steady-state and dynamic performance for changes in control targets.

DFIG under unbalanced grid voltage conditions is controlled by the model predictive direct power control (MPDPC) method and a power compensation scheme (Hu et al. 2015), eliminating the need for coordinate transformation and extraction of negative stator sequence currents. This improves the power quality of stator currents injected into the grid and achieved excellent steady-state and dynamic performance.

3.1.6 Predictive direct power control (P-DPC)

For the combination and implementation of predictive control with the DPC approach, active voltage vector selection is indispensable and based on the knowledge of the position of the grid-voltage vector (Song et al. 2014). Authors in Bouafia et al. (2010) presented a deadbeat predictive DPC technique. Work in Zhi et al. (2010) and (Eltamaly et al. 2020) proposed P-DPC techniques with a predictive selection of voltage vector sequences. Active and reactive powers' values (predicted and the reference values) are utilized for framing the cost function, which is then minimized to calculate the action time sequence required for the switching signal. Work in Aguilera et al. (2013) proposed a generalized P-DPC strategy based on a cost-function minimization strategy for rectifiers by analyzing power characteristics. Research work in Hu and Zhu (2011) and (Hu and Zhu 2013) introduced compensation terms in the conventional P-DPC.

Predictive Direct Power Control with cost-function minimization (Song et al. 2014) achieves rapid dynamic response and excellent steady-state performance for three-phase grid-connected converters. An improved three-vectors-based P-DPC (Vazquez et al. 2015) has better overall harmonic performance and reduces both active and reactive power ripples. A new P-DPC controller, named optimal switching sequence, OSS-DPC (Hu 2013), has excellent closed-loop performance under transient and steady states by eliminating the problem of an optimal sequence selected from the grid voltage sector information. Dead-beat predictive DPC strategy (Martinez-Rodriguez et al. 2014) improves voltage vector sequences for reversible grid-connected converters.

An adaptive DPC (positive-sequence-based solution (pos-DPC)) (Kazemi et al. 2010) for a three-phase PWM rectifier guarantees robustness against parameter uncertainties under unbalanced grid voltage operation with adaptive laws. Authors in Zhang et al. 2014c propose a novel approach of a single switching table to realize three vectors for reducing active and reactive power ripples. This results in a simple and robust PDPC control structure with reduced switching frequency making it useful for high-power wind energy applications under unbalanced grid voltage. A comparison of the control as mentioned above strategies for PQ improvement for specific performance parameters shown in Table 2. Table 3 gives an overview of the advantages and disadvantages of the same.

3.1.7 Miscellaneous control strategies

Several other strategies are available in various literature, which are applicable to address the power quality of the DFIG wind energy system. Research work in Liu et al. (2013) implements a control methodology suitable for large-scale modular structure DFIG converters to control dc-link capacitor with reference to GSC of DFIG under unbalanced grid conditions. providing stability for DFIG even under step change in active grid output power at the DFIG terminals. A grid-voltage feed-forward adaptive current control (Vrionis et al. 2014) improves the controller performance for grid-connected LCL-filtered inverters in the weak grid. DC-Capacitor Current Control (Bejaoui et al. 2013) for GSC of DFIG is robust to the deviations in measuring the current of the dc-capacitor.

A Novel Control based on the linear-quadratic method (Hu et al. 2013) for the coordinated control of RSC and GSC of DFIG enables adaptation to special grid situations. Work in Nian and Song (2013) presents a Coordinated Control (proportional–integral regulator + dual-frequency resonant compensator) in the positive (dq) + reference frame for DFIG achieving RSC and GSC regulation for both the positive-/negative-sequence currents and fifth-/seventh-order harmonic currents. Optimized PI-R current regulator (Zhou et al. 2015) adopted under distorted grid voltage for the RSC of DFIG under fifth- and seventh-order sequences harmonic components ensures stable and reliable DFIG operation under distorted grid voltage conditions. A cost-effective internal model principle (IMP)-based optimal selective harmonic controller (Valouch et al. 2015) for grid-connected inverter compensates selected harmonic frequencies.

A current control technique (Cheng and Nian 2015) based on the extended reactive power theory for grid-connected converters eliminates power ripple, mitigates grid current harmonic distortion of grid currents and realizes simultaneous control of grid phase current peaks. A reduced-order generalized integrator (Maccari et al. 2015) for the RSC and GSC of DFIG has enhanced performance and high output power quality. A robust DLQR (Zhu et al. 2016) suitable for current control of grid-connected three-phase inverters ensures good tracking of reference and rejection of disturbances ensuring stability under grid parametric uncertainty and variations. Research work in Song and Nian 2015c presents a Dual-Loop Control Strategy (conventional current loop and an additional flux loop) for DFIG converters under grid Voltage Disturbances to improve stator active and reactive power and eliminate stator flux oscillations.

A modularized control strategy based on the VPI regulator for the DFIG system (Wang et al. 2016) avoids extraction of grid voltage negative and harmonic components. Work in Nian et al. (2016) presents a control strategy for voltage imbalance at the point of common coupling (PCC) for DFIG based on a resonant feedback regulator. It negates the generation of negative sequence rotor current references by providing direct rotor voltage reference. This results in independence from DFIG parameters. Moreover, the short-circuit ratio (SCR) at the PCC also taken into consideration. In (Cheng et al. 2017), for a DFIG under network unbalance, a direct stator current vector control strategy based on reduced-order vector integrator (ROVI) and PI controller employed. Instantaneous power theory commands the stator currents eliminating dependence on generator parameters. This improves the control, achieving control system stability, elimination of PLL, robustness against frequency disturbances and parameter deviations, and the rejection of voltage unbalance.

Work in Abulanwar et al. (2016) provides an advanced voltage control strategy for improving DFIG power quality connected in a weak grid. It implemented at the point of common coupling (PCC) of DFIG to the weak grid. It overcomes the voltage fluctuations at PCC and shows better damping for wind shear and tower effect oscillations. In (Yao et al. 2015) reference grid current replaces the grid current for use in grid current controller for three-phase grid-connected inverter, based on space vector pulse-width modulation (SVPWM). This achieves a waveform with better power quality and improves the dynamic response of the grid-connected inverter. Research work in Cai and Erlich (2015) provides an adaptive control strategy for grid side converter of DFIG connected in a weak grid. This is necessary to achieve controller stability and provide reinforcement to power system stability. The control analysis carried out for different grid weaknesses, assessed by online grid station measurement.

Authors in Yan et al. (2016) propose an improved grid-voltage feed-forward strategy based on a simplified repetitive predictor for compensating harmonics in grid-connected inverters caused by distorted grid voltage. It utilizes a second-order Butterworth low-pass filter in the conditioning circuit. It introduces three predictive steps considering delays in the conditioning circuit, control of the digital controller, and the zero-order hold ZOH characteristic of PWM,

Table 2 Comparison of individual PQ improvement strategies

References	Strategy	Suitability for DFIG control	Computational cost	Sensitivity to disturbances	Automatic disturbance compensation	Control complexity
Baggu et al. 2015)	Modified SDC-DPC	High	Medium	High	High	Medium
Gao et al. 2021b)	VPI-based DPC	High	High	Medium	High	Medium
Li et al. 2018)	Coordinated DPC	High	Low	High	High	Low
Nian et al. 2015a)	MCCF based SVM-DPC + PI-R	Medium	High	Medium	High	High
Zhang et al. 2019a)	Improved DPC with duty cycle control	Medium	Medium	Medium	Medium	Low
Nian et al. 2015b)	DCC + DPC	High	Medium	High	High	High
Yan et al. 2019)	Modified DPC + PI-R tuned at sixth the network voltage frequency	High	Medium	Medium	High	Medium
Mohammadi et al. 2014)	SVOFVC + DPC	High	Medium	High	High	Medium
Shehata 2015)	SM-DPC	High	Medium	High	High	High
Zhang et al. 2019b)	ISMC + CB-DPC	High	High	High	High	High
Xiong and Sun 2016)	DPC based on nonlinear back-stepping	High	Medium	High	High	High
Zhang and Jiang 2021)	SVM-DPC + PI-R	Medium	Medium	High	High	Medium
Zhang et al. 2020)	SMC + PI	Medium	Medium	Medium	Medium	Low
Babaei et al. 2010)	SMC + PR	Medium	High	High	Medium	Medium
Teodorescu et al. 2011)	Sliding mode repetitive control	Medium	High	Medium	Low	Medium
Shtessel et al. 2014)	Multi-resonant SMC	High	Low	Medium	Low	Medium
Kang and Kim 2015)	Novel SMHC	Medium	Low	High	Medium	High
Hemdani et al. 2015)	ISMPC with constant switching frequency	High	Medium	High	Low	High
Martinez et al. 2012)	SMC	Medium	Low	Low	High	Low
Martinez et al. 2013)	SMC with constant switching frequency	High	Medium	High	High	Medium
Susperregui et al. 2014)	MRAS-SMC	High	High	High	Medium	Low
Pande et al. 2013)	Robust discrete SMC	Low	High	Medium	Medium	High
Kassem et al. 2013)	robust ISMC	High	High	Medium	High	Medium
Abdeddaim and Betka 2013)	HOSMC	High	High	Medium	Low	High
Djerioui et al. 2014)	Sliding mode observer for SMC	High	Medium	High	Medium	Low
Patnaik and Dash 2016)	FABT-SMCPCS	Medium	Low	Low	High	Low
Hornik and Zhong 2011)	Odd-harmonic RC	High	High	Low	High	High
Escobar et al. 2008)	Odd-harmonic RC	Medium	Low	Low	Low	Low
Chen et al. 2013)	Harmonic RC	Low	Low	Medium	Medium	Low
Chen et al. 2013)	Dual mode-structure RC	High	Low	Medium	High	High
Sha et al. 2011)	$H\infty$ RC	Low	Low	High	Low	Medium
Zhong and Hornik 2013)	Sinusoidal PI + RC	Low	Medium	Low	High	Medium
Trinh and Lee 2014)	Robust RC	Low	Medium	High	Medium	Medium
Kurniawan et al. 2014)	$nk \pm m$RC	High	Medium	Medium	Low	High
Lu et al. 2014)	Improved RC	Medium	Low	Medium	Low	High
Song and Nian 2015a)	Frequency adaptive odd-harmonic RC	Medium	Low	High	High	Low
Abusara et al. 2015)	BRC	Medium	High	Low	Low	Medium

Table 2 (continued)

References	Strategy	Suitability for DFIG control	Computational cost	Sensitivity to disturbances	Automatic disturbance compensation	Control complexity
Yin et al. 2014)	Predictive Dc-link voltage control	High	High	Medium	Medium	Medium
Shi et al. 2020)	PDVTC + PDPC	Medium	High	Medium	High	Medium
Rahoui et al. 2021)	IOFL-MPC	High	Medium	Low	Low	Medium
Liu and Kong 2014b)	Low complexity MPPC	High	Medium	High	Medium	High
Rodriguez et al. 2013)	Parallel adaptive observation based MPPC	Low	Low	High	High	Medium
Xiao et al. 2016)	HPO based MPPC	Medium	Medium	Medium	Low	High
Liu et al. 2014)	ESO based MPC	High	Low	Low	High	Low
Song et al. 2013)	Finite time MPC	Low	High	High	Low	Low
Hu et al. 2015)	APOE based MPDPC	Medium	Medium	Medium	Low	Medium
Zhang and Qu 2015b)	MPDPC with power compensation	High	High	Medium	Low	High
Hu et al. 2015)	FS-MPDPC	High	Medium	High	High	Medium
Aguilera and Quevedo 2011)	Three vector based LC-MPDPC	High	High	High	Medium	Medium
Zhang et al. 2014b)	LC-MPDPC	High	Medium	Medium	Low	High
Sun and Wang 2016)	PDPC with power compensation	Medium	High	High	High	High
Bouafia et al. 2010)	Deadbeat predictive DPC	Medium	High	High	Low	Low
Aguilera et al. 2013)	P-DPC based on power characteristics	High	Medium	High	High	High
Song et al. 2014)	P-DPC based on cost function minimization	Low	Medium	High	High	Low
Vazquez et al. 2015)	Three-vectors-based P-DPC	High	Medium	High	Medium	High
Hu 2013)	OSS-DPC	High	Medium	High	High	Medium
Martinez-Rodriguez et al. 2014)	Dead-beat predictive DPC	Medium	Low	Medium	Medium	Medium
Kazemi et al. 2010)	Adaptive DPC (positive-sequence-based solution (pos-DPC))	High	High	Medium	Medium	High
Zhang et al. 2014c)	PDPC with reduced switching frequency	High	Medium	High	High	Low

respectively. Work (Nian et al. 2015c) presents decoupled control of rotor-side converter (RSC) and grid-side converter (GSC) for a doubly fed induction generator (DFIG) under unbalanced grid voltage conditions using resonant regulators. Extracting positive and negative sequence components is not required leading to less computational load and system complexity. It also provides independence from generator parameters.

3.2 Energy utilization

DFIG wind energy system should provide synchronized power output such that the power generated is more reliable and cost-effective. The potential of a DFIG-WECS to provide secure and reliable energy to the consumers while maintaining its quality is enormous and has a significant bearing on its operations. Optimization achieved by improving operational performance and energy management, utilizing modern control techniques such as a centralized system controller. In this context, they benefit from using energy storage technologies (ESS) to provide electrical energy during high load demand periods for low wind speeds (Luo et al. 2015).

3.2.1 Energy storage technology (ESS)

It enables storing energy in various mediums and converts it back to its original form when necessary. Their integration

Table 3 Overview of advantages and drawbacks of PQ strategies

PQ strategy	Advantages	Drawbacks
Direct power control (DPC)	Simple implementation	High and non-constant switching frequency
	Fast dynamic response	Difficult converter loss calculation and switching noise filters design
	Low THD in normal case	Requirement of fast processor and A/D converters
	High power factor	High sampling frequency
	Robustness against system parameters	Poor THD for line voltage distortion
Sliding mode control (SMC)	Fast dynamic response	Chattering phenomenon for discrete implementation
	Reliable transient performance	Difficult controller design for transient and zero steady state performance
	Acceptable THD for good design	
	Robustness against grid disturbances and parameter variations	
	Easy implementation	
Predictive control	Inclusion of non-linearities	Precise model of the filter for optimum performance
	Excellent steady-state and transient responses	Complex and long calculations
	Constant switching frequency	Sensitivity to parametric changes
	Bounded current error	
	Precise current control with minimum THD and harmonic noise	
	Reduced torque and flux, active/ reactive power ripples	
Repetitive control (RC)	High gain for fundamental frequency harmonics	Slow dynamic response
	Rejection of odd and even harmonics	Rapid fall in gain on both sides its resonant frequencies
	Higher quality output current for a wide range of output power	
	Easy implementation	
Model predictive DPC (MPDPC)	Accurate and effective vector selection	High sampling frequency
	Steady-state performance improvement for power ripples and current harmonics	
	Optimum voltage vector selection using cost minimization function	
Predictive DPC (P-DPC)	Excellent steady-state performance	Necessity for active voltage vectors selection
	Rapid dynamic response	Necessary knowledge of the grid-voltage vector position
	Robustness against parameter uncertainties	

is necessary for increased wind power penetration into the power systems (Luo et al. 2015). The energy storage devices can store the excess generated energy and supply the stored energy to the consumers when there is a shortage of power generation. ESS supplies a compensating power ΔP_c for reducing or eliminating the wind power variability P_w, and maintaining power in the grid, P_{grid} almost constant (Suberu et al. 2014).

$$P_{grid} = P_w + \Delta P_c \tag{7}$$

ESS technologies' integration is in the intermediate DC link of the DFIG wind energy system for power exchange and utilizes grid side converter as an interface (Wee et al. 2013). ESS is also utilized for stabilization of weak wind grid and helps steady-state and dynamic stability in a weak grid, and acts as an energy storage system during wind power curtailment.

In the case of a wind energy system linked to medium voltage distribution lines, wind power output equals the transmission capacity of the power grid, resulting in a weak grid connection with load-sensitive voltage control. Maturity of the technology, energy status, and socio-economic standards of a given site, its adaptation to the location of interest, any operational constraints and the supplier's profile are detrimental to ESS implementation in a project (Lu et al. 2009). All the existing ESS technologies classified under different categories based on (Medina et al. 2014):

- **Time duration**: Short-term, Medium-term, and Long-term.
- **Form of energy storage**: Mechanical, Chemical, and Electrical.

There are several storage techniques in use today, depending on the needs of the power system. Some of the existing ESS technologies are compressed air energy storage (CAES), advanced adiabatic compressed air energy storage (AA-CAES), battery energy storage scheme (BESS), Super-capacitors, super magnetic energy storage (SMES), Flywheel, Pumped Storage and Hydrogen storage (Zhao et al. 2015). To achieve the future goal of delivering reliable power consistently, whatever the wind power generation, careful selection of ESS technologies with desired operation conditions and storage capacity and power ratings of the storage devices are required (Rodrigues et al. 2014).

Table 4 portrays the benefits of ESS in both technical and economic aspects. The introduction of EES as a grid code requirement is necessary in order to give freedom of choice to the power plant owners or the grid operator as regards the technology that matches the desired application. It is also necessary for a proper forecasting tool to support the decision process of specifying power and energy requirements of EES, for developing the optimum management of ESS, and to diminish the impacts of wind forecast errors more effectively.

3.2.2 Wind power forecasting

Accurate, reliable, online wind power forecasting methods are necessary due to the increasing penetration level of wind power into power systems. This enables power system operators to maintain the economical, efficient and secure operation of the power system. Wind power forecasting is essential to reduce reserve generation requirements, efficient provision of balancing services, efficient use of existing transmission, active management of wind and demand, and sizing dedicated storage technologies (Ren et al. 2014).

The wind power forecasting methods utilize physical and statistical models to attain the objective. The output of the wind power forecasting method is the wind power forecast, providing hourly predictions for look-ahead times up to 48 h. The forecasts can be provided for individual wind farms or all wind farms in a particular region or supply area (Zhang et al. 2014d; Dragoon 2010). The requirements for wind power forecasting methods can be outlined as follows:

- The forecasts should be of wind power output (in MW), rather than wind speed, with look-ahead times extending to 48 h.
- The forecasts should be readily available for individual wind farms, regional groupings of wind farms, and the total wind power installed in a TSO’s area.
- The forecasts should be accurate and supplied with an associated level of confidence dispatchers tend to be more conservative when dealing with significant forecast uncertainties.
- The forecast should predict changes in wind power reliably.
- There should be a good understanding of the meteorological conditions, leading to poor quality forecasts.
- Historical data should be used to improve the forecast over time.

Table 4 Benefits of ESS technologies

Technical benefits	Economic benefits
Power management—Bulk energy time-shifting, electricity price arbitrage with load leveling and peak shaving, uninterruptible power supply	Reduced electricity cost for customers and sellers, contributing to economic development and employment opportunities
Distributed Generation: efficient use and contribution of renewable energy, stabilization of islanded grid, DG support, active and output power smoothing, alleviating intermittence of renewable source power generation, compensation of power imbalance between mechanical input and electrical output of wind turbine (WT)	Stabilization of the electricity market price irrespective of volatility imposed by fossil fuels
Conventional generation: regulation applications, setting the optimal operation point, superior part-load efficiency, a stand-by source for distribution substations, frequency and voltage control, support during peak electrical load demand	Reduction in generator costs due to efficient use of renewable and off-peak generation and elimination of peak generation
Electric grid support: ramp support and black-start for the grid, improved grid service reliability, transmission congestion relief, deferral of transmission and distribution upgrade, Spinning and standing reserve, Improved power quality and reliability, time-varying management of power according to the grid-codes	Avoids transmission congestion charges and defers transmission and distribution capacity upgrades, improving ancillary services
Future implication: transportation and heat generation	Enables cost-sharing for market-driven electricity dispatch
	Reduced emission of GHG and reduced carbon cost

Evaluation of wind power forecasts consists of four functions: performance assessment, model diagnosis, model selection, and model ranking (Zhang et al. 2014d; Wan et al. 2021). Figure 7 depicts the physical flow of information in a wind power forecasting system. The wind power forecasting methods can be classified based on time scale as follows:

- Very-short term: seconds to minutes, applicable to wind turbine control and power system frequency control
- Short-term: hours to days, applicable to economic dispatch, reserve requirements, day-ahead electricity market
- Medium-term: days to weeks, applicable to unit commitment and maintenance scheduling
- Long-term: weeks to months or years, wind power planning, and power system planning

3.2.2.1 Types of wind power forecasting methods The first is the physical method that uses numerous physical considerations for the best forecasting accuracy. The second technique is a statistical method that attempts to determine the link between the online measured power data. This technique utilizes both classic statistical models (such as ARIMA models, ARCH models, Kalman Fitters (KF), etc.) and machine learning (ML) models (Artificial neutral networks—ANN, Support vector machine-SM) (Costa et al. 2008; Bazionis et al. 2022; González-Ordiano et al. 2021; Jiang et al. 2021; Wang et al. 2021; Wan et al. 2021; Du et al. 2019). Table 5 tries to project the advantages and drawbacks of forecasting approaches to ascertain an optimal approach for the appropriate application. Future wind power forecasting methods should consider the following factors to enable proper sizing of ESS technologies for application in wind energy systems:

(1) Improving and extending physical, statistical, and hybrid forecasting approaches for reducing forecasting errors and enabling long-term planning.
(2) Probabilistic forecasting and ensemble forecasts, with aid from several NWPs, improve accuracy in wind power forecasts and reduce reserve capacity (Xiao et al. 2015; González-Ordiano et al. 2021).
(3) Forecasts at the regional level in order to evaluate any possible effects on the dependability of the system. The reference sites' choices and combinations should be considered in regional forecasting. Increasing the spatial and time resolution of NWPs, better taking into account local phenomena, would help to improve the forecast. Further research on automatic adaptive parameter estimation is required since wind speed and power forecasting are site-dependent (Jung and Broadwater 2014; Jiang et al. 2021).
(4) Additional use of online wind measurement data has the potential for improved forecasts, especially for very short-term and short-term wind power forecasting.
(5) New approaches for complex terrains to help improve forecasting accuracy.
(6) It is also required to implement a new performance monitoring strategy that makes use of PMUs in order to monitor renewable energy facilities that are connected to the grid in real-time. The optimal PMU placement may also help to monitor the renewable energy sys-

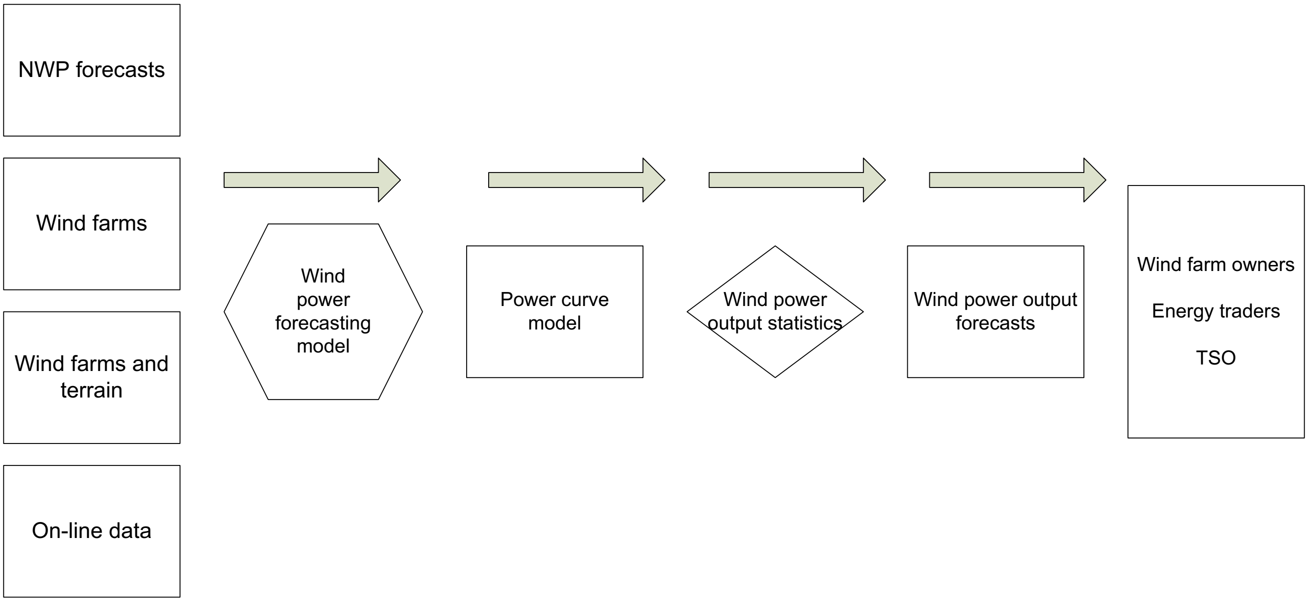


Fig. 7 Physical flow of information in a wind power forecasting system

Table 5 Comparison of Wind power forecasting approaches (Tascikaraoglu and Uzunoglu 2014; Wang et al. 2021)

Wind power forecasting approach	Advantages	Drawbacks
Physical approach	Applicable for longer prediction horizons	Weak handling of smaller-scale phenomena
		Unsuitable for short forecast times
		Significant computational resources and time
Statistical approach	Easy availability of tools	Requirement of historical records
	Simple structure and data correction capability	Difficulty in nonlinear modeling
	Higher adaptability to online measurements and high generalization performance	Dependence on parameter tuning
	Less complex and high data error tolerance	Training procedure and a large number of training data
	Gains knowledge from training data	Complex optimization process and longer training time
	Suitable for small training data sets	High complexity and a long process time
		Requires more effort, depending on the user's expertise level
		Requirement of previous knowledge about the system
Hybrid/combined approach	Basic structure, more straightforward implementation, and higher performance	It does not guarantee the best predictions along the prediction horizon
	Suitability for a wide range of prediction time	Slow response to new data
	Adaptability to new data	Harder to code
	Easier to find literature examples	Dependent on the designer's knowledge
	Robustness to rapid wind speed changes	Computational time inefficiency
	High accuracy and effectiveness in reducing systematic error	

tems in real-time and parallelly benefit in improving the power quality (Theodorakatos et al. 2020, 2021; Babu and Bhattacharyya 2015a, 2015b, 2015c, 2020; Babu et al. 2021, 2022a, 2022b, 2022c).

4 Conclusion and future scope

DFIGs and their competitive advantages make them the favorite choice for wind energy conversion systems that can be connected to large power networks. An overview of the various problems that are associated with the interconnection of the DFIG wind energy system in the electric grid has been provided in this article. Additionally, an attempt has been made to classify and summarise control strategies for DFIG power quality improvement in order to achieve increased wind power penetration in the electric grid. They could be extended for robust future grid operation with the support of ESS technologies improving the reliability of the wind energy system. Accommodation of new storage technologies takes into account an unprecedented number of options for energy production and consumption. ESS technologies aid wind power penetration in the following manner,

- ESS with high power ramp rates helps smooth power wind power by mitigating the voltage and frequency variations at the connection point and strengthening the wind energy system. This improves the stability and enables ESS integration into grid codes.
- Wind energy systems with ESS have improved penetration while maintaining a continuous power supply.

By reducing mistakes in wind power prediction, power reserve requirements can be reduced, making the ESS cost-effective. Research should focus on the coordination between the forecasting tools and the energy storage system to minimize the power imbalance and to ensure economic size optimization of the ESS. This would enable improved performance of the energy storage technologies. Power quality aspects in this regard cannot be overlooked, as in the near future the electric grid codes would be modified with respect to micro-grids, island grids and ESS technologies to qualify for integration in the primary electric grid for upholding the system reliability.

Further research for increased wind power penetration should address the following:

- Advances in power electronic devices and control techniques.
- Advancement in power converter topologies for minimizing power conversion losses in wind energy system configuration.
- Enhanced supply of quality power by designing and implementing advanced control strategies.

- Subsidy on renewable energy products from the state and central governments.
- Focus on cost reduction of ESS technologies.
- Improving and extending physical, statistical, and hybrid forecasting approaches with aid from several NWPs for reducing forecasting errors, reducing reserve capacity and enabling long-term planning.
- Regional forecasting for the purpose of evaluating the possible influence on system dependability by employing automatic adaptive parameter estimates to cut down on the reliance on wind speed and power forecasts at the site.
- New approaches for complex terrains for use in online wind measurement data for improving forecasting accuracy.

New regulations and policies, frequent extreme weather events, island grids, and utilization of utility grids as the backup to shape the future of DFIG wind energy systems to benefit both utility systems and individual consumers of energy safely and reliably. Successful operation and evolution of DFIG wind energy systems require using control strategies for PQ improvement assisted by ESS technologies and wind power forecasting methods to achieve optimum performance and provide grid resiliency to power quality issues.

Author contributions The paper was designed by the first author, and the work of the article was approved by the second author.

Funding Not applicable.

Data and material availability Not applicable

Code availability Not applicable.

Declarations

Conflicts of interest Not applicable.

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