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A critical review of voltage and reactive power management of wind farms

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A B S T R A C T

Wind generation is currently the major form of new renewable, generation in the world. The wind power is totally dependent on wind flow, due to randomness and uncertainty of wind flow, the wind power generation is quite fluctuating in nature and large scale wind farms may cause significant impact to the power system safety, quality and stability. The active power mainly depends upon the potential of the wind power produced and wind turbine generator design. The reactive power demand on the other hand depends upon conversion devices and recovered power quality fed to the grid. The wind farms which accesses to power grid cause fluctuations and reactive power redistribution and sometimes lead to voltage collapse. Similarly, the dynamic voltage stability is a major challenge faced by distribution network operators. The easy solution comes into picture is to install reactive power source devices with optimization of the existing assets to deliver enhanced reactive power to the grid. With solution to reliability, voltage regulation, reactive power requirements, grid integration problems, weak grid interconnection, off grid wind power generation and its integration to power grid, wind power penetration in distribution grid, wind power uncertainty, flicker and harmonics etc. The categorization of issue considered the goal of our work is the reactive power management of wind farm in most technical and economical way without compromising quality power system voltage, and considering the wind turbine technology for already commissioned wind farm, and change in WT technology in present scenario. More than 100 research publications on voltage and reactive power control of wind farms, extending from year 2003 to 2013 have been critically examined, classified and listed for quick reference.

Contents

1. Introduction

Wind energy is playing a vital role in world energy markets and wind energy has been focused as a clean and endless energy

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Nomenclature

ANFIS adaptive network – based fuzzy inference system
CUPS custom power device technology
DSTATCOM distributed static synchronous compensators
D-VAR dynamic var
DVC dynamic var compensator
FACT flexible AC transmission system
FES flywheel energy storage system
GTOINV gate turn off thyristor inverter
STATCOM static synchronous compensators
SVC static var compensator
PHIL power hardware – in-loop

sources, its penetration level has been increased throughout the globe. The growth rate of renewable investment increases fast at the end 2013, it is 318 GW. But the unpredictable level of the nature of wind causes fluctuating wind power which gives rise of instability problem to already existing network, along with other associated problem such as voltage regulation, reactive power, fluctuation, harmonics, flickers etc.[1]. Increasing use of wind generation imposes the requirement for a wind farm to be capable of contributing network support and operation on the same way as a conventional power generating system.

The active power supply mainly depends upon the potential of the wind power produced and wind turbine generator design. The reactive power demand on other hand depends upon conversion devices and recovered power quality fed to the grid. The wind farms which accesses to power grid cause fluctuations and reactive power redistribution and sometimes lead to voltage collapse. Voltage variation due to variable wind generation and dynamic voltage stability is a major challenge faced by distribution network operators [2,3].

Reactive power control is important because all wind farm technology do not have the same capability. The wind farm is usually installed in remote areas, therefore reactive power has to be transported over long distances resulting in power loss. The wind farm has to provide reactive power control in response to voltage variation [4–6]. The reactive power control requirement is related to characteristic of grid because the influence of injection of reactive power in various voltage levels depends on network short circuit capacity and impedance. The reactive power compensation become utmost requirements for wind farm operation and contribution to the power grid, uncompensated reactive power cause stress on the hosting grid as well as casting effects. In general reactive power compensation of wind farms have the main purpose to keep the voltage profile of a wind farm at the appropriate level and ensure minimum losses in transferring power to the main grid also comply with connection requirement related to reactive power exchange set by grid code. The basic device for reactive power compensation is Under Load Tap Changer (ULTC) of the station transformer. If the action of ULTC does not comply grid requirement than other reactive power compensator devices, static capacitors, FACTS devices such as Static Var Compensators (SVC), Unified Power Flow Controller (UPFC), Unified Power Quality Conditioner (UPQC) and Distributed Static Synchronous Compensators (DSTATCOM) aimed at regulating reactive power requirements. A decision on the application VAR compensation technique depends upon the feasibility study taking into account technical requirements and economical consideration. These devices are now suggesting for control of reactive power requirements of wind generators, studies also shows their acceptability in voltage stabilization control [7–11]. This increases the acceptability of wind power penetration even in distribution network world-wide.

Among number of control strategies of reactive power one of the strategy is to utilize inherent reactive power capability of power electronic based wind generators. If the different induction generators are analyzed it is observed that reactive power management depends on WTG used in the wind farm. For wind power generation by use of the squirrel cage induction generator SCIG, it demands reactive power, the rotor of this machine runs at constant speed. Usually reactive power is provided through mains or in the capacitor bank. So wind farm active (reactive) power injected (demanded) into the power grid leading to variation in the wind farm terminal voltage. On other hand DFIG and FCWG has inherent characteristic of reactive power capability which can be utilize to enhance voltage and transient stability during grid disturbance. The permanent magnet induction generators PMSG are connected to grid via back to back converters which provide path between stator and power system also these converter decouple system frequency with frequency at stator of synchronous generators [12–14]. One of the most difficult requirement for wind generator is capability to ride through a fault, wind generator were tripped once the voltage at their terminal reduced below 80%, earlier that was accepted as its impact on the grid was less but with increased penetration of wind energy and with revised grid code requirement the fault ride through and power control capability of wind farm is at voltage 15% or low. The wind machine should be capable to withstand LVRT and HVRT [15]. The necessary dynamic reactive power need assessment of wind farm to meet utility interconnection requirement is also important [16].

The major issues from outcome of research papers steam lined. The issues generally comprise of, Voltage and Reactive Power Requirements and reactive power compensations of Wind Farms, Control Algorithm and Primary and Secondary Converters, Wind-Farm Grid Integration Requirements fulfillments, ESS for Weak Grids and MG Integration, SVC /FACT Devices for reactive power management and Grid Stability. All these are required to maintain the power quality fed into grid, apart from the challenges of meeting common grid code requirements, capable of meeting LVRT and HVRT, active power, voltage regulation and frequency requirement.

Comprehensive review on the topic of voltage and reactive power management of wind farm, classification, techniques/methodologies etc. presented in the paper. Over 102 publications [1–102] are critically reviewed and classified into four major categories. The first [1–16] is on general wind power requirements related issue. The second category [17–62] reactive power requirements of wind farms, which is further subdivided, [20–41] use of STATCOM for managing reactive power requirements of wind farms, [42–48] includes application of SVC techniques for resolving the issue of voltage and reactive power requirements, [52–62] application of capacitor banks, DVR, SDBR and other devices. The third category [63–80] is an energy storage system for weak grid and hybrid wind farm for mitigation of reactive power requirements. The fourth category [81–92] is wind farm integration with the grid and use of HVDC for off grid wind farms. The final and fifth category [93–102] specifies reactive power management with other works say use of the control algorithm, primary voltage converter, secondary voltage converter, controllers, etc., however, some publications include more than one category and have been classified based on their dominant field.

This paper is divided into five sections. Starting with an introduction in Section 1. Section 2 describes power quality affected with wind power penetration. Section 3 covers the segmentation of reactive power requirements of wind farms, various techniques for voltage and reactive power management and key findings are presented in Section 4. Finally the conclusions and recommendations are included in Section 5.

2. Impact and power quality affected with wind power penetration

Wind power impact on the power system can be classified into short duration and long duration effects. Short duration effects having a time scale millisecond to minutes to hours and related to system balancing, whereas long duration or long term effects are related to wind power penetration effect on the grid effect the power quality, voltage, reactive power but in long term month to years support power adequacy, reduction in emission etc. Various impacts of wind generation in the time scale of power system is indicated in Fig. 1.

On the local level, voltage variations are the main problem associated with wind power. This can be the limiting factor on the amount of wind power which can be installed. In normal operational condition, the voltage quality of a wind turbine or a group of wind turbines may be assessed in terms of the parameters, steady state voltage under continuous production of power, voltage fluctuations, flicker during operation, flicker due to switching. The voltage variation issue results from the wind velocity and generator torque. The voltage variation is directly related to real and reactive power variations. The voltage variation is commonly classified as voltage sag/voltage dips, voltage swells, short interruptions, long duration voltage variation. The voltage flicker issue describes dynamic variations in the network caused by a wind turbine or by varying loads. Thus the power fluctuation from wind turbine occurs during continuous operation. The influence of connecting a wind farm on the grid voltage is directly related to the short circuit power level. The short circuit power level in a given point in the electrical network represents the system strength.

In an ideal AC power system, the voltage and frequency at every supply point would be constant and free from harmonics, the power factor would be unity. As per international standards developed by the working group of Technical Committee-88 of the International Electro-technical Commission (IEC), IEC standard 61400-21 describes the procedure for determining the power quality characteristics of the wind turbine. The power quality affected with wind power penetration in power system [17–19], in general overall permissible variation in power system w.r.t. voltage, sag, swell, flicker, frequency, etc., is defined, as illustrated in Table 1. It all depends upon grid size, type of wind machines, level of wind power penetration and various types of power generation (thermal, hydro, nuclear) whether wind power generation is off grid or on the grid, the length of power transmission system etc.

3. Reactive power management

The reactive power control requirement is related to characteristic of grid because the influence of injection of reactive power in various voltage levels depends on network short circuit capacity, impedance and type of wind generator used in the wind farm. In review process research papers for 11 years considered and categorized in four segments as listed in Table 2, all the segments directly or indirectly deals with reactive power management of

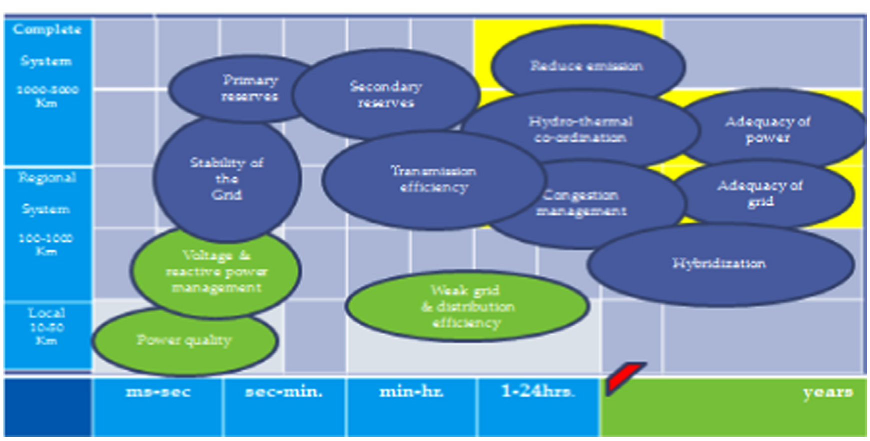

Fig. 1. Impact of wind power in power system.

Table 1
Power system, electrical parameter limits for power quality.

Type	Power quality	Duration	Time	Min Max	
	Average voltage		10 min	0.85 Un	1.1 Un
	Flicker		–	–	7%
	Sag	Short	10 ms–1 s	0.1 U	0.9 U
		Long	1 s–1 min		
		Long-time disturbance	41 min		
Voltage	Under voltage	Short	0–3 min	0.99 U	
		Long	43 min		
	Swell	Temporary short	10 ms–1 s	1.1U	1.5 U
			1 s–1 min		
		Temporary long-time	41 min		
	Over voltage		0–10 ms		6 kV
Frequency	Slight deviation		10 s	49.5 Hz	50.5 Hz
	Severe deviation			47.0 Hz	52.0 Hz

wind farms under different conditions and with different compensation measures having individual merits and demerits.

3.1. Reactive power management of wind farms

For control of voltage/reactive power management, the various approaches used by different researcher are analyzed. In general the devices used by researchers are STATCOM, SVC, DVR, OLTC, SDBR, FACT Devices, UPFC or UPQC or in combination with other device. One by one important reactive power compensation device in cluster are discussed.

3.1.1. STATCOM for reactive power management

STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are, however, other uses, the most common use is for voltage stability. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system. Another way to enhance a Wind Power Plant with ability to deliver or absorb reactive power from the grid is to use Static Synchronous Compensation. STATCOM can be treated as a solid state synchronous condenser connected in shunt with the AC system. The output current of this controller is adjusted to control either the nodal voltage magnitude or reactive power injected at the bus. STATCOM is a new breed of reactive power compensators based on VSC. In Table 3 methodology and approach under different circumstances viz. type of wind turbine and generator, grid condition, with application of STATCOM used by a different researcher given.

It is observed that for reactive power management STATCOM are widely used by the researcher, it provides reactive power support to FSIG, SCIG, and PMSG installed wind farm and off grid wind power generation [20–24,27,28,33,35,36,38]. With power storage system it gives, active and reactive power control in distribution grids [25,29,30].To attain power quality, it can be used along with harmonic filter [31,34]. In scattered wind farm application, distributed STATCOM be utilized [32]. Amongst all, STATCOM is best suited for dynamic stability.

Table 2
Segmentation of reactive power management of wind farms.

Category	Papers
Reactive Power Managements of Wind Farms	[1–62]
ESS for Weak Grid. Hybrid	[63–80]
Wind Farm Grid Integration and HV DC Network	[81–92]
Other related works, Control Algorithm, PVC & SVC, Controllers	[93–102]

3.1.2. SVC for reactive power management

Static VAR Compensator is used by many researchers for reactive power management of wind farm. It is an electrical device for providing fast-acting reactive power. SVCs are part of the Flexible AC transmission system device family, regulating voltage

Table 3
Use of STATCOM for Reactive Power Management.

Combinationapproach	Methodology/result
PMSG, STATCOM	Cascaded three level inverter, STATCOM power rating 5MVA, Conditioning inverter switching frequency 5 kHz, good dynamic response for voltage variation by restoring PCC voltage [20].
SVC and STATCOM,DFIG	9MW, 575 V, 60 Hz DFIG, 10MVARSTATCOM and SVC connected parallel to load the bus. Static and dynamic response. STATCOM proved better [21].
Thermal Power, DFIG, STATCOM	100MVA SG 10MVA IG with STATCOM used. Economic power dispatch considered[22]
STATCOM, SDBR	1.3MW wind turbine, STATCOM, SDBR hybrid having better performance as compared to SDBR itself [23].
FSWG, STATCOM	CIGRE Nordic 32 system used which include 22 power source nodes, 52 transmission lines and 22 loads in the test system total reactive load 1368MW. Wind Farm include 100 sets of 2MWFSIG, Proves the transient stability [24].
STATCOM and BESS	STATCOM-BESS at PCC Bang Bang controller for current injection. Improve power quality [25].
FSIG, STATCOM	STATCOM is modeled in real time Digital simulator WF composes of FSIG, PSCAD/EMTDC [26].
STATCOM, WF	SWAM-VSC-STATCOM model provide steady state and dynamic operation [27].
STATCOM, Large WF	STATCOM improves electric power quality and dynamic stability[28]
STATCOM and BESS, IG	STATCOM response is improved by using a PID controller [29].
SCIG, STATCOM, Weak Grid	1.5MW SCIG three pair, three phase Dynamic Simulation and STATCOM used for analyzing dynamic capability for weak grid integration [30].
STATCOM and Harmonic Filter, WF	MSOGI harmonic voltage detector along with a droop controller at PCC by absorbing reactive current of each fifth and seventh harmonic [31].
IG,DSTATCOM	3MW WTSCIG, 25 kV distribution systems. 3MVAr DSTATCOM [32].
STATCOM, WF,FC	Power Factor and voltage grid requirements [33].
STATCOM, WF	STATCOM as a shunt active filter reduces the harmonics and provide reactive power and voltage support [34].
SCIG,STATCOM	STATCOM responded well in mitigating voltage sag, Large Scale WF in radial mode [35].
WF, STATCOM	STATCOM at optimal location help voltage stability and reactive power management in to great extant [36].
DFIG, STATCOM	Optimal location of the STATCOM based on evaluation index [37].
IG, STATCOM	STATCOM with PID and OPFB controller, QV control of WF [38].

Table 4
Use of SVC for reactive power management.

Combinationapproach	Methodology/result
SCIG,SVC	SVC.IEEE-39 bus test system 100MW wind power, SVC not only improves load ability limit as well as stabilized weak grid [39].
SVC and TCSC	3number, 3MW WT equipped with capacitor bank SVC and TCSC under fault condition and give LVRT capacity to wind farm [40].
SVC-RPR,SCIG	PSO algorithm wind power penetration 45% SVC-RPR is effective at low power generation and poor at its high power generation [41].
SVC,DFIG	IEEE 14-Buses test system Two time domain SVC model considered and compared in presence of grid fault [42].
SVC, Large WF,PSS	SVC with PSS having better damping capacity and provide system stability and reactive power support with large wind farm [43].
SVC, DFIG,OWF	DFIG based OWF along with proper supply of reactive power to wind farms, thus improvement of stability of an OWF [44].
SVC,LSWF	The active power output of WF is improved under condition of transient stability of grid [45].

Table 5
Use of other devices for reactive power management.

Combinationapproach	Methodology/result
DFIG secondary voltage converter	Optimal tracking SVC provides better voltage regulation [46]
GSC, RSC, DFIG	Steady state and transient's stability by dynamic Q control [47]
FSWG, SDBR	Dynamic RPC and voltage improvement can be achieved in large WF by insertion of SDBR in series with FSWT [48]
GSC, DFIG	The capability region of DFIG can increase up to 1.2 pu speed with proper selection WRM [49]
AVC, LWF	AVC narrows down the voltage fluctuation [50]
DFIG, OLTC	DFIG as a continuous variable in voltage control and dynamic optimization of reactive power in the distribution system [51]
FRC.WF	Fully rated converter based wind turbine shows better reactive and active power response [52]
DFIG & SCIG	DFIG support reactive power requirement of SCIG during fault [53]
DVR,SCIG	DVR be used to improve LVRT [54]
IG,FACT Devices	Increase LVRT [55]
Capacitor &Reactor Bank,WF	Central controller regulates both p.f and voltage at the point of utility interconnection [56]

Table 6
Comparative effectiveness of control and reactive power compensating devices on electrical & other parameters.

Effect on electrical & other parameters	OLTC	Static capacitors	Capacitor & reactor banks	AVC	DVR	SDBR	STATCOM	SVC	UPFC	TCSC
Reactive power control	★	★★	★★★	★★			★★★★	★★★	★★★★	★★
Active power control	★		★★	★★	★★	★★	★	★		★★
Voltage stability	★	★★	★★	★★			★★★★	★★★	★★★★	★★★
Voltage control	★	★★	★★	★★			★★★★	★★★	★★★★	★★
Flicker control			★				★★★★	★★★	★★★★	
Harmonics reduction			★						★★★★	
Rotor angle stability					★★	★★★	★★	★★	★★★★	★★★
Power flow control									★★★★	★★★
Oscillation damping			★		★★	★★★	★★★	★★	★★★★	★★★

and stabilizing the system. Prior to this, power factor compensation was the preserve of large rotating machines such as synchronous condensers. The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. If the power system's reactive load is capacitive (leading), the SVC will use reactors to consume VARs from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched on, thus providing a higher system voltage, SVCs with an auxiliary injection of a suitable signal can considerably improve the dynamic stability performance of a power system. It is observed that SVC controls can significantly influence nonlinear system behavior, especially under high-stress operating conditions. These consist of conventional thyristors which have a faster control over the bus voltage and require more sophisticated controllers compared to the mechanical switched conventional devices. In Table 4 the methodology/results and solution approach adopted by different researchers indicated.

The researchers [39,42,44,45] have successfully used Static VAR Compensator for reactive power management of large scale and small scale wind farm. It is effectively managing reactive power support and grid voltage when in use with different type of wind power generation system, however the performance is not better in the case of high wind power generation [41]. The SVC used in conjunction with other device say TCSC, STATCOM, and PSS maintain stability, support LVRT and increase damping capacity [40,43].

3.1.3. Capacitor banks, DVR, SDBR and other devices

Researchers have used other devices and method for reactive power control, some of them indicated below in Table 5.

The authors in [57], addressed the area control arises due to reactive power demand of large wind farm in the system. On solution approach they have used IEEE39 bus system, incorporating large scale wind farm, Monte Carlo based parabolastic analysis of VCA carried out and simulation used. In [58], the author's proposed reactive power management of a DFIG in Micro grids, based on voltage sensitivity analysis.

Power factor controller often turns to terminal voltage regulation mode at abnormally high or low grid voltage, to avoid this reactive power adjustment for voltage drop buses identified as coherent buses which are responsible for voltage stability problem. The buses which help in improving the problem also identified. Steady state and dynamic performance evaluated. Compensation used Sensitivity analysis carried out at target bus /central bus, method illustrated in IEEE-13 bus distribution network dynamic model is considered for DFIG, converters, and internal controller with their operational limits. Stochastic fluctuation in wind speed is modeled with NREL Turbism.2 number 2MW IG used.

Distribution line simulated with resistance and inductance. Three phase balance system considered. In [59], the author presented LVRT and HVRT Control Strategy for DFIG based WT system, considering that during low voltage period power convertor control system will generate more reactive power into the transmission system so that voltage level at grid during transient times will increase to sufficient value to retain grid condition. During high voltage condition reactive power will be absorbed by a power converter system from the grid so that high voltage during the transient period will come down to the nominal value as such wind turbine remains connected to the grid during LVRT and HVRT. The authors in [60], presented ability of reactive power generation capacity of VFCS DFIG. The solution approach is DFIG of flexible, reactive power control characteristic and instead of installing centralized reactive power compensator, a wind farm can take advantage of DFIG to generate reactive power, also DFIG required converter capacity which only accounts for 30% of DFIG rated capacity. Simulation is carried out for total capacity 9 MW. Using 6 number 1.5 MW induction generator rating 690 V connects to 35 kV electrical collection systems through 2 MVA transformer. Study of potential stability problem due to imbalance reactive load proposed in [61], with solution approach that the

Table 7
ESS used in wind farm.

Combination approach	Methodology/result
BESS& STATCOM	Wind generation and storage modeling carried out. Control strategy utilized voltage and frequency control of the battery. 8MW/4 hour battery used. BESS with Quanta technology used [63]
BESS&STATCOM	STATCOM connected at PCC BESS, to rectify power quality issues. Current controlled based hysteresis controllers are used to generate switching signals to inverter; scheme shows its utility in standalone mode and power quality mode [64]
BESSVRFB	Model of WF in Dig Silent, controlled and dispatched by integrated wind farm controllers frequency response, modeling a VRFB rated at 25% of WF capacity with six hours storage at full power output. LVRT capacity and frequency response observed [65]
BESS	The modulation technique used combination of six step mode and SVM method, concept of ESS interfacing by the grid side inverter has been tested in Simulink- PLECS digital simulation platform. Operational strategy used the three conditions first wind power generated less than demand, equal to demand and more than demand [66]
ESS &VSC	MATLAB simulation used and PMSG & DFIG modeled along with power system component 5 bus model system with 60MW wind farm used the short circuit considered 5500MVA. ESS and SVC also modeled. To facilitate the comparison SVC rating set equal to ESS +10-5MVAr. The analysis carried out at different conditions for both ESS and VSC connected wind farm [67]
BESS	The methodology used, controls the voltage source inverter in current control mode with an application of BESS, magnitude of source the current is determined by the power balance between source, load and power. The scheme of ESS for stabilizing the weak generating grid simulated on MATLAB/SIMULINK, Block set. Model lib. Include induction generator, converter load, etc. [68]
SMES	MATLAB /Simulink. SMES, PCS, simulated.PCS consist of three phase three level AC/DC converter and incorporate a two quadrant three level DC-DC converter, State space averaging method three level control schemes is designed and three level control of SMES namely external, middle and internal level control used [69]
SMES	Fuzzy logic controlled SMES,100MVA synchronous and 50MVA induction generator electrical behavior considered, achieved a better transients response and voltage improvement in WF [70]
FES	Three control modes of FES device voltage control, frequency control and active power stabilization, MATLAB/Simulation, Fuzzy logic regulator used. 300KW, 6 PMSG, WT, total 1.8MW. Control algorithms used. The test MG implemented LFC.13 bus 120KV, 50 Hz main grid and 25 kV in MG side [71]
Fuel Cell	Integration of a fuel cell with DFIG, vector control scheme for two back to back PWM converter control the flow of power between grid, fuel cell and generator [72]

oscillation boundary of the system in presence of unbalanced three phase reactive load, oscillation boundary of the system are collected by using various damping component values of three phase load illustrating instability problem caused by imbalanced reactive load. DFIG is very sensitive to unbalanced grid voltage creating serious problem to electric torque resulting to fatigue of mechanical component and oscillatory dc link capacitor voltage reducing its life. Nonlinear stability analysis has been performed to DFIG with unbalanced reactive load. Unbalanced reactive load may cause but not sufficient condition for low frequency oscillation, further research is required for the interaction of control algorithm and unbalanced load. PWM inverter scheme for grid connected WPP for power quality measure [62].

The Comparative effectiveness of control and reactive power compensating devices on electrical and other parameters such as active power, voltage stability, voltage, flicker control, harmonics reduction, rotor angle stability, power flow and oscillation damping etc. are given in Table 6.

3.2. ESS for weak grid and hybrid

Alternative to spilling wind energy and possible solution for wind energy storage system are flywheel, super capacitor, superconducting magnetic storage system, batteries, compressed air system, hydro pump station and hydrogen production are defined. Most of these ESS tap into the intermediate DC link of back to back converter system for power exchange. The battery storage device can store the power as well as control active and reactive power at the point of interconnection, also sustain system stability [63], the Grid side inverter can also be used as interface for energy storage system and deficit of power is supplied by BESS [65]. The battery energy storage system is also utilized for stabilization of weak wind grid [67]. The approach for control and stabilization for micro grid connected wind farm with reactive power management by Superconductive Magnetic Energy Storage System presented in [69], similarly fuzzy logic controlled SMES presented by authors in [70] to achieve a better transients response and voltage improvement in WF. The Integration of Wind Power Generation into AC Micro grids by using Flywheel Energy Storage is also the solution approach [71]. The authors in [72] proposed integration of fuel cell with DFIG in which, vector control scheme for two back to back PWM converter control the flow of power between grid, fuel cell and generator.

The solution approach and methodology used in ESS used in wind farm given in Table 7.

Among all the energy storage system battery energy storage system is proven to be best for control of active and reactive power, maintainer of system voltage of the wind farm and help steady state and dynamic stability in weak grid, also act as an energy storage system at the time of wind power curtailment [63–68].

In case of wind farm connected to medium voltage distribution lines where a situation arises that wind power generation is equal to transmission capacity of power grid known as weak grid connection, which having voltage regulation sensitivity to change in load. Also with the random nature of wind power WF generate fluctuating power. SCIG demands reactive power. The interconnection of wind farm to weak grid by using unified power quality compensator (UPQC) presented in [73]. Simulation carried out 36, WT SCIG with total capacity 21.6 MW, each turbine attached with fixed reactive compensation capacitor bank 175 kVAr, connected by transformer 630/0.69 kVA. MATLAB Simulink used. System, turbine rotor associated model, induction generator, and dynamic compensator viz. A simulation model of UPQC used, in the strategy it can be seen as power buffer. As such, compensation strategy using UPQC successful demonstrated. In [74] distribution system, using SCIG model, use of fixed capacitors, SVC and STATCOM. MATLAB/Simulink used for simulation, SCIG wind generator and 33 bus distribution system of Tai Power Company used for simulation.1.5MW wind turbine used. 25MVA main transformer with system short circuit rating 780 MVA. The result indicates that with the application of FACT device, the voltage fluctuation at POI and WG with wind speed change is small as a improve dynamic response. The voltage response at POI and WG is better when STATCOM is used as compared to fixed capacitor and SVC.

In [75], the authors proposed CF-UPQC for FSWG for micro grid, mitigate voltage sag, voltage swell, reactive power compensation, current harmonic rejection and frequency regulation. For all the

Table 8
Wind farm hybrid.

Combinationapproach	Methodology/result
PMSG,STATCOM &VSC	Control voltage stability for hybrid wind farm. Control strategy (1) the management of active and reactive power injected by PMSM is achieved by grid side VSC (2) control of PMSM along with dc link regulation by machine side VSC. Modeling of electrical PMSM, turbine mechanical system, VSC model. The PMSM, IM and VSC and control strategy are implemented via realistic model using sim power system block set of MATLAB [76]
FSWT & VSWT Hybrid	Model system is used PMSG 5MVA is connected to 11.4 KVA distribution system through frequency converter. Two IG rated at 2.5MVA connected in series and parallel to high voltage side of 5/11.4 kV transformer and short underground cable. WT, converter and inverter modeled [77]
FSIG & DFIG Hybrid	Simulation by using PSCAD/EMTDC for different fault conditions. It shown that FSIG can effectively be stabilized by DFIG during fault condition. Wind farm model is used, in each WF 1DFIG and 3SG used. The IEEE NON Elastic water column without surge tank turbine model and PID control including pilot and servo dynamic speed governing system is used for synchronous generator. DFIG control, rotor side converter control, simulated [78]
SCIG & STATCOM	A wind farm comprising of six 1.5MW total 9MW SCIG considered, and same is to be connected to 33 kV distribution system at 6MW load point. The system consists of 132 kV, 50 Hz, grid supply feeding to 33 kV distribution network. Two loads in system 50MW at 0.9pf lag and 6MW 0.9p.f lag. Dynamic compensation by STATCOM [79]
SVC-STATCOM Hybrid	Partly sealed SVC and STATCOM device in single unit having current injection capability. Modeling and simulation on PSS/E and RTDS 100MVA wind farm(DFIG) [80]

Table 9
International grid code compliance requirement for integration of large scale wind farms.

Grid code, country	LVRT requirements				HVRT requirements		Power factor	
	During fault		Fault clearance		During swell			
	V_{min} [PU]	T_{max} [s]	V_{min} [PU]	T_{max} [s]	V_{max} [PU]	T_{max} [s]	Leading	Lagging
Australia	0.0	0.4	0.7	2.0	1.3	0.07	0.93	0.93
Canada	0.0	0.15	0.75	2.0	1.2	0.2	0.9	0.95
Denmark	0.0	0.15	0.6	0.7	1.2	0.1	0.995	0.995
Germany	0.0	0.15	0.9	1.5	1.3	0.25	0.95	0.925
India	0.15	0.3	0.85	3.0			0.95	0.95
Ireland	0.15	0.625	0.9	3.0			0.95	0.95
New Zealand	0.0	0.2	0.9	1.0			0.95	0.95
Spain	0.0	0.15	0.85	1.0			0.91	0.91
UK	0.15	0.14	0.8	1.2			0.95	0.95
USA (WECC)	0.0	0.15	0.9	1.5	1.2	1.0	0.95	0.95

controllers the mathematical modeling carried out. MATLAB/Simulink used, topology carried out for voltage sag, current harmonics and frequency variations, CF-UPQC simulated. The effect of FSIWTG on steady state under unbalanced condition, supply frequency fluctuation conditions observed. Results indicated that, CF-UPQC, behave satisfactorily, under steady state and transient conditions. UPQC is one of the best solutions in case of SCIG weak grid interconnection and micro grid problems related to power quality for FSWG.

Fixed speed induction machine, the wind farm were common in the late 1980 s and 1990 s, at that time wind power production was very less. FSWT were not capable of controlling their reactive power consumption and having very low LVRT capability. So they become obsolete day by day with the wind power generation system where the grid code requirement is very stringent. Technical solution generated, in order to assure that wind farm comply with the grid code for their entire life span. Most commonly used approach is based on the use of STATCOM, DBR to compensate reactive power requirements, but this approach increase cost factor, but not increase steady state active power capacity of the wind farm. The alternative is a hybridization of induction generator with permanent magnet synchronous generators or with a doubly fed induction generator to adjust reactive power requirement with hybridization in proper ratio. The researchers [76–79], has presented with different solution approach, the active power capacity enhancement and reactive power support to wind farm having an induction generator with hybridization by PMSM, STATCOM, VSC, VSVT and DFIG. Also, given solution for weak grid even it is shown that hybridization is a classic solution for STATCOM. However the simulation carried out using MATLAB/SIMULINK or PSCAD/EMTDC to prove the results under various fault conditions. Table 8 gives hybridization of wind farms.

3.3. Wind farm grid integration and HV DC network

For large non grid connected wind farms where the requirement of reactive power is more, as well as the transmission losses are high, the authors [81–84] has considered the use of HVDC in PMSG wind farm where DC architecture is most suited. In [81], the authors proposed PMW rectifier and DC voltage is boosted up to several hundred of kilovolt. The 200MW wind farm is simulated. Solution approach elimination of reactive power and voltage problem in large scale wind farm by integrating HECI park where the fluctuant power, whole power is consumed, with DC architecture with the help of DC/DC converter, HVDC transmission line. Offshore wind farm power transfer through long transmission lines, the problem of voltage fluctuations, harmonics and flickers are sorted out by use of VSC-HVDC transmission[82], the controller which is designed based on DPC having good performance and quickly compensates reactive power, DC voltage and there is little DC fluctuation when active power changing. For multi terminal HVDC, control droop design was used [83]. The effect has been worked out on HVDC network, for loss of AC network [84] and it is observed that there is no significance difference of loss of AC network over transient stability on DC network. In study in AC/DC hybrid system of Shandong province [85] it was lastly concluded that LVRT is compulsory requirement for wind farm. The approach of transferring off grid large wind power with VSC–HVDC is better approach not only reactive power but also reduce transmission losses.

The researchers [86–91] have presented the technical requirement related to the connection of wind farm to the main grid/different grid code used in various countries. International grid code compliance requirement for integration of large scale wind farms are detailed in Table 9. Grid codes require that wind farms must be capable of operating continuously within the voltage and frequency variation limits encountered in normal operating conditions. In addition, they should remain in operation in case of frequency deviations outside the normal operating limits for a specified time and in some cases with a specific active power output. By having the ability to remain connected to the grid for a wider frequency range, wind farms support the system during abnormal operating conditions and allow for a fast system frequency restoration. In Table 10 frequency limit in the international grid code to be followed by wind farm depicted. The use of static capacitors in distributed way is one of the solutions to meet grid code[86]. To ensure an appropriate level of safety, reliability, electrical and soil parameters, whether wind farm generation is fed into the grid or isolated load decode the wind turbine selection, voltage regulation, system stability, voltage fluctuations, harmonics are other electrical issues[87]. Power performance indicators are related to wind turbine, type of generators based on four type fixed speed concept based on SCIG, limited variable, speed-rotor wound induction generator, improved variable speed with DFIG, variable speed permanent magnet generator and SCIG. Use of STATCOM, SVC required for power quality and reactive power management [88].

Fixed-speed wind turbines with squirrel cage induction generators have a very limited LVRT capability. They are constantly absorbing reactive power from the grid for their magnetization. During low voltage faults they tend to over speed and they can become unstable, suppressing further the grid voltage. Variable-speed wind turbines with full rated converters can ride through the faults without significant problems and they can deliver reactive power for voltage support.

The Constant voltage target is not suitable to the entire wind farm. Constant power factor control target should be selected to ensure voltage stability, but also reactive power control and voltage control strategy [89]. Plants control their reactive power using voltage or VAR/p.fcontroller. The grid code requirement of voltage control as per grid operator is defined as per steady state requirement and dynamic requirements. Switched capacitor is installed when more steady state VAR is needed and STATCOM is installed when more dynamic range of VAR is needed. Plant voltage control is based on proportional control. Centralized voltage control also used with central controller, communication delay can be problematic in order to fulfill fast response to voltage disturbance.

In [90], the authors have presented centralized voltage control scheme used in WPP with dynamic VAR. The disconnection of wind farm under voltage disturbance cannot be acceptable when wind farm contribute significant part of total network [91], the fixed speed wind turbine SCIG directly connected to grid; shows satisfactory LVRT and HVRT capability; dynamic response can be improved with use of FACTdevices. DFIG& PMSM rotor speed can widely change according to wind speed, regulating their active and reactive power as such meet strict regulation power curtailment and reactive power control, and facing problem in transient response under fault condition. The LVRT and HVRT capability of DFIG is very limited. Strict regulation on power curtailment is defined.

The wind speed model considers the effect of tower shadow and interaction of blade rotation with wind turbulences. Turbulence intensity, site parameter effect on wind turbulence/ratio of the grid impedance effect of grid parameter on flicker is required to be taken into account. The comprehensive wind speed and WT model can be applied for power quality study [88]. The results indicate voltage fluctuations are widely affected by grid strength and X/R ratio of grid internal impedance. The flicker emission will decrease with higher fault level. In [92], the authors presented, large scale Wind farm connected to the power grid with integration and operation issues that is to meet fault ride through condition. The simulation carried out through PASCAD/EMTDC. SCIG considered, modeling of wind turbine and two case studies carried out one FSIG connected with SVC at PCC and second combination of DFIG and FSIG.

Table 10
Frequency limit in International grid code.

Country	Frequency limits Hz	Maximum duration
Australia	$49.5 < f < 50.5$	Continuous
	$49.0 < f < 51.0$	10 min.
	$48.0 < f < 51.0$	2 min.
	$47.5 < f < 52.0$	9 s.
Canada	$59.4 < f < 60.6$	Continuous
	$58.5 < f < 61.5$	11 min.
	$57.5 < f < 61.7$	1.5 min.
	$57.0 < f < 61.7$	10 s.
	$56.5 < f < 61.7$	2 s.
	$55.5 < f < 61.7$	35 sec
Denmark	$48.5 < f < 51.0$	Continuous
	$48.0 < f < 51.0$	25 min.
	$47.5 < f < 52.0$	5 min.
	$47.0 < f < 52.0$	10 s.
India	$49.0 < f < 50.5$	Continuous
	$47.5 < f < 51.5$	WF remain connected
Germany	$49.0 < f < 50.5$	Continuous
	$48.5 < f < 51.5$	30 min.
	$47.5 < f < 51.5$	10 min.
	$46.5 < f < 53.5$	10 s.
Ireland	$49.5 < f < 50.5$	Continuous
	$47.5 < f < 52.0$	60 min.
	$47.0 < f < 52.0$	20 s.
UK	$47.5 < f < 52.0$	Continuous
	$47.0 < f < 52.0$	20 s.
USA	$60 < f < 59.5$	Continuous
	$59.5 < f < 59.3$	10 min.
	$59.3 < f < 58.7$	10 s.

Wind farms contribute to voltage regulation in the system, as conventional power plants do. They must have the ability to generate or absorbs the reactive power in order to influence the voltage level at the point of common coupling (PCC).

3.4. Other related works, control algorithm, PVC and SVC, controllers

The authors [93–98], presented optimization of the algorithm by using the sweep algorithm, fuzzy logic analytic hierarchy process and Mean, Variance Mapping Optimization(MVMO) algorithm respectively for reactive power management and voltage control of wind farm. Using fuzzy logic analytic hierarchy process, sweep algorithm [93–94] modeled approach based on simulation suggested for distributed generation and its reactive power requirements. Control strategy based on SOSM, a super twisted algorithm with variable gains applying MIMO system with objective stator reactive power regulation and active power optimization [95], for DFIG and with proper optimization of algorithm approach the loss of active power is avoided and better performance of wind farm and secondary voltage profile. In case of use of MVMO actual field condition simulated [96]. Data acquisition system considered, with actual data status of transformer OLTC, Var source availability of WPP and actual limit of grid code requirements at PCC. Simulation used, 18 WG of 5MW considered, connected to grid via 220 kV line and two number 100MVA transformer equipped with OLTC, through 30 KM cable of rating 110 kV. The excessive charging current of submarine cable is compensated by connecting shunt reactor of rating 500 Ω, on one side of cable. Taking use of tracking, actual wind generator condition, transformer OLTC setting and reactive power compensation equipment within WF online reactive power control carried out. Suggested approach is successful optimally operate WPP and control reactive power demand. Using adaptive particle swarm optimization embedded in Newton Raphson load flow program (APSO), the rotor side as well as line side controllers are used along with APSO[97]. Adaptive Network based Fuzzy Inference System

[98], utilized for stability enhancement of a power system with a PMSG and DFIG based offshore wind farm.

The LVRT requirement force WT to maintain their operation and supply reactive power. When grid fault take place the disconnection of WT leads to shortage of reactive power which can cause system outage. Detect grid fault to minimize transient stage of wind turbine under LVRT.The authors [99], presented control scheme of LVRT in wind turbine using DPC based sliding mode control. Two MW PMSG wind power system simulated, System consist of generator side and grid side inverter and DBR improve system stability by using control. The control of grid side converter using DPC-SMC improve the LVRT control performance DPC-SMC scheme has characteristics of robust and fast dynamic response and disturbance of DC-link reduces compared to PI controllers when fault occurs.

The researchers in [100], presented the application of rotary frequency converter for a wind farm system to match the frequency between grid and wind farm. The converter has a synchronous generator and DFM. The synchronous motor is connected to wind farm to supply voltage to induction generator, both are mechanically coupled by shaft, tuning the current of the secondary winding supplied by Cyclo- converter or self-commuted inverter GTO INV controls the output power. The test model simulated, normal generation considered 800MW, wind generation of 300MW with RFC connected to 1100MW load infinite bus. LFC test performed using a simplified model, but using the nonlinear characteristic of generator and MATLAB/Simulink different conditions simulated with and without RFC for different capacity of wind farms and result analyzed. It is seen that RFC improved the wind power quality and better alternative than use of HVDC.

In [101] presented the static and dynamic performance of wind turbine with ADRC controller. Wind turbine and wind generator modeled, 1.5MW DFIG considered and simulated on MATLAB. The wind turbine system control with auto disturbance rejection simulation which consists of the extended state observer, tracking differentiators and nonlinear state error feedback simulated. Mathematical model of VSCF wind turbine used. ADRC has shown excellent performance as compared with PID. The authors in [102], presented the voltage and reactive power control through grid side controller.

4. Key findings

Thorough review of 102 research papers in the issue of voltage and reactive power requirements of wind farm reveals that simulations and mathematical modeling carried out by most of the researchers and some researchers have carried out the real implementation of proposed system or field conditions and results evaluated for reactive power requirement under steady state, transients conditions. Some of the key points concluded as under:

- The wind farm having installed Permanent Magnet Synchronous Generators which are generally high capacity wind machines, the use of STATCOM for reactive power management and improvement of power system voltages proves to better alternative.
- In case of Squirrel Cage Induction Generator wind plants and in VSVF which give rise to flexible power flow the SVC, STATCOM, DVR, and, UPFC are successful to maintain reactive power and voltage requirements.
- The constant voltage target is not suitable for all the wind farms. Constant power factor control target should be selected to ensure voltage stability, but also reactive power control and voltage control strategy.
- The STATCOM used to improve the behavior fixed speed wind generator facing this problem during voltage dip and increase stability margins, but increase mechanical stress also.
- Capacitor / ultra-capacitor, hydro pump storage, flywheel, SMES, batteries STATCOM with battery storage system is better technology for bidirectional control of reactive power, improve the power quality.
- Use of AVR, PWM Inverter method, although used for reactive power management are relatively used in less capacity wind farm or small wind farm.
- BESS is used to reduce the local wind generation curtailment under high local wind power generation and low system load.
- Fly Wheel Energy Storage System is also considered for integration of wind plants in micro grid.
- In case of isolated wind generation to avoid reactive power requirement DC network for large scale non-grid connected wind farm proposed and analyzed. DC to DC converter and HVDC transmission system considered to avoid transmission losses.
- Grid code requirements of voltage control as per grid operator is defined as per steady state requirements and dynamic requirements. Switched capacitor is installed when more steady state VAR is needed and STATCOM is installed when more dynamic range of VAR is needed.
- In case of off grid, large wind farm, the requirement of reactive power is more at the same time being off the grid, for such bulk wind power transfer to main grid without the use of SVC, STATCOM or FACT devices the HVDC system is the best option with DC to DC converter.
- Rotary Frequency Converters also used in wind farm, frequency control device to match the frequency between grid and wind farm, RFC improved the wind power quality and better alternative than the use of HVDC.

5. Conclusions and recommendations

Wind turbine coupled with induction generator always have problem of voltage and reactive power. Researchers have used the devices/methodology as STATCOM, Static Var Compensators, FACT devices, OLTC & Switching Capacitors, Combination of SVC & STATCOM, FRC, Voltage Compensation methods, PWM Inverter, Dynamic Breaking Resisters, Voltage Droop method and combination of Capacitor and Inductor. Amongst the various methodologies, the use of OLTC, DBR and Manual switched Capacitor banks cannot take care of voltage flicker and harmonics. For PMSG, the use of STATCOM proves to better alternative. Improve the behavior of fixed speed wind generator during voltage dip and increase stability margins, but increase mechanical stress also. The constant voltage target is not suitable to the entire wind farm. Constant power factor control target should be selected to ensure voltage stability, but also reactive power control and voltage control strategy. Under the issue energy storage system for weak grids and hybrid, energy can be stored by using capacitor / ultra-capacitor, hydro pump storage, flywheel, SMES, batteries and fuel cells. STATCOM with battery storage system is better technology for bidirectional control of reactive power, improve the power quality. It can store as well as control active and reactive power at PCC also sustain system stability. Grid code requirements of voltage control as per grid operator is defined as per steady state requirements and dynamic requirements. The majority of grid code needs compliance of, namely low and high voltage ride through active and reactive power response during fault and after the fault. In case of off grid large scale wind farms, HVDC transmission system considered to avoid transmission losses.

SVC can improve static and dynamic stability of WF. DFIG can also support the reactive power requirement of the wind farm. The long term and short term effect of wind power penetration, relative merit, demerits and effectiveness of various methods and devices on electrical attributes, power quality requirements and grid code compliances requirements for wind power integration given.

The present researches in reactive power management for wind farms are towards, how best the increasing penetration of wind power generation, in the power system is accommodated; without compromising towards the power quality; meeting grid integration requirements; voltage stability etc. is dealt with by using reactive power compensating devices for mitigation and how, where and which device is utilized in an optimal way. However, few of the areas amongst many, mentioned below need more exploitation:-

- Analysis of transient stability of wind turbine generator system with STATCOM with Economic Dispatch of Thermal Units with the Impact of Wind Power.
- The effect of unbalanced reactive load on production of low frequency oscillation.
- The role of wind forecasting on controller complexity.
- Predictive control issues where action is to be taken with wind speed forecast such as to avoid the unnecessary OLTC, short term tap changing.
- The use of SVC & STATCOM in the actual field condition of the system, taking different types of wind farms and conventional power along with high penetration effects.
- There is a lack of information in published research for capacity and location selection, for installation of SVC and STATCOM.
- Comprehensive feasibility study for most appropriate compensation using the SVC, STATCOM Hybrid for a specific situation, which is highly price sensitive.

According to the presented review comparative effect of various reactive power controlling devices will help the selection of necessary methods for a particular situation under constraints of grid code compliance and meeting and delivering quality power within framework to the consumers.

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