Power Quality Challenges and Mitigation Measures in Grid Integration of Wind Energy Conversion Systems

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***Abstract*—Wind energy generation is a promising renewable energy source harvested through Wind Energy Conversion Systems (WECS). Since WECS have different characteristics from conventional power plants, their integration into the power system grid results in significant technical problems in terms of power quality. This paper reviews the challenges in power quality that are associated with integration of grid connected WECS in power systems and existing approaches to mitigate against these challenges. The paper focuses on control based mitigation techniques. Recommendations on future research areas to address power quality challenges resulting from integration of WECS are given.**

***Keywords*—WECS, synchronization Voltage fluctuations, Harmonics, frequency fluctuations, virtual inertia.**

I. Introduction

Increase in electrical energy demand and the rising cost of fossil fuels due to their limited reserves have given rise to the growth of renewable energy application [1-2]. Significant environmental issues associated with generating energy from conventional sources have also contributed to fast development of renewable energy sources. In 2015, wind energy was the largest source of new power generation in the United States and Europe, while in China it was the second largest. Globally, 63 GW of wind power generation was added in 2015 giving a total of approximately 433 GW[3]. Wind power generation is growing rapidly due to its increasingly competitive prices. Many countries around the world continue to enact policies to promote use of renewable energies[4].

Wind energy is harvested using wind energy conversion systems (WECS) which can be standalone [1] or grid connected [5]. A grid connected wind energy conversion system (WECS) is integrated with the grid through a power electronic interface. Different power electronics interfaces are utilized for grid connection of WECS[6] . WECS have different features as compared to conventional power plants with regard to grid integration[7]. They are distributed with many small units, independently controlled and intermittent while conventional power plants are large and centrally controlled. WECS have active power that follows wind speed variation with reactive power controlled at the generation plant level. On the other hand, conventional power generation plants have speed governors and automatic generation control for active power control as well as automatic voltage regulators for voltage control. Another difference is that conventional power plants use synchronous generators while WECS use different types of generators such as squirrel cage induction, double fed induction, or permanent magnet synchronous generators[5]. Owing to these differences, the integration of wind power generation results in technical issues to the power system grid in terms of power quality [8-9]. At the WECS side, the generation is intermittent and non-dispatchable with high fluctuations caused by varying wind speeds. At the grid side, there may be frequency variations caused by load and generation change as well as voltage sags resulting from short-circuit faults. These disturbances interact with the grid connected WECS and may lead to uncertain operating conditions. Power supply is said to be of good quality if it remains constant at acceptable, steady values of voltage and frequency with smooth sinusoidal waveform[10]. Power quality affects the overall stability and reliability of power grids[11].

Numerous research findings concerning different power quality challenges as a result of wind energy integration have been reviewed in literature. These include power fluctuations, voltage fluctuations, frequency fluctuations and fault ride through capability [12-16]. Many mitigation measures have also been reviewed [15-16]. However, few authors focus on modern control based mitigation methods. Thus there is need to review existing and modern control based mitigation methods with the aim of guiding further research work in this field. This paper offers a review of power quality challenges as a result of integration of WECS into the power grid and focuses on modern control based mitigation techniques. Recommendations on future research areas are also given. The outline of the paper is as follows: In Section II, power quality problems as a result of integration of WECS are reviewed. Existing control based methods for power quality improvement are summarized in Section III. Conclusions and future research areas to address power quality challenges are recommended in Section IV.

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II. Power Quality Challenges Due To Integration of Wind energy Conversion Systems

From the literature reviewed, the main challenges in power quality as a result of grid integration of WECS are identified as power fluctuations, voltage fluctuations, frequency fluctuations, harmonics and fault ride through capability.

A. Power Fluctuations

Power generated by a WECS is proportional to the cube of wind speed and thus fluctuates significantly when wind speed varies. The challenges caused by wind power generation fluctuations include active and reactive power generation fluctuations causing flickers at the point of common coupling (PCC), grid frequency fluctuations and increased instability problems in the power system [12]. The power fluctuations may also cause power swings on the transmission lines making them incapable of meeting the load demand [13]. With large penetration of wind energy generation into a grid, a larger reserve power is required to balance the grid during weak wind conditions.

B. Voltage Fluctuations

In grids with high penetration of wind energy generation, wind speed variation can cause significant voltage output fluctuations at PCC, thus affecting the normal operation of the power system [14].The size of the voltage variation and unbalance at the PCC is also dependent on the system impedance and short circuit power level. This means the effects of voltage fluctuations are more pronounced in weak grids. Voltage fluctuations disturb sensitive electronic equipment and often lead to significant reduction in their life span. The impacts of WECS on the system voltage fluctuations can be categorized by voltage sag, voltage swell, voltage flicker and voltage unbalance [15-18]. IEC 61400-21 requires that the average voltage fluctuation within a 10-minute duration should be within ±5% of its nominal value for a WECS.

C. Frequency Fluctuations

Disturbances that cause power imbalance between demand and generation in a power system result in frequency excursions. Conventional generation power plants are able to regulate frequency during such disturbances because the synchronous generators used store large quantities of kinetic energy as a result of inertia from their large rotational masses. The kinetic energy can be absorbed or released in compensation for the imbalance in mechanical and electrical power of these generators [19]. In a conventional synchronous generator, its speed governor controls the mechanical power input to regulate system frequency. The exciter adjusts field voltage to control system voltage [19]. Once a frequency fluctuation occurs as a result of a disturbance, the rotational inertia in the system counters the initial frequency fluctuation until the primary reserve restores the frequency to steady-state [20]. The power electronic converters that interface WECS to power grids are static with no rotational energy, leading to almost zero inertia. This means that high penetration of wind power generation in a system grid reduces its equivalent rotational inertia. Frequency stability is defined as the ability of a power system to maintain steady frequency following a severe system disturbance resulting in significant imbalance between generation and load [21]. Since frequency is inversely proportional to the system equivalent inertia, low moment of inertia in a grid results in frequency stability degradation, thus causing large frequency oscillations during severe disturbances[22].Frequency control is more difficult in systems with low rotational inertia since frequency dynamics are faster in such cases [23-24].

D. Harmonics

Harmonics in power systems are associated with distortion of the voltage or current's waveform produced by nonlinear elements especially power electronic devices and reactive power compensators [11].WECS contribute to harmonics due to the switching of the power electronics in the interfacing inverters. The total harmonic distortion at PCC depends on the design of the interfacing inverter in terms of topology, control method and choice of components.

E. Fault Ride Through Capability

Fault-ride through capability requires a WECS to remain connected to the network and stable during the network faults. This is because at high wind penetration, disconnection from grid can threaten security standards or lead to system cascaded failure [25-26]. Thus a WECS should remain connected and stable during a fault when voltage at PCC drops below its nominal value for a short period of time. WECS are also supposed to remain operational during asymmetrical and symmetrical faults and voltage dips for voltage recovery support by supplying the required reactive current [27].

III. Control - Based Mitigation Methods

For systems with low penetration of wind generation, power quality issues are usually implemented at the WECS level, and the solutions are usually at the WECS and local grid level. For high wind generation penetration levels, grid-level mitigation methods are required [28-29].

A. Mitigation methods against Power fluctuations

Power fluctuations are mitigated by power smoothing methods which can be classified into Energy storage based and non-energy storage based methods[30]. Energy storage systems (ESS) that can be integrated in a WECS for power smoothing include ultra-capacitors, batteries, superconductive magnetic energy storage (SMES), fuel cells and flywheel energy storage system (FESS) [31-33]. Non-energy storage based methods include inertia control methods [34-35], pitch angle control methods and DC link voltage control methods [36-37]. A detailed review on application of Electrical Energy Storage Systems to mitigate against power fluctuations in large wind power plants is presented in [37].

B. Mitigation methods against Voltage fluctuations

From the reviewed literature, the various methods employed to mitigate against voltage fluctuations can be classified into conventional methods and electrical energy storage systems based methods.

1) Conventional Methods

Reactive power compensation is one of the most effective mitigation methods against voltage fluctuations. Traditional devices for voltage control include passive reactive compensators, transformer tap changers, synchronous condensers and phase shifting transformers [21]. Flexible Alternating Current Transmission Systems (FACTS) are power electronic devices that control active and reactive power transmission in power systems [38]. They are classified as series, shunt or shunt-series, depending on their connection to the power system grid [39]. Series connected FACTS include static synchronous series compensator (SSSC) and thyristor controlled series capacitors (TCSC)[40].Shunt connected FACTS include static synchronous compensator (STATCOM) and static VAR compensator (SVC). Combined series-shunt connected devices include unified power flow controller (UPFC) which control voltage and power flow simultaneously [41],[38]. The advantages of FACTS utilization in power systems are outlined in [40]. Comparison of the performance of the various FACTS devices is shown in Table I[15].

TABLE I. COMPARISON OF FACTS DEVICES

Service \ FACTS Technology	SVC	STATCOM	TSCS	SSSC	UPFC
Reactive power generation / absorption	Good	Excellent	Limited	Excellent	Excellent
Voltage control	Good	Excellent	Limited	Limited	Excellent
Flicker mitigation	Good	Excellent			Excellent
Harmonics reduction		Good		Good	Excellent

Legend: Excellent (red), Good (yellow), Limited (blue)

The type, size and location of FACTS devices significantly affect their impact on transmission systems[41-42].This means that the most appropriate and best sized FACTS devices should be installed at the best location to achieve effective mitigation against voltage fluctuations in a system [43]. "FACTS allocation" problem consist of finding the optimal type, size and location of FACTS devices and is an active research area [40],[43].

2) Electrical Energy Storage based Methods

Energy Storage Systems (ESS) have flexibility in their capacity of charging and discharging. They can be incorporated in a WECS to maintain the local voltage level at PCC within required limits by supplying the required reactive power. This objective is achieved through a grid connected full scale converter[44]. Planning for ESS installation requires proper selection of the type, location and size of the ESS, depending on the reactive power requirements of the grid connected WECS.

C. Mitigation methods against Frequency fluctuations

The main mitigation methods against frequency fluctuations identified in literature are superconductive magnetic energy storage (SMES) and virtual inertia systems.

1) Superconductive Magnetic Energy Storage (SMES)

A Superconducting magnetic energy storage (SMES) is a superconducting coil that stores energy in a magnetic field generated by the dc current flowing through it [45]. It can rapidly absorb and release energy in response to fluctuations of the wind power generation. It also has high efficiency, long life time and high power density, making it an appropriate solution to energy storage in wind power generation. Applications of SMES in grid connected WECS include minimization of system frequency fluctuations and regulation of output power [30]. SMES has been applied in [45] to minimize output frequency fluctuations of a wind farm for an isolated power system. The limitation of SMES technology is the high capital investment required [37].

2) Virtual Inertia based methods

One of the modern solutions to frequency fluctuation challenges in power systems with large penetration of wind energy generation is addition of virtual inertia. Virtual inertia is created by innovative control of grid side interfacing inverter. Such virtual inertia systems should operate in an autonomous way within a short time interval (typically less than 10s) to mitigate against frequency fluctuation [46]. Fig.1 shows the effects of virtual inertia[46]. The most popular virtual inertia implementation methods are synchronverters, Virtual Synchronous Machine (VSM), droop control method and inducverters.

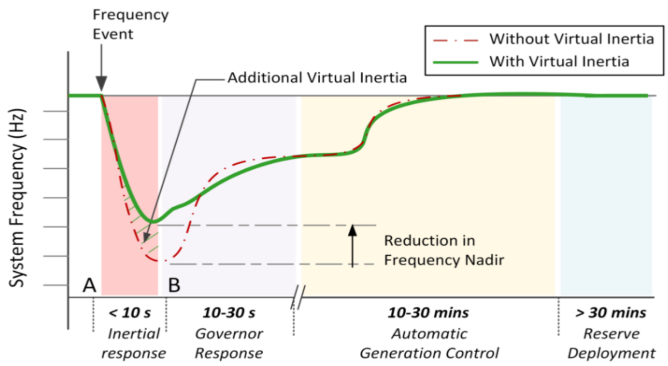

Fig 1: Effects of Virtual Inertia

a) Synchronveters

A synchronverter is an inverter that is equipped with a control algorithm to emulate the operation of a synchronous generator for frequency control [47]. It drives the inverter-based WECS with the same dynamics as a synchronous generator from the grid point of view. This control methodology allows operation of the power system in the traditional way without major structural changes in operations [48]. The mathematical equations of a synchronverter form an enhanced phase locked loop (PLL) which makes it capable of maintaining synchronism with the terminal voltage.

b) Droop control method

A droop control technique emulates the operation of a governor and exciter in conventional synchronous generators and determines output frequency and voltage of a distributed generator according to the active and reactive powers derived from their terminals [48]. The authors in [49] studied the similarities between frequency-droop controllers and VSM-based control. Droop control method enables load sharing among parallel connected VSC units as well as stand-alone operation during transient and steady state operation, similar to traditional synchronous machines. However, it is limited in speed of transient responses and improper transient active power sharing.

c) Virtual Synchronous Machine(VSM)

Virtual synchronous machine (VSM) method was proposed by Beck and Hesse in 2007 for renewable energy integration [50]. It consists of a power electronics converter, an energy storage device and a dispatching algorithm to mimic a synchronous generator for frequency control [22]. The energy storage device is a DC source like batteries or a super capacitor. The schematic of the VSM is shown in Fig 2.

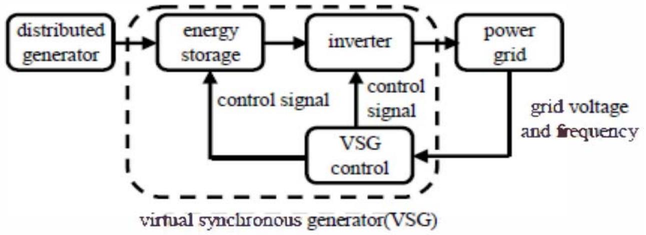

Fig 2: Block diagram of a virtual Synchronous machine(VSM)

The VSM mimics the damping and inertial properties of a synchronous generator by absorbing or injecting active and reactive power based on the system frequency changes [50]. Different implementations of the VSM concept are explained in [48]. The authors in [46-47] simulated a synchronverter and observed system frequency after a step-increase of 2 kW load. Fig.3 shows the results. Simulation of a virtual synchronous generator was done in similar conditions as shown in Fig. 4[46], [57].

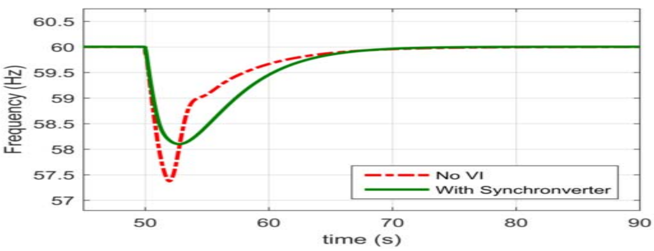

Fig 3: Simulation of a synchronverter showing system frequency after a step-increase of 2 kW load [47].

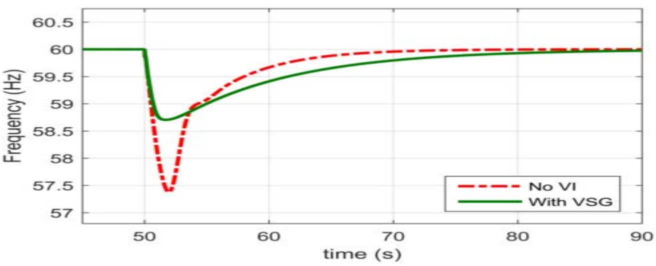

Fig 4: Simulation of a virtual synchronous generator showing system frequency after a step-increase of 2 kW load.

From Fig. 3 and Fig.4, it can be seen that the VSM gives better performance in terms of minimum frequency but has longer settling time than synchronverter. Higher settling time leads to higher energy exchange. The synchronverter is thus more suitable for isolated power systems as it can operate independently as a grid forming unit. On the other hand, the VSG is a grid following unit with added inertial response capabilities. It is thus more suited for grid connected power systems.

d) Inducverter

An inducverter is a recent control topology that mimics induction generator behavior in a power system [51]. It enables auto-synchronization with a grid without the requirement of information about grid voltage. It thus eliminates the extra synchronization unit and phase-locked-loop (PLL), resulting in a simplified control strategy with improved performance. The inducverter has a physical part consisting of a converter with a filter circuit and a software part which is the controller. Fig. 5 shows the block diagram of an inducverter[51]. Although the concept is still new, it has the potential to address the challenges in the conventional outer synchronization loop, while preserving synchronization and damping properties of a virtual inertia system [52].

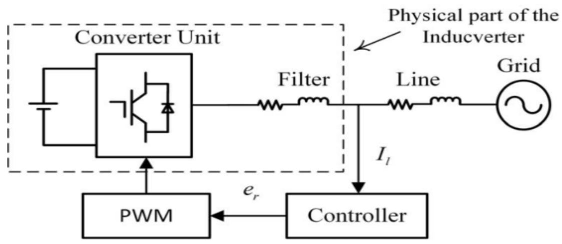

Fig 5: Block diagram of Inducverter

D. Mitigation methods against Harmonics

The main mitigation measures against harmonics in grid connected wind energy conversion systems include filters, virtual impedance control method and multifunctional grid tied inverter.

1) Filters

Passive filters have traditionally been used in grid connected systems to mitigate against series harmonics. Their limitations include larger size, fixed compensation, specific load ranges and filter impedance [53]. Active filters generate harmonic currents to cancel out the harmonic currents caused by nonlinear loads by use of power electronic switching [53-54]. Shunt active power filter (SAPF) is a common solution to mitigate against harmonics through current harmonics compensation and reactive power [55]. Hybrid active power filters are also popular especially for high power applications [56].

2) Virtual impedance control method

Virtual impedance is an innovative lossless circuit-oriented control concept. It is utilized for harmonic compensation by shaping the control output impedance[54]. A virtual impedance is placed between the interfacing inverter output for a WECS and the main power grid to enable improved harmonic compensation sharing among multiple WECS units according to their ratings [54]. Virtual impedance control method results in improved harmonic mitigation and improved system performance during transient and steady state faults [58].

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3) Multifunctional grid tied inverter

This is an advanced grid connected inverter, which interfaces a WECS into the power system grid with an auxiliary service of compensating harmonic and reactive current to enhance power quality at the PCC [59-60].

E. Methods to enhance Fault ride through capability

A survey of fault ride through capability enhancement methods used in various topologies of WECS is presented in [61]. The main control based methods are pitch angle control, crowbar method, use of energy storage systems [62-64] and voltage compensation[44],[65]. A comparative analysis of these methods is presented in [26].

IV. CONCLUSION

In this paper, the major power quality issues as a result of WECS integration into the grid have been reviewed. The existing state of the art control based mitigation methods have also been studied. For power quality improvement with regard to grid integration of wind energy conversion systems (WECS), future research areas are recommended as follows:

1) Optimization of existing control strategies of WECS topologies to mitigate against voltage fluctuations, harmonics, and frequency fluctuations should be explored.

2) Innovative control schemes of grid interfacing inverters for WECS that enable coping with grid-side disturbances should be implemented to improve WECS fault ride-through capability.

3) Detailed mathematical modelling, intelligent control and tuning of Virtual Synchronous Machine (VSM) parameters to improve its performance in voltage and frequency control of WECS is a potential research direction.

4) The application of inducverters is a relatively new technique that can potentially address the challenges of PLL synchronization method at the same time preserving the synchronization and damping properties of virtual inertia. It is a potential research area.

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