Abstract—Grid integration of intermittent renewable energy sources like wind and solar is usually associated with power quality disturbance especially when the penetration level is high. This paper investigates the power quality issues associated with grid connected wind power plant (WPP) and how to overcome such problems using static synchronous compensator (STATCOM) – a member of Flexible A.C Transmission System (FACTS) devices. The major power quality issue investigated in this paper is harmonic distortions. Other power quality parameters such as voltage dip, voltage swell, flicker, transient, short and long interruptions were also briefly introduced. The entire system including the STATCOM control scheme is simulated in Simulink environment of MATLAB. Simulation results show that the harmonic contents at the output of the system with unfiltered linear loads are quite high, thus showing power quality deterioration. Fast Fourier Transform (FFT) analysis on the voltage and current waveforms of the system show that the STATCOM control scheme is capable of cancelling out the reactive and harmonic parts of the load current thereby restoring the smooth sinusoidal waveform of the voltage and current at the wind point of interconnection (POI), or point of common coupling (PCC) which signifies power quality improvement.

Keywords—power quality; STATCOM; THD; FFT; WPP.

I. INTRODUCTION

Power quality is a term used by engineers to refer to the problems associated with voltage, current or frequency deviation that result in failure or equipment malfunction. It is usually related to maintaining a smooth sinusoidal waveform of bus voltage, current and frequency [1]. Thus, a perfect power supply is one that is highly available within prescribed voltage and frequency tolerances, with smooth sinusoidal wave form and also enables equipment work properly. On the other hand, any disturbance in the magnitude, frequency or purity from the balanced three phase sinusoidal wave form can lead to deterioration of the power quality. Power quality is of great concern to consumers, utilities and equipment manufacturers. It becomes especially important with the insertion of sophisticated devices, whose performance is very sensitive to the quality of power supply [2]. Power quality study is gaining much emphasis due to the increased proliferation of sensitive equipment and the need of maintaining excellence in electrical power generation [3]. Increased research in grid integration of wind turbine and the actual project development makes power quality issues more and more important both in theory and practice.

Among all forms of power quality issues in grid connected wind power plants (WPP), harmonic distortion is more common since any deviation from a perfect sinusoidal wave shape in voltage, current or frequency is an indication of the presence of harmonics in the power system. Due to the wide-spread use of power electronic devices in residential, commercial and industrial loads, electric utilities have experienced an increase in the level of harmonic frequencies on their electrical delivery systems. Hence, the potential harmonic effects on power equipment and system operation are becoming a concern for the utilities.

In response to the aforementioned challenges, some utility operators and wind farm vendors usually assess the quality of power supplied to major customers through measurement and analysis to ascertain whether the harmonic levels are within allowable limits as recommended by regulating bodies like IEC and IEEE. Fortunately, intensive research in power electronics has lead to the development of flexible a.c transmission system (FACTS) devices for power quality improvement. Such devices are capable of mitigating power quality disturbances with respect to grid codes and provide power system stability by controlling the power flow in a transmission network using power electronic controlled devices [4]. FACTS devices are categorized into two, namely; Thyristor-based FACTS controllers and GTO based FACTS controllers. Members of the first category include Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR), e.t.c. The second category includes static synchronous compensator (STATCOM), Static Synchronous Series Compensator (SSS), Unified Power Flow Controller (UPFC), e.t.c.

II. POWER QUALITY PARAMETERS AND THEIR CONSEQUENCES

A. Harmonic Distortions

Harmonic distortion refers to the periodic deviation of voltage (or current) sine wave from a smooth sinusoidal shape and usually occurs when frequencies of the multiple integers of the fundamental frequency are added to the pure sinusoidal waveform of the voltage (or current). Harmonics are therefore
integer multiples of the fundamental frequency. Total harmonic distortion (THD) is a measure of all the values of the waveform that are distorted.

At the generation end, harmonics are usually caused by power electronic converters used in variable speed wind turbine, while at the receiving (consumer) end, harmonics are caused by non-linear loads (equipments that do not use voltage or current in normal sinusoidal shape) such as computers, television, arc furnaces, arc welders, mercury lamps, electronic ballasts, battery charger, variable speed drives, medical diagnostic equipment and fluorescent lamps [5]. Other causes of harmonics include resonance phenomena, transformer saturation, light dimmers and switch mode power supplies.

Harmonics can cause significant damage to transmission and distribution network as well as to consumer equipment. The most notable effects of harmonic distortions are; overload operation of electric motor, nuisance tripping of circuit breaker, misbehaved operation of fuses, tripping of variable speed drives, overheating of electric motors and transformers, incorrect power measurement and failure or damage to electrical equipments like contactors and power factor correction capacitors.

Harmonic distortions can be mitigated by application of active conditioners, input chokes, passive filters, isolation transformers, and equipments with build-in power factor correction capability such as FACTS devices like STATCOM, DVR, SVC.

- **Harmonic Distortion in Bus Voltages**

  The total harmonic distortion of bus voltage, \( V_{THD} \), is defined as the ratio of the square root of the sum of squares of the rms value of the harmonic component, \( V_h \), to the rms value of the fundamental component, \( V_1 \) [6].

  \[
  V_{THD} = \sqrt{\frac{\sum_{h=2}^{40} V_h^2}{V_1^2}} \times 100
  \]  

  For 132kV, the voltage THD limit is <3\% [7].

- **Harmonic Distortion in Line Currents**

  The total harmonic distortion of line current, \( I_{THD} \), is defined as the ratio of the square root of the sum of squares of the rms value of the harmonic component, \( I_h \), to the rms value of the fundamental component, \( I_1 \) [6].

  \[
  I_{THD} = \sqrt{\frac{\sum_{h=2}^{40} I_h^2}{I_1^2}} \times 100
  \]  

  For 132kV, the current THD limit is <2.5\% [7].

  It can be seen from equations 1 and 2 that THD is the rms value of the waveform when the fundamental is removed. The fundamental of a smooth sinusoidal voltage (or current) waveform is the system frequency (50Hz in some countries and 60Hz in others).

- **Flicker**

  Flicker is a term used to relate the short lived voltage variation that is associated with annoying changes in the luminance of lamps. It is usually caused by the two modes of operations of the WPP, namely; switching operations and continuous operations. Flicker from switching operation usually occurs as a result of start-up and shut down of the wind turbines (WTs). Continuous operations like blade pitching, wind turbulence, tower shadow, wind sheer, and yaw misalignment can also cause flicker. Furthermore, industrial loads such as welding machine, electric boilers and electric arc furnaces also cause flicker [8].

  The long term flicker, \( P_{lt} \), which is usually evaluated over 2 hours period is expressed in [9] as:

  \[
  P_{lt} = C(\phi_k) \frac{S_n}{S_k}
  \]  

  Where \( S_n \) = Rated apparent power of the WT, \( S_k \) = Short circuit apparent power of the grid, \( \phi \) = Phase shift and \( C \) = Flicker coefficient

  The limiting value for flicker coefficient is 0.4 for average value of 2 hours [10].

  The main effect of flicker is the annoying and noticeable changes in lightning levels.

  Flicker can be mitigated by controlling the power factor angle; controlling the voltage at PCC and by application of FACTS devices like STATCOM, SVC and UPFC.

- **Voltage Dip / Voltage Sag**

  A voltage dip (or voltage sag) is defined as a sudden reduction of the voltage to a value between 1\% and 90\% of its nominal value followed by a voltage recovery after a short period of time, conventionally 1 millisecond to 1 minute. In other word, it refers to the sudden reduction in the potential of electric grid usually between 10\% and 90\% of its nominal value followed by a rapid return to its normal value for duration of 0.5 cycles to 1 minute [11].

  Voltage dip, \( \Delta U_d \), at the wind point of common coupling (PCC), or point of interconnection (POI) can be expressed as a function of rated apparent power of the WT, \( S_n \), Short circuit apparent power of the grid, \( S_k \), change factor, \( K_u(\phi) \), and Phase shift, \( \phi \) [12].

  \[
  \Delta U_d = 100K_u(\phi_k) \frac{S_n}{S_k}
  \]  

  The acceptable voltage dip limiting value is \( \leq 3\% \) [13].

  In grid connected WPP, voltage dip is usually said to occurs when large wind turbines are started up together – in which case, the current drawn from the electric grid will rise to a high value for duration of milliseconds. It can also occur as a result of the start up of large motors or when there is grid short circuit [14]. Other sources of voltage dip in power system include power line switching, lightning stroke, utility and facility faults, balanced or unbalanced faults, large load changes and starting of heavy electrical loads.

  The main consequences of voltage dip include loss of data, shutdown (system halts), fail function of equipment and disconnection of sensitive loads. Other effects of voltage dip include light flicker, failure of transformers and motors, overload operation of motors, tripping of variable speed drives and loss of computer or controller memory.
In complex systems like grid connected WPP, a severe voltage dip can lead to cascading failures as result of disconnection of the wind generators that can further results in loss of generation; which will consequently affects the stability of the net power system [5]. Furthermore, the fault clearance is usually followed by high inrush current during the recovery process. The WT is required to be able to “ride through” a severe voltage dip and other power quality disturbance by remaining in operation and connected to the grid during the fault. Hence, voltage dip should be given more attention in order to avoid cascading failures in complex power system.

Depending on the condition and location in the power system, voltage dip can be mitigated by installing devices such as ferroresonant transformer, sag proofing transformer, uninterruptible power supply (UPS), coil-hold in devices, flywheel and motor-generator (MG), and FACTS devices like STATCOM, SVC and DVR.

### D. Voltage Swell

Voltage swell is a term used to refer to the increase in the rms value of a voltage or current at power frequency from 1.1p.u to 1.8p.u for duration of 30 to 60 seconds [15]. Voltage swell at the PCC is given as a function of the turbine’s maximum apparent power, $S_{\text{max}}$, grid impedance (Resistance, $R$, and Reactance, $X$) and the phase shift, $\phi$ [16]:

$$
\Delta U_s = \frac{S_{\text{max}} (R \cos \phi - X \sin \phi)}{U_{\text{n}}^2}
$$

The limiting voltage rise value is < 2% [17].

In grid connected WPP, voltage swell is usually caused by large load changes such as starting up and shutting down of large capacity WTs as well as by power-line switching. Other origins of voltage swell include sudden drop of loads, open neutral connection, unsymmetrical faults, and energizing a large bank of capacitor.

The main consequences of voltage swell include equipment malfunction, insulation breakdown, disconnection of equipment, failure or damage on power factor correction capacitor, damage to electric contactor, light flicker and tripping of variable speed drives.

Mitigation of voltage swell can be achieved by the use of transformer with tap changing, connection of large load at the PCC, application of soft starter, - a device capable of providing smooth connection and by installing FACTS devices like STATCOM.

### E. Voltage Transient

Voltage transients are sudden and significant deviations from normal levels usually of short durations (microseconds or milliseconds) and vary greatly in magnitude [18]. They are usually caused by lightning, electrostatic discharges, or load switching. Transient disturbances are sometimes called surges. The frequency of the transient is defined in [19] by the following expression:

$$
f = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}
$$

Where $f = $ Frequency of the supply

$L = $ Inductance

$C = $ Capacitance of the grid

In grid connected WPPs, transient can occur when some WTs are suddenly switched on or off, or when there is lightning discharge. Similarly, the inrush current that arises due to the connection or disconnection of induction generator can also give rise to voltage transient. Transient disturbances can also occur when mechanical switches are used to switch power factor correction devices (such as reactive power compensation capacitors). Other sources of transients include, load switching, utility fault clearing and facility faults.

The main consequences of voltage transients are insulation failure, loss of data, equipment damage, overheating of equipment, and reduced lifetime of transformers and motors. Other effects include errors on microprocessor controlled equipment, computer system data alterations, tripping of variable speed drives, misbehaved fuse operation and damage to electrical contactors and other electronic equipment.

Voltage transients can be mitigated by installing equipments with build-in power factor correction capability like STATCOM, DVR and SVC.

### F. Short Interruptions

This is a term used to refer to the total interruptions of electrical power supply for a duration ranging from few milliseconds to one or two seconds. It is usually caused by the opening and automatic re-closure of protection devices. The main impacts of short interruption are; tripping of protection devices and stoppage of sensitive equipment like computer.

### G. Long Interruptions

When the total interruption of electrical power supply exceeds two seconds, then, it is referred to as long interruptions. It is usually caused by failure of protection devices or equipment failure in the power system.

### III. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

#### A. Basic Configuration

STATCOM is a member of GTO based FACTS family. It is a shunt connected reactive power compensation device that can regulate bus voltage at the wind POI. Depending on the condition, a STATCOM can control the electric power system parameters by generating or absorbing reactive power. STATCOM is a shunt connected FACTS device whose output current (inductive or capacitive) can be controlled independently of the a.c system voltage [20]. It is capable of helping WPP to stabilize after disturbances.

Basically, STATCOM consists of two-level voltage source converter (VSC) with d.c energy storage; a coupling transformer connected in shunt with the a.c system and control devices (Fig. 1). The VSC converts the d.c voltage across the d.c energy storage device into a set of three phase a.c output
voltage. The three phase voltages are in phase with the a.c voltage and are coupled with the a.c system through the reactance of the coupling transformer. Active and reactive power control can be achieved by varying the magnitude and phase angle of the STATCOM. Thus, when fed from an energy source or energy storage device, a STATCOM can generate or absorb independently controllable real and reactive power at its output terminals. In other words, it can provide a.c power when connected to a source.

STATCOM is analogous to an ideal synchronous machine, in which case, it can generate a balanced three phase sinusoidal voltage at fundamental frequency with controllable amplitude and phase angle. Hence, it can regulate the voltage profile of the bus to which it is connected.

B. STATCOM Topology for Power Quality Improvement in Grid Connected WPP

The STATCOM control scheme is connected with the interface of an induction generator and some linear loads at the PCC with the grid network (Fig. 2). In order to maintain the power quality of the grid network, the output of the STATCOM is varied in accordance with the control strategy. The STATCOM used here is IGBT based and is capable of providing the reactive power support to the induction generator and the nonlinear load in the grid network. Specifically, the STATCOM is used to provide the reactive power support to the grid connected WPP. The design is made in such a way as to provide the required reactive power to the WPP under normal operation and also to operate as reactive power source when the wind is below the cut-in (i.e. the minimum wind speed required to starts the turbine).

The a.c voltage difference across the transformer leakage reactance results in an exchange of reactive power between the STATCOM and the power system in such a way that the a.c system bus voltage can be regulated to improve the voltage profile of the system. The VSC generates a controllable a.c voltage source behind the transformer leakage reactance. The VSC voltage is compared with the system a.c bus voltage. If the voltage magnitudes are equal, the reactive power exchange is zero. When the system a.c bus voltage is greater than the VSC voltage, the a.c system sees the STATCOM as an inductance connected to its terminals. If however the system a.c bus voltage is lower than the VSC voltage, the system sees the STATCOM as a capacitance connected to its terminals.

C. Advantages of STATCOM over other FACTS Devices

In this paper, STATCOM is used as the FACTS device for power quality improvement because of the following advantages that it offers over other FACTS family:

- It provides harmonic filtering
- It provides power factor correction
- It is faster in terms of voltage control and reactive power support
- It provides both capacitive and inductive compensation
- It has the capability of controlling output current over the rated maximum capacitive or inductive range independent of the a.c system voltage
- It has increased transient rating in both capacitive and inductive operating regions
- It can maintain full compensating current at depressed line voltage
- It can control output power and provide power oscillation damping by self generation and or absorption of reactive power
- The reactive power provision is independent from the actual voltage on the point of interconnection with the grid network
- It can produce full capacitive output current at low system voltage

IV. SIMULATION RESULTS AND DISCUSSION

A wind energy system is simulated in Simulink environment of MATLAB and connected to a simulated grid network having a non-linear load as shown in Fig. 3.

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Fig. 1. Basic Configuration of a STATCOM.

Fig. 2. STATCOM in a Grid Connected WPP for Power Quality Improvement.

Fig. 3. Proposed Grid Connected WPP with STATCOM Controller.
A. Simulation Results Without STATCOM Controller

The STATCOM controller is first switched off and a simulation is run. Result obtained (Fig. 4) shows how the wind penetration and the non-linear load contributes in deteriorating the voltage and current wave forms from being of smooth sinusoidal shape, thereby deteriorating the power quality of the system.

![Fig. 4a. 3-Phase Voltage at the Wind POI without a STATCOM Controller.](image)

![Fig. 4b. 3-Phase Current at the wind POI without a STATCOM Controller.](image)

FFT analysis on the above voltage and current waveforms of Fig. 4 gives THD level of 1.40% and 3.20% respectively which are high enough to deteriorate the power quality of the system as shown in Fig. 5.

![Fig. 5a. FFT Analysis of Voltage Waveform at the Wind POI without STATCOM Controller.](image)

![Fig. 5b. FFT Analysis of Current Waveform at the Wind POI without STATCOM Controller.](image)

B. Simulation Results With STATCOM Controller

The simulation is re-run with the STATCOM controller switched on and all other load parameters intact. The result shows how the STATCOM control scheme mitigates the harmonic current and provides the necessary harmonic compensation thereby cancelling the voltage and frequency variations on the system (Fig. 6). The power quality of the system is thus improved.

![Fig. 6a. 3-phase Voltage at the Wind POI with a STATCOM Controller.](image)

![Fig. 6b. 3-phase Current at the Wind POI with a STATCOM Controller.](image)

FFT analysis on the voltage and current waveforms of Fig. 6 gives THD level of 0.13% and 0.38% respectively. These low values of THD signify improvement on the power quality of the system as shown in Fig. 7.

![Fig. 7a. FFT Analysis of Voltage Waveform at the Wind POI with STATCOM Controller.](image)

![Fig. 7b. FFT Analysis of Current Waveform at the Wind POI with a STATCOM Controller.](image)
V. CONCLUSION

The paper has presented power quality parameters related to an electrical power system with large wind power penetration. Specifically, emphasis is given on harmonic distortion due to the increased use of nonlinear loads by consumers. The paper have also presented a STATCOM control scheme for power quality improvement in a grid connected WPP consisting of non-linear load and waveform analysis using FFT. Simulation results show that the harmonic contents at the output of the system with unfiltered linear loads are quite high. FFT analysis on the voltage and current waveforms of the system show that the STATCOM control scheme is an excellent means of cancelling out the reactive and harmonic parts of the load current thereby restoring the smooth sinusoidal waveform of the voltage and current at the wind POI, which signifies power quality improvement.

References