Optimum Impacts of Renewable Energy Generation on Voltage Dip and Voltage Profile in a Distribution Network

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Abstract— Growth in electrical energy demanded is not the sole reason to consider for an alternative energy supply options, aside from the fact that initial capital of a conventional power generation methods is higher, most of the conventional methods of electrical energy generation using coal, fossil fuels etc, are producing carbon dioxide when burned to generate energy. Human-induced climate change is already being blamed for the higher-than-usual incidence of extremely damaging weather experiences such as global warming, etc. Renewable energy generation (REG) are sustainable energy supply options and environmentally friendly that can significantly reduce reliance on fossil fuels, carbon dioxide induction and environmental risk caused by the conventional energy generation. The renewable energy generation is a subsystem on its own, In an attempt to integrate this renewable energy generation into the power system, to bring the component subsystem to one system and ensure its function together as a system, some integration/technical implications such as the impact of REG on voltage profiles, voltage dips, voltage swell, harmonic, voltage stability during grid disturbance, voltage control, reactive power consumption by most REG, interfacing, power factor problem, and frequency deviation have to be studied and investigated. The impacts of REG of wind on voltage dip and voltage profile in a distribution network are investigated in this research paper. Its behavious and contributions during grid disturbance is also examined. The outcomes indicate that the increase in integration of REG penetration levels, improves the voltage profile and also reduced voltage dip of a distribution network. During fault conditions, despite the fact that REG does not conduce to the voltage dip, it may not remain connected to the network if it cannot meet up with grid code requirement. Nevertheless, with a reactive compensatory device, REG remains connected to the network even during a disruption.

Index Terms— Electrical buses, Power quality, Grid code, Voltage dip, reactive power.

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1 INTRODUCTION

IN In the past, individual REG such as wind turbines, solar power, or smaller wind farms were connected to distribution networks due to the smaller amount of integration, thereby it is seen as negative load by most of the transmission operators [1]. In late years, owing to increased emphasis on renewable energy resources, development of suitable isolated power generators driven by energy sources such as wind, solar, has assumed greater significance, as REG from larger farms reached comparable levels with conventional power plants. Nevertheless, REG may not suddenly replace a conventional method of power generation, but with an increase in its penetration levels in a distributed network, it can bring down the total reliance on the conventional method of power generation. REG can often be utilized as back-up power to enhance reliability, deferring investment in distribution networks, reducing line losses, displacing expensive grid-supplied power, deferring construction of large generation facilities, providing alternative sources of supply in a shops and capable of reducing environmental pollutions produced from a conventional method of power generation [2], depending on the system configuration and management, these advantages may not be accessed. Local air pollution is strongly connected to energy supply choices, with coal and oil products being major contributors to urban and rural air pollution. Recently, REGs are becoming an efficient and clean alternative to the traditional electric energy sources, and latest technologies are making REGs economically feasible. However, distribution system operators' concern grew due to the contribution of renewable energy generation to the power quality challenges like voltage dips, voltage swell, harmonic, voltage instability, voltage control, intermittency, reactive power consumption by most wind generators, interfacing, power factor problem, and frequency deviation etc. Due to these challenges, power system operators issued a number of requirements for REGs to fulfil in order to get grid connection agreement. These requirements were called grid codes, and they got more demanding as renewable energy generation penetration levels increased. For the efficient integration of renewable energy generation into the grid, all these integration challenges mentioned above must be investigated to really experience the impacts of REGs and their contributions towards those aforementioned shortcomings and the method of mitigating them. Lots of research work has been done on REG integration into a distribution network, to mention a few [1]-[3]-[4]-[5], yet they are not sufficient. Nevertheless, researchers will continue to contribute their own research quota till REG's integration will get to the point of comparing to a conventional power generation without fear of integration challenges by the utility or private owned power producers.

2 POWER SYSTEM AND ELECTRICAL BUS

Power System is the interconnection of various buses. Each of these buses is associated with four electrical parameters, namely voltage (V) with magnitude and phase angle (δ), active power (P) and reactive power (Q). These four parameters are not completely known (Table 1 shows both known and unknown parameters), but in practical situation only two are known and the remaining two parameters can be calculated using load flow analysis. With load flow analysis, voltage magnitudes and angles at each bus in the steady state can be obtained. Load flow also determines if the grid voltages remain within specified limits under normal or emergency operating conditions, and whether equipment such as transformers, generator, REGs and conductors/transmission lines are overloaded. Thus, Buses classification in Figure 1 is based on the known parameters. A bus in a power system can be described as the vertical line at which the several components of the power system like REG, generators, loads, and feeders, etc., are connected.

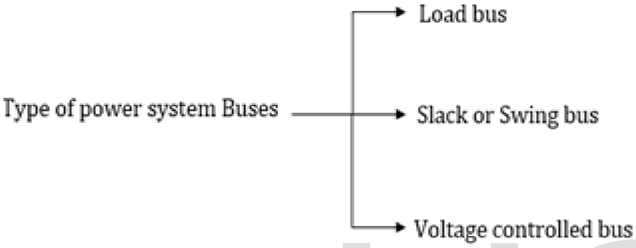

Figure 1: Electrical buses classification

Table 1: Electrical buses known and unknown parameters

Type of Buses	Know or Specified Quantities	Unknown Quantities or Quantities to be determined.
Generator or P-V Bus	P, | V |	Q, δ
Load or P-Q Bus	P, Q	| V |, δ
Slack or Reference Bus	| V |, δ	P, Q

2.1 Generator Bus/Voltage Control Bus

This bus is also called the P-V bus, and on this bus, the voltage magnitude corresponding to generate voltage and active power corresponding to its rating is assigned. Voltage magnitude is maintained constant at a specified value by injection of reactive power. The reactive power generation and phase angle of the voltage are to be computed.

2.2 Load Bus

The load bus is also called the P-Q bus and at this bus, the active and reactive power is injected into the network while magnitude and phase angle of the voltage are to be computed. Here the active power and reactive power are specified, and the load bus voltage can be permitted within a tolerable value, i.e., 5 %. The phase angle of the voltage is not very significant for the load.

2.3 Slack, Swing or Reference Bus

The slack bus is also known as Swing or Reference bus. The slack bus does not exist in actual life, instead it is acquired for the consideration of losses occurring during power transmission. In reality, there exists only two buses in power system, load bus and generator bus for which active power is specified. Since active power delivered by the generator bus and used up by the load bus differs, this signified that a power loss is equal to the difference between the generator bus (P) and load bus (P). This is because the system losses are not known just before the power flow solution, it is not possible to specify the real power injected at every passenger vehicle. The slack bus will provide the necessary force to maintain the power balance in the system. Hence, the real power of one of the generator buses is allowed to swing, and the slack bus is supplied between the scheduled real power generations and the sum of all loads and system losses. Thus, the swing bus voltage magnitude is determined and its voltage phase angle is commonly taken as the system reference and set equal to zero. This loss can only be calculated after the solution of Load Flow, therefore, to supply power loss, an extra generator bus is considered for which bus magnitude and voltage is specified and active power and reactive power are to be calculated. This active power of slack bus is the equivalent power loss occurring in different system. Based on this above explanation, it is now easier to define Slack bus in a power system. **Slack bus** is the bus that absorbs the active or reactive power from the power system. The slack bus does not carry any load, on this bus, the magnitude of voltage and phase angle of the voltage is specified, the phase angle of the voltage is usually set equal to zero. The active and reactive power of this bus is usually determined through the solution of equations. The slack bus is a fictional concept in load flow studies and arises because the I^2R losses of the system are not known accurately in advance for the load flow calculation, therefore, the total injected power cannot be specified at every bus. In fact, power flow forms the core of power system analysis and it is sometimes used as starting point for many other types of power system analyses. More also, power flow analysis is at the heart of contingency analysis and the implementation of real-time monitoring of power systems which details will not look into in this research paper. Installing a REG at a faraway location to the load bus, the impact may be significantly small, as a result, REGs should be installed as close to the load bus as possible in order to capture the full benefits.

2.4 Regs Versus Power Quality

Power quality determines the fitness of electrical power to consumer devices. Synchronization of the voltage, frequency and phase allow electrical system to operate in their intended manner without significant loss of performance. Without the proper power quality, an electrical device or load may malfunction, fail prematurely or not operate at all. The challenges of maintaining appropriate frequency and voltage level are increasing due to increasing interest in REG because power flow is no longer unidirectional [6]. A distribution network power quality can be linked directly to the voltage quality, current, frequency, network itself, REG connected to the network, power flow and also the customer connected to the network. Figure 2 depicts the block diagram of power quality classifications.

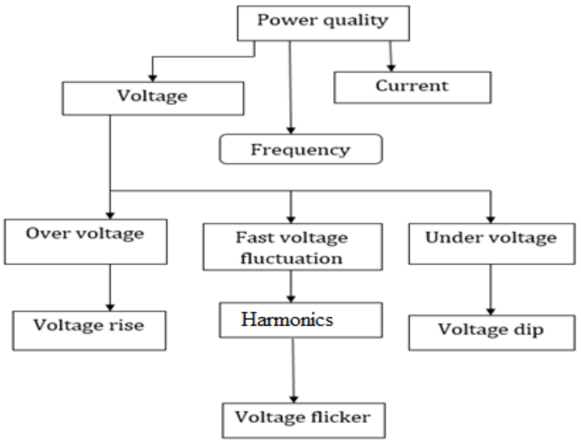

Figure 2: Power quality classifications

3 VOLTAGE QUALITY

Voltage quality in a distribution network is usually associated with voltage rise, over-voltage, fast voltage fluctuation, voltage flicker, under-voltage and voltage dip. The different waveforms of the problem associated with voltage quality in a distribution network are shown in Figure 3. Equipment connected to a distribution network and the events in the network determine the voltage quality at the terminal of the generators. As the equipment connected to the network is affected by the voltage quality, the same way, generator unit will be affected which can cause a reduction in equipment lifetime, damage to the power system component, damage to the customer equipment, undue and forced tripping of the power system equipment or generator units which can be linked to the impacts of voltage disturbance in the network [1]. When there are voltage quality problems in a network, the energy flow may be interrupted causing an electrical machine to over speed, voltage collapse and over voltages which can damage electronic equipment. Whenever REGs are connected to a distribution network, a differentiation should be taken in between variations, normal or abnormal voltage variations.

3.1 Voltage Rise

A rise/swell is an increase in Alternating Current (AC) voltage for a duration of 0.5 cycles to 1 minute's time. For a voltage rise, high-impedance neutral connections, sudden (especially large) load reductions, and a single-phase fault on a three-phase system are common sources. The consequences can be data errors, flickering of lights, damage to electrical equipment, degradation of electrical contacts, semiconductor damage in electronics, and insulation degradation. Much like sags, voltage rise may not be apparent until their results are seen.

3.2 Over Voltage

Overvoltage can be identified as a result of long-term problems that create a rise. It is an extended rise/swell. It is also common in the regions where supply transformer tap settings are set incorrectly and loads have been brought down. This is common in a seasonal region where communities reduce power usage during off-load and the output set for the high usage part of the season is still being supplied even though the power need is much smaller. It can be compared to a pipe that is supplying water to a small farm land, by putting a thumb over the end of the water pipe, the pressure increases because the hole where the water comes out has been made smaller, even though the amount of water coming out of the hose remains the same. Over voltage conditions can produce a high current draw and cause the unnecessary tripping of downstream circuit breakers, as well as overheating and putting stress on equipment. Since over-voltage can be more constant, excess heat may be an outward indication of an overvoltage. Equipment (under normal environmental conditions and usage), which normally produces a certain amount of heat, may suddenly increase in heat output because of the strain induced by an overvoltage.

3.3 Voltage Dip

Voltage dips/sags are short duration under voltages. It is a reduction of AC voltage at a dedicated frequency for the duration of 0.5 cycles to 1 minute's time. It is commonly caused by grid faults, or switching of loads with heavy start-up currents. Likewise, the starting of large motors inside an industrial facility can result in a significant voltage drop (sag). A motor can pull six times its normal running current, or more, during starting. It leads to a reduction in Root Mean Square voltage for a short period of time, which can be caused by the inordinate increase in the grid current, disturbance on a network, or as a result of reactive power consumption of some of the distributed generators like induction generators. It can cause failure and malfunction of equipment and setting off sensitive loads [7]-[8]. The most common faults on a utility supply are single line-to-ground faults, three phase faults are more severe, but not mostly common. The implication of single line-to-ground, often results from weather conditions such as, wind, lightning, and ice, insulators breakdown, animal contact, fault due to accidents or construction. Transmission or distribution system fault can affect more customers, even customers located at the far ends can still experience a voltage dip resulting in equipment mis-operation when the fault is severe. The voltage dip condition may last until the fault is cleared by a protective device such as the line circuit breaker or a substation circuit breaker. Sometimes, the damage being caused by dip is not apparent until the results are seen over time (damaged equipment, data corruption, errors in industrial processing).

3.4 Under-Voltage

Under-voltages are the outcome of long-term disturbance that create a dip/sag. The term "brownout" has been ordinarily used to delineate this problem, and has been replaced by the term undervoltage. Brownout is ambiguous in that it also refers to a commercial power delivery strategy during periods of extended high demand. Under-voltages can create overheating in motors, and can contribute to the failure of non-linear loads such as computer power supplies. The solution for sags also applies to under-voltages. More importantly, if an undervoltage remains constant, it may be a sign of a serious equipment fault and configuration problem.

3.5 Harmonics

Harmonic distortion is referring to a component of a waveform that occurs at an integer multiple of the fundamental frequency. (e.g., 180 Hz is the third harmonic of a 60 Hz fundamental frequency; 3×60 = 180). Symptoms of harmonic problems include overheated transformers, neutral conductors, and other electrical distribution equipment, as well as the tripping of circuit breakers and loss of synchronization on timing circuits that are dependent upon a clean sine wave trigger at the zero-crossover point.

3.6 Voltage Flicker

Flicker is the impression of fluctuating luminance or colour occurring when the frequency of the variation of the light stimulus lies between a few hertz [9]. It is the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time. It is regarded as one of the most severe power quality problems, it is induced by voltage fluctuations, which are caused by heavy loads, such as reciprocating machines or dynamic load like electric arc furnaces (EAFs) and energisation of transformers that operate periodically in a weak power distribution system, switching of capacitors, lines, cables etc.

3.7 Tripping of Generator

Depend on the protection system of a particular REG connected to a network, it is expected that the REG should trip off or disconnected for extreme higher voltage quality variation and severe fault occurring in the network. This can also cause tripping of multiple generators connected to the same network, which can have serious effects like large scale blackout, and loss of production of customers connected to the network [1].

3.8 Voltage Control

Some conditions must be satisfied in order to have efficient, secure and honest functioning of the force scheme. The bus voltage magnitude should be within acceptable limits, voltage control and reactive power management should be able to improve system voltage dips, transient stability and the reactive power flow should be reduced so that the active and reactive power losses can be minimized [10]. Furthermore, the biproduct of the minimum reactive power flows can reduce the voltage drop at a transmission line, distribution network and transformers. Suitable control algorithms, software tools and voltage control devices such as shunt reactor, shunt capacitors, synchronous generator and converter-based Flexible Alternating Current Transmission System (FACTS) are required to determine the network voltage controls and coordinate or strengthened the grid voltage to an acceptable limit such as converter-based FACTS which have excellent dynamic reactive power and voltage control capability [10].

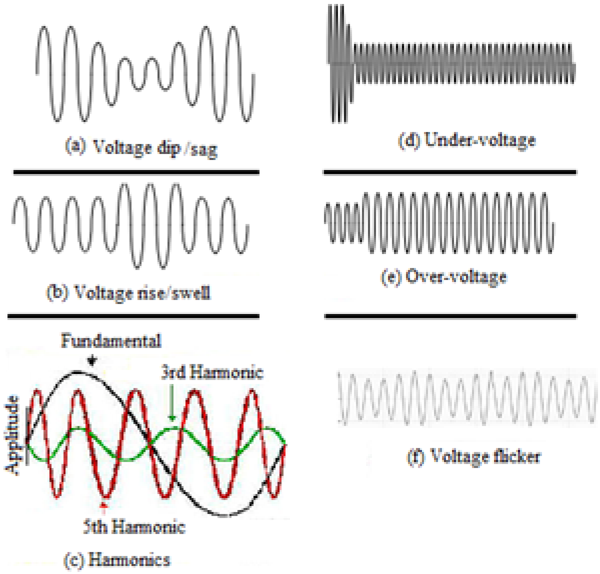

Figure 3: Voltage quality problems waveform

4 CONCEPT OF GRID CODE REQUIREMENT

A grid code is a technical specification which defines the parameters that a facility connected to a public electric network has to meet up with safety requirements and ensure safe, secure and economic functioning of the electric system. The facility can be an electricity generating plant, a load, or another network. The grid code is assigned by an authority responsible for the system integrity and network operation. The contents of a grid code vary depending on the transmission company's requirements. Typically, a grid code will specify the required behaviour of a connected generator during system disturbances. These include voltage regulation, power factor limits and reactive power supply, response to a system fault (short-circuit), response to frequency changes in the grid, and requirement to ride through short interruptions of the connection.

A grid code establishes the relationship between the network owners, operators and the REG developers, including the right of access to the network. The primary objective of the grid connection code is to specify the minimum technical and design grid connection requirements for renewable energy generation connected to or seeking connection to a low voltage distribution system. The compliance with this grid connection code is applicable to the REG (Wind energy conversion WEC, solar, and so on) depending on its rated power, and the nominal voltage at the Point of Connection (PoC). Technical aspects include the reliability of the networks to which the REG connects, interconnection standards, protection, voltage control, stability and operational safety procedures. Fault ride-through and reactive power requirements, which depend on the REG technology, affect the networks to which the REG is connected. Grid code development is a technical function with substantial economic and regulatory consequences [11].

With the rapid increase in penetration of REG power in the power system, a number of transmission system operators issued grid codes imposing specific requirements concerning grid support during steady-state operation as well as grid faults or disturbances. It becomes necessary requirement for REG farms behave as much as possible as conventional power plants to sustain the network voltage and frequency. Due to this requirement, the utilities in many countries have recently established or are developing grid codes for operation and grid connection of REG farms. The aim of these grid codes is to ensure the continued growth of REG generation does not compromise the power quality as well as the security and reliability of the electric power system [12]-[13]-[14]. This could be different from country to country. Southern Africa grid code requirements for REG of wind power integration into the grid is depicted in Figure 4.

4.1 Voltage Variation and Dips

Figure 5 is applied to all types of faults (symmetrical and asymmetrical i.e. One-, two- or three-phase faults), If several successive fault sequences occur within the area B and evolve into area C, disconnection is allowed. In connection with symmetrical fault sequences in areas B and D, the Renewable Power Producer (RPP) shall have the capability of controlling the reactive power. In case of area D, the RPP shall stay connected to the network and provide maximum voltage support by absorbing a controlled amount of reactive current so as to ensure that the RPP helps to stabilize the voltage within the design capability**.**

4.2 Deduction from Figure 4

- REG power plant (wind energy converter) must continue operation with voltage range of 0.9-1.1 pu.
- Between 1.1-1.2 pu, reactive power must be controlled and REG remains connected to the network.
- Above 1.2 pu, REG (wind energy converter) must be disconnected.
- Below 0.9 pu, reactive power must be controlled and if not up to 0.9 pu, REG must be disconnected.

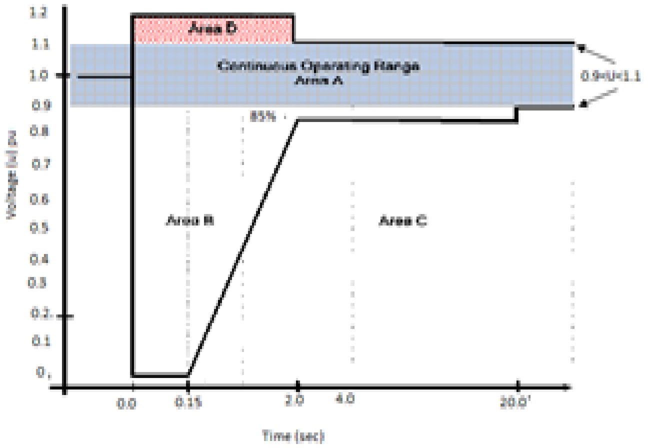

Figure 4: Symmetrical and asymmetrical fault requirements for South Africa [15]

4.3 REG Classification by Category

Sizes of REG of wind to be integrated into the South Africa distribution network are classified into three categories based on the size of the facility and the connection voltage. According to the South Africa grid code requirements, subcategories of REG with rated power in the range of 0 to 13.8 kVA are referred to as category A1. Subcategories of REG with rated power in the range of 13.8 kVA to 100 kVA are referred to as category A2. Subcategories of REG with rated power in the range of 100 kVA to 1 MVA are referred to as category A3, where A1 to A3 are to integrate into the low voltage distribution network. B, C are 1 MVA to 20 MVA and above 20 MVA respectively, are to integrate on the medium and high voltage network [16] as described in Table 2 below.

Table 2: REG classification for distribution network connection

Sub categories of REG	Power Range	Connection Voltage	Voltage Limits
A1	0 < x ≤ 13.8 kVA	LV	-15+10 %
A2	13.8 kVA < x < 100 kVA	LV	-15+10 %
A3	100 kVA ≤ x < 1 MVA	LV	-15+10 %
B	1 MVA ≤ x ≤ 20 MVA, 0 < x <1 MVA	MV & HV	±10 %
C	≥ 20 MVA	HV	±10 %

4.4 Deduction from Table 2

REG synchronization of the interconnected power system with a voltage limit ranges in Table 2 above means that the voltage at the point of connection of REG to the grid according to the South African grid connection code for renewable power plants connected to the distribution network must be:

- The voltage range of -15 % to +10 % means minimum voltage of 0.85 pu and maximum voltage of 1.1 pu for low voltage.
- The voltage range of ± 10 % means minimum voltage of 0.9 pu and maximum voltage of 1.1 for medium and high voltage around nominal voltage.

5 REACTIVE POWER COMPENSATION PRINCIPLES

In alternating current systems, power may periodically reverse direction during each cycle of voltage or current. Stored energy in the magnetic or electric field of a load device such as a capacitor or a reactor during a quarter of a cycle is sent back to the power source in the next quarter cycle, thus causing an offset between the current and the voltage waveforms. However, this reactive power that oscillates between the AC source and the capacitor or reactor does it at a frequency equal to two times the rated value (50 or 60 Hz). The two component's power thus, one component flows steadily from source to load and can perform work at the load, the other one which is reactive power, is due to the delay between voltage and current and cannot do useful work at the load. For this reason, it can be compensated using voltage/current reactive (VAR) genera-

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5.1 Reactive Power Compensation

VAR compensation is defined as the management of reactive power to improve the performance of AC power systems. Most power quality problems can be attenuated with an adequate control of reactive power [17]-[18]. The problem of reactive power compensation is viewed from two aspects, namely load compensation and voltage support. Load compensation: the objectives are to increase the value of the system power factor, to balance the real power drawn from the AC supply, compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads. Voltage support: it is generally required to reduce voltage fluctuations at a given terminal of a transmission line. As well, it can improve the voltage of the network when the grid voltage is too low because the presence of reactive power tends to increase network voltage.

5.2 Why Dynamic Voltage and Reactive Power Support?

Reactive power control is very important in the power system to prevent grid voltage collapse and voltage instability in the occurrence of certain contingencies. It is very important during power system disturbances such as faults. Reactive power is made available by components which are included in the system itself and by other components which are added to the system for balancing the system reactive power [19].

6. STATIC SYNCHRONOUS COMPENSATOR – STATCOM

The STATCOM is a shunt connected reactive power compensation device (flexible alternating current transmission system FACTs device) that is capable of generating and/ or absorbing reactive power in which the output voltage can be varied to control the specific parameters of an electric power system [20]. STATCOM is a Voltage-Source Converter (VSC), which converts a Direct Current (DC) input voltage into AC output voltage in order to compensate the active and reactive power needed by the system [21]-[22]. It exhibits constant current characteristics when the voltage is low or high, under and over the limit, this allows STATCOM to deliver constant reactive power. The relation between the AC system voltage and the voltage at the STATCOM AC side terminals provides the control of reactive power flow. If the voltage at the STATCOM terminals is higher than the system voltage, reactive power will be injected from STATCOM to the system and STATCOM will work as a capacitor. When the voltage at the STATCOM is less than the AC voltage, STATCOM will work as an inductor, and reactive power flow will be reversed, when the grid voltage is equal to the STATCOM voltage, there will be no exchange of energy [22]-[23]-[24]-[25]. The connection of the STATCOM and the equivalent circuit are shown in Figure 5, V1 represents the grid voltage to be controlled and V2 is the voltage generated by the STATCOM, X is the power system reactance, P is the active power, Q is the reactive power, δ is the phase angle of V1 with respect to V2. In a steady state operation, the voltage V2 generated by the STATCOM is in phase with V1 (δ = 0), only reactive power flows (P=0). If V2 is lower than V1, Q flows from V1 to V2 (STATCOM is absorbing reactive power). On the reverse, if V2 is higher than V1, Q flows from V2 to V1 (STATCOM is generating reactive power). The amount of reactive power is given by

$$Q = \frac{V_1(V_1 - V_2)}{X} \qquad (1)$$

A capacitor connected to the DC side of the STATCOM acts as a DC voltage source. In steady state the voltage V2 has to be phase shifted slightly behind V1 in order to compensate for transformer and STATCOM losses and to also charge the capacitor.

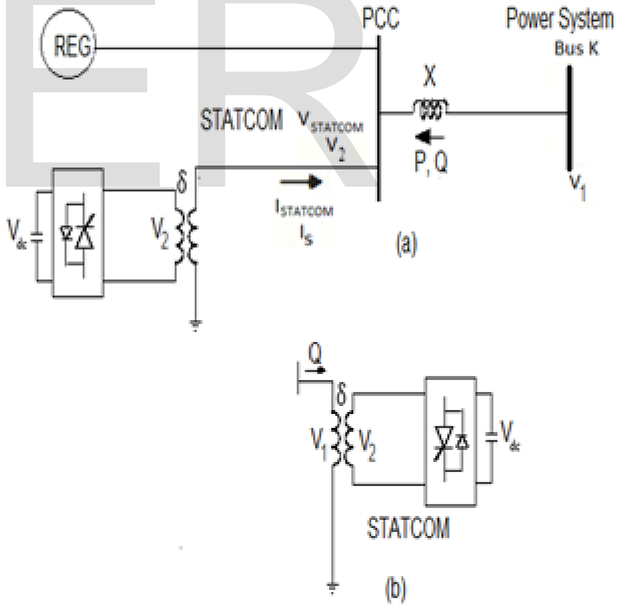

Figure 5: STATCOM Scheme and equivalent circuit representation

6.1 Principle of Operation

Considering Figure 6 below, V2 is STATCOM voltage and V1 is grid voltage. If the voltage V2 is below V1, the current through the inductor is slightly phase shifted in relation to the voltage V1 which provides an inductive current, then Qs becomes positive and the STATCOM absorbs reactive. If the voltage V2 exceeds V1 the current through the inductor is slightly phase shifted in relation to the voltage V1 which provides a capacitive current, then Qs becomes negative and the STATCOM generates reactive power. If the voltage V2 is equal to V1 the current through the inductor is zero and therefore there is no exchange of energy [26].

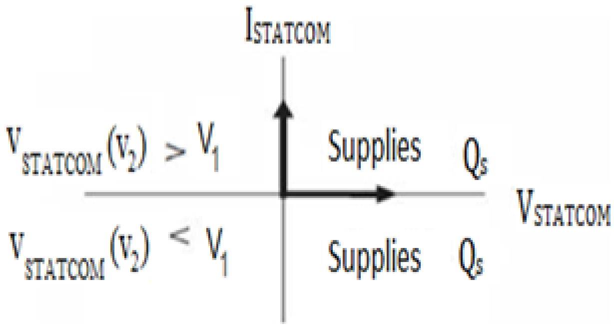

Figure 6: STATCOM power operation

6.2 STATCOM Control Operation

The block diagram of a STATCOM control operation is shown in Figure 7 below. The three-phase voltage V1 is synchronized by phase-locked loop (PLL), the direct axis and quadrature axis components of three phase alternating current such as Vd, Vq, Id, and Iq are computed by the output of the PLL (angle θ = ωt). The measured d and q components of (AC) positive-sequence voltage and current, together with (DC) voltage Vdc are controlled. An outer regulation loop consists of an AC voltage regulator and a DC voltage regulator. The reference current Iqref for the current regulator is from the output of AC voltage regulator (Iq = current in quadrature with a voltage that controls reactive power flow). The reference current Idref for the current regulator is from the output of the DC voltage regulator (Id = current in phase with voltage that controls the active power flow).

An inner current regulation loop consisting of a current regulator. The magnitude and phase of the voltage generated by the Pulse Width Modulation (PWM) converter (V2d V2q) from the Idref are being controlled by current regulator, while DC voltage regulator and the AC voltage regulator (in voltage control mode) produces Iqref reference currents.

The feed forward type regulator which predicts the V2 voltage output (V2d V2q) from the V1 measurement (V1d V1q) and the transformer leakage reactance assist the current regulator. The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected to the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V2 from a DC voltage source.

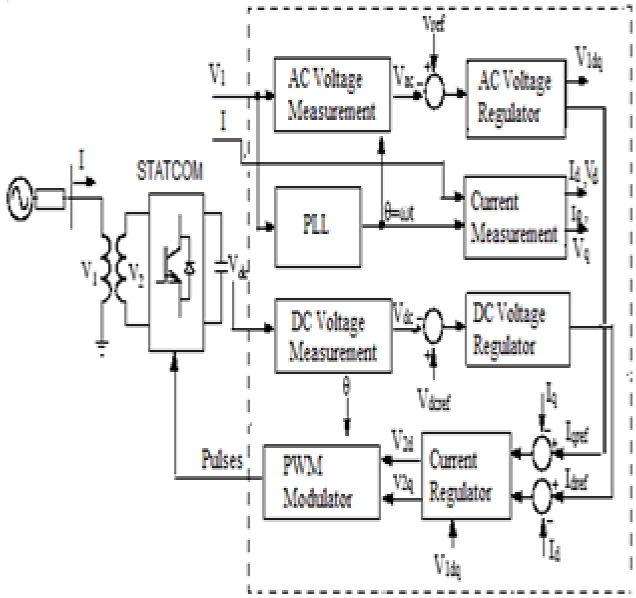

Figure 7: STATICOM and its Control System

6.3 Applications of STATCOM

Over the last two decades, advancements in static reactive compensation (STATCOM) technology based on voltage source converter (VSC) concepts have produced significant benefits:

- Improves power factor.
- Assist voltage after grid faults.
- Stabilization of weak system voltage.
- Reduced transmission losses.
- Enhance transmission capacity.
- Flicker mitigation.
- Power oscillation damping.
- Reduce harmonics.

6.4 REG Connection and Penetration Level

REG of wind converter such as Doubly Fed Induction Generator (DFIG) interacts with the grid through the rotor and stator terminals. REG Penetration level in the context of this research investigation means that it is the amount of REG power injected into a distribution network. For an example, if the rated power of the REG to be integrated into the network is equal to 2 MVA at a power factor of 0.98, and the total load demanded in a network is equal to 4.3 MVA, by calculation, the REG penetration level of such a network is equal to 47 % REG penetration level. REG penetration level can be defined thus:

REG capacity penetration level = ×100 (2)

Where

IREGC = Installed REG capacity

TLD = Total load demanded

7. TEST SYSTEM DESCRIPTIONS

The research investigation in this paper made use of IEEE 13-BUS test system in Figure 8(a) and is modelled in SIMULINK in Figure 8(b). The test system is a standard test system to be used, which has challenging voltage management features, as it exhibits extreme voltage issues. It is one of four standard distribution models developed by the IEEE Power Engineering Society's Power System Analysis, Computing and Economics Committee [27]-[28]; the test feeder is short and relatively highly loaded for a 4.160 kV feeder. It presents several key distribution system components such as operating expense lines, spot and distributed loads, substation transformers, Wye and delta connected loads, mixture of constant kW, kVar, constant electrical resistance and current, shunt capacitor at buses and voltage regulator, etc. It is really suggestive of the types of distribution systems to be used for research purposes. However, the network is modified, all the underground lines are modelled as overhead lines because there is no underground cable in the MATLAB/Simpower systems library, the output of REG is balanced three-phase, and can only be connected where there are complete three phases (three wires) in the network and all the loads are made to be three-phase and the total loading of the network is 4.3 MVA.

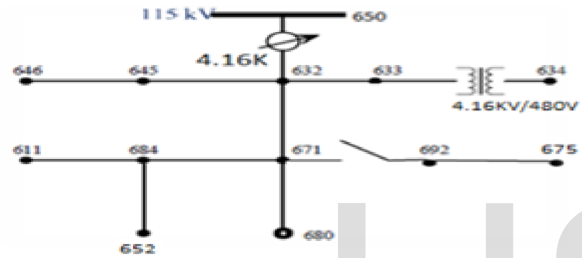

Figure 8a: IEEE 13 Node feeder test system [29]

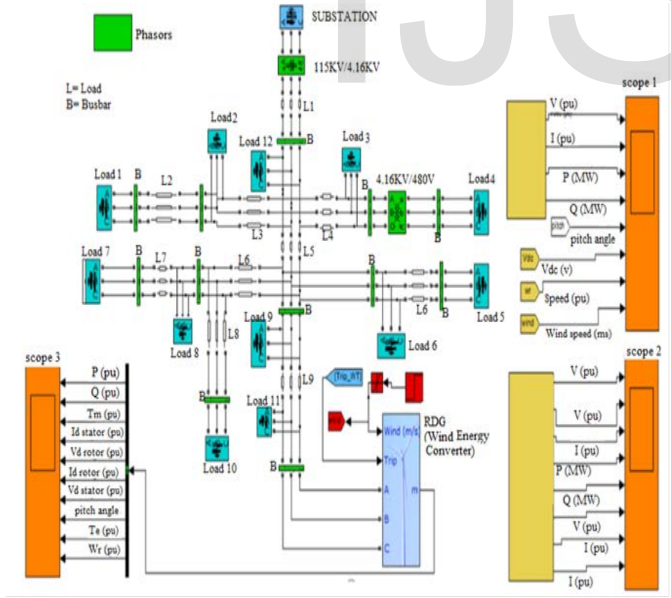

Figure 8b: RDG Modelling in SIMULINK

7.1 Result and Discussion

The impact of REG on the electric grid is no longer negligible since the proportion of REG in an electric production is increasing on a daily basis. If the grid voltage decreases below the acceptable limit when there is a disturbance in the network, REG may be automatically disconnected based on the grid code act specifications. However, with large amount of REG integration to a distribution network and increase in the penetration levels with voltage/reactive control capability in line with grid code requirement, REG may withstand certain voltage dips/swells and remain connected during fault and post fault condition. This research investigations are divided into scenarios, the first scenario is the simulation of the test system used to obtain the base voltage profile, the application of fault to the base case to observe the extent of the dip cause by the fault and the behaviours of grid voltage. The second scenario is the investigation of the impact of REG integration on the network voltage profile, third scenario is the impact of REG on voltage dip. The last scenario is the investigation of the REG integration impact on the distribution network when there is a provision for grid reactive power control/voltage support by absorbing a controlled amount of reactive current.

7.2 First Scenario: Simulation of the Test Network

The test system is simulated, the result is shown in the figure 9 below, the voltage is within an accepted range 0.97 pu, except there is an occurrence of Voltage spike, impulse or surges between 0.01 s to 0.04 s before the grid voltage maintains its stability. This short voltage swell may be as a result of energizing of network transformer, switch mode power supply and soft starter which can be prevented by a good earthing system, choke or ferrite and voltage surge suppressor [30]. The occurrence of grid disturbance at the centre of the system between 0.2 s to 0.3 s creates severe dips which can be referred to as a short-term reduction in voltage of less than half a second in the network as depicted in Figure 10, the network voltage reduced from 0.96 to 0.82 pu during the disturbance, which is not acceptable in compliance with the international standard network permissive voltage drop of the nominal value (±10 %) [31]. More also, the severity of voltage dip in any network depends on the rural location/remote from the power source, long distance from a distribution transformer with interposed loads, unreliable grid system, power distributors tolerances not suitable for voltage sensitive equipment, switching of heavy loads, unbalanced load on a three-phase system and equipment not suitable for local supply. This voltage dip if cannot be avoided in a distribution network, at least, it must be minimized. Because the voltage dip in a distribution network can cause the production rates to fluctuate, equipment may not operate correctly, dimming of lighting systems, variable speed drives close down to prevent damage, relays and contactors drop out, and unreliable data in equipment test. The methods of controlling dip in a distribution network are not limited to the use of a transformer with a tap changer, constant voltage (ferro-resonant) transformer, servo-controlled voltage stabilizer, switch mode power supply, saturable reactor, soft starters on larger electrical equipment, connect larger loads to points of common coupling and choose equipment with dip resilience etc [30].

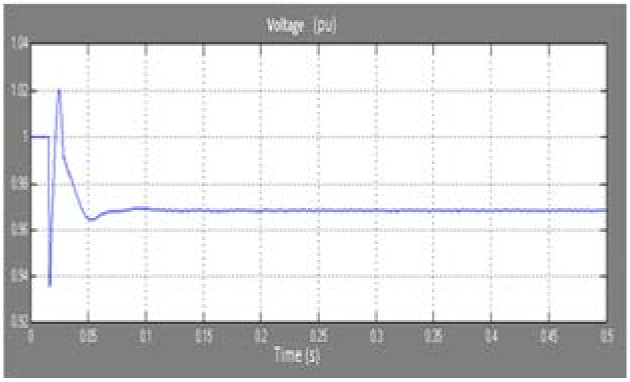

Figure 9: Grid voltage without disturbance

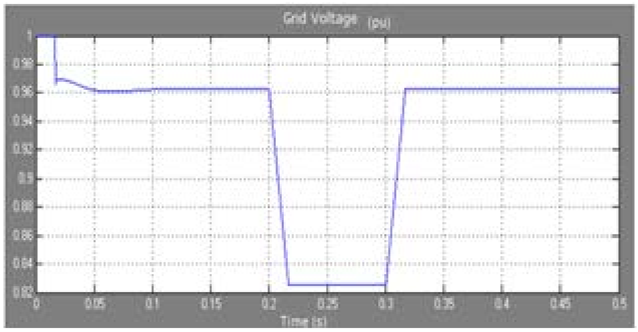

Figure 10: Grid voltage with disturbance

7.3 Second Scenario: Impact of Reg on the Network Voltage Profile

To investigate the impact of REG integration on voltage profiles of a distribution network, REG is connected to the network at the point of common coupling and simulated, it is observed that the integration of REG improved the voltage profile of the network with increase in the penetration levels as depicted in Figure 11 while the power is delivered to the grid. The grid voltage is within the acceptable range in relation to the grid code act (0.85 to 1.1 per unit) as discussed in session 4.4 above. Therefore, REG must remain connected to the network.

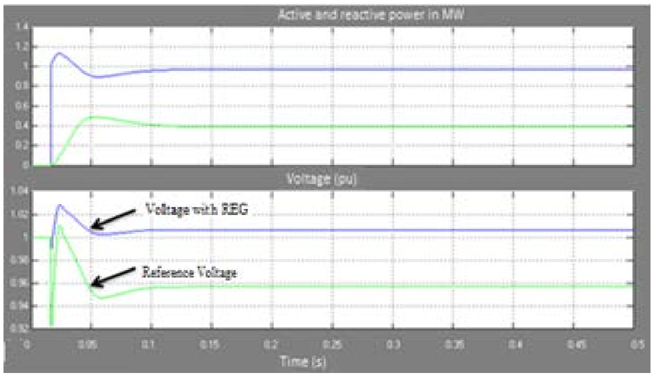

Figure 11: Grid voltage profiles, active and reactive power

7.4 Third Scenario: Impact of Reg on Voltage Dip

When there is a disturbance in the network after the integration of REG, between 0.2 s to 0.3 s and the network is simulated for 0.5 s, the base voltage dip improves from 0.82 pu to 0.85 pu as shown in Figure 12 (part B green colour) but the active power drop slightly during the fault condition and back to normal after the fault is cleared. The integration of REG into a distribution network based on this simulation does not contribute to the voltage dip during fault conditions, but it reduces the voltage dip from 0.82 pu to 0.85 pu (about 0.03 pu reduction). However, with the voltage dip improvement with REG, it must still be disconnected from the network during fault conditions. This is because the voltage improvement is not up to the minimum grid code required for connection and there is no provision for grid reactive power control or voltage support by absorbing a controlled amount of reactive current as stipulated in the grid code act and therefore, the utility and private power generation owner/Renewable Power Plant owner will not have the assurance for grid voltage stability if the REG is remained connected during fault and post fault condition. Traditionally, distribution network design does not need to consider reactive power control or issues of stability as the network is passive and radial, and remained stable under most circumstances provided the transmission network is itself stable. However, this is likely to change as the penetration of these REGs increases and their contribution to network security becomes greater.

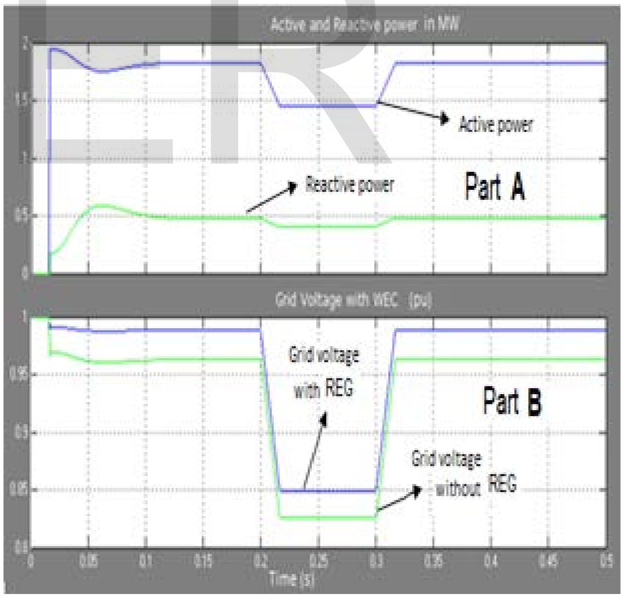

Figure 12: Voltage dips with REG and grid disturbance

7.5 Fourth Scenario: Reg Impact Versus Grid Reactive Power Control on am Distribution Network

The reactive power compensatory device such as STATCOM is connected at the point of common coupling of REG and the grid, the simulation is repeated for 0.5 s, while the grid disturbance occurs between the duration of 0.2 s to 0.3 s. During the fault condition, the grid voltage is less than the STATCOM voltage, the current through the STATCOM inductor is phase shifted in relation to the grid voltage, thereby provides a capacitive current (STATCOM will work like capacitor banks to counteract or correct a power factor lag or phase shift in an AC power supply), then Qs becomes negative and the STATCOM generates reactive power. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. The STATCOM produced reactive and modulated current and voltage as shown in Figures 13, therefore, it generates reactive power Q = -3.6 MVar in Figure 15 (second trace green colour) within the duration of the fault to compensate for the voltage dips and improve the voltage to 0.91 pu in Figure 14 second trace and Table 3 while maintained voltage at 1.0 pu after the fault is cleared, which means REG can remain connected to the network during this period of grid disturbance in relation to grid code act. P and Q in (MAV) are the STATCOM reactive power, a positive value indicates inductive operation while a negative value indicates capacitive operation. The Iq in Figure 14 is the quadrature-axis component of current (reactive current) flowing into STATCOM (pu), a positive value indicates capacitive operation while Iqref is the reference value of quadrature-axis component of current flowing into STATCOM. Vdc in is the STATCOM voltage, the modulation index is of the Pulse Width Modulator (PWM), a positive number 0<m<1. m=1 corresponds to the maximum voltage V2, which can be generated by the VSC without overmodulation.

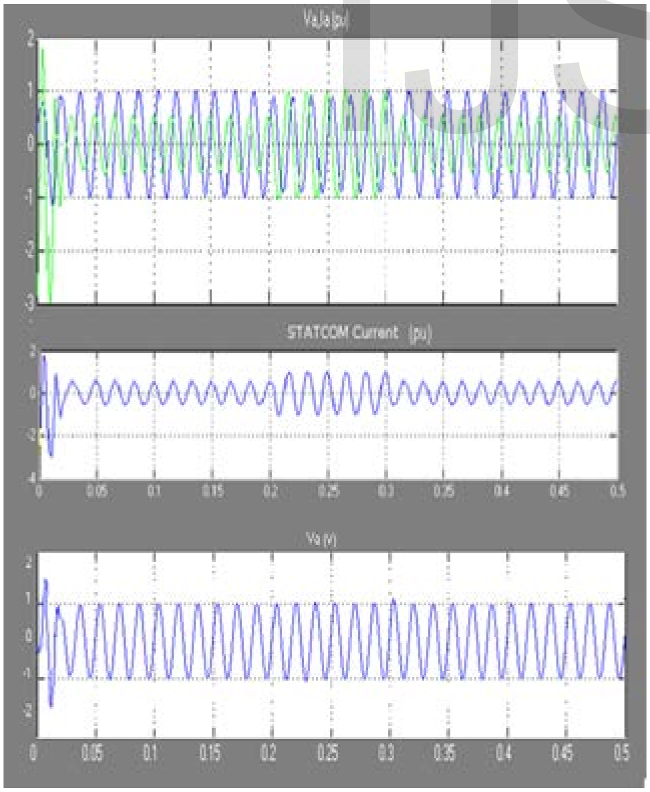

Figure 13: STATCOM modulated current and voltage

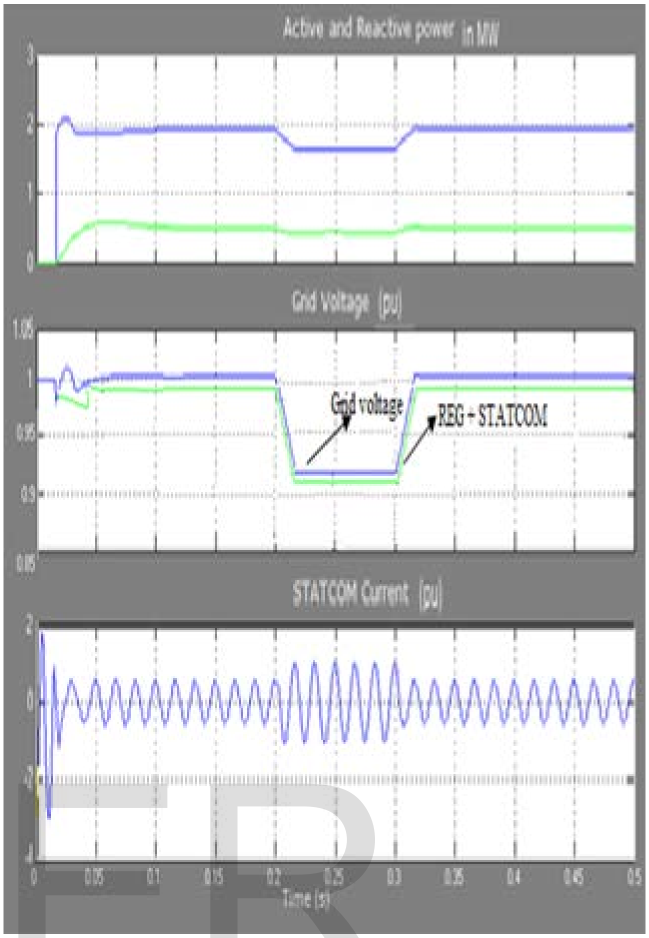

Figure 14: REG plus disturbance plus STATCOM

Table 3: Analysis of REG integration with respect to grid code

Scenario one	Base case (pu)	Base case + REG (pu)	Grid code (pu)	Remark
	0.95	1.001	0.90-1.10	Continue operation
Scenario two	Base case + fault	Base case + fault + REG	Grid code	Remark
	0.82	0.85	> 0.90	Disconnected
Scenario three	Base case	Base case + REG + reactive control	Grid code	Remark
3.	0.82	0.91	> 0.90	Remain Connected

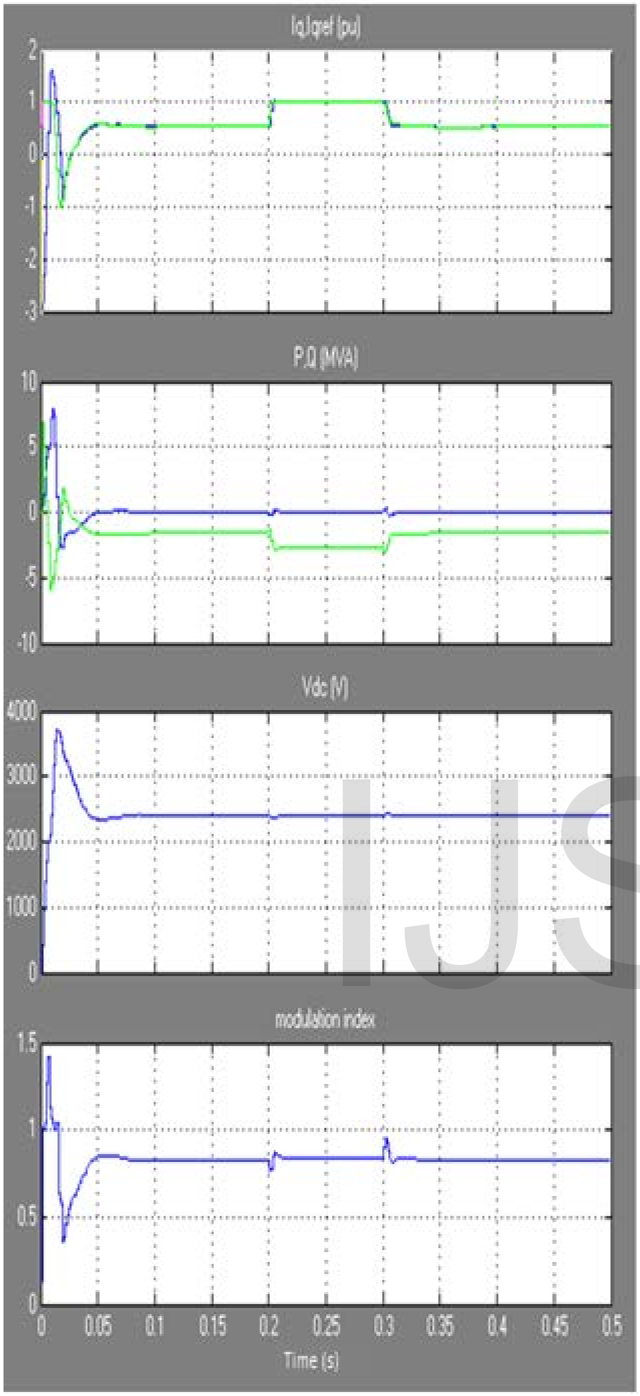

Figure 15: STATCOM active and reactive power controllers

8. CONCLUSION AND RECOMMENDATION

Distribution network voltage profiles and voltage dips improvement can be greatly influenced by the increase in the REG penetration levels. With the adventure of the grid connection code requirement and reactive power control in a power system, integration of REGs can be a success and the fear of power quality challenges will not be a grow concern to the utility and private owned power producers. Most of the automated industries are increasingly run by small microprocessors that are sensitive to voltage variation, these microprocessors can control blazingly fast automated robotic assembly and packaging line systems that cannot afford fluctuations or downtime. REG remains alternative means by which downtime can be reduced in a power sector. This research paper has shown successfully that, integration of REG into a distribution network can improve voltage profiles and limit voltage dips caused by grid disturbances without disconnecting REG from the network. It is recommended for the utility and private owned power producers that for a REG to remain connected to a distribution network during grid disturbances, reactive power control should be provided in the network.

9. APPENDIX

A. Load Data

Load parameters: bus 632 = 200 + j 116 kVA, bus 633 = 170 + j 100 kVA, bus 634 = 480 + j 270 kVA, bus 645 = 170 + j 110 kVA, bus 646 = 230 + j 132 kVA, bus 671 = 300 + j 200 kVA, bus 692 = 170 + j 151 kVA, bus 675 = 375 + j 202 kVA, bus 684 = 118 + j 93 kVA, bus 611 = 270 + j 80 kVA, bus 652 = 950 + j 770 kVA, bus 680 = 128 + j 86 kVA.

Transformer data: substation 115/4.16 kV, X/R is 8/1, in line transformer is 4.16 kV/480 V, X/R is 2/1.1, and frequency is 50Hz.

REG (Wind converter DFIG data): 13.8 kVA, 100 kVA, 300 kVA, 600 kVA, 1 MVA and 2 MVA, PF = 0.98.

B. Converter Parameter

12 Pulse Generator	50 HZ, 30^0
Pulse width (degree)	40
Power electronic device	2 Thyristors
	DC load
Resistive load	4.6 MW
Inductor	0.5e3 H
DFIG power	2 MVA at 0.9 p.f
Rectifier	2 Universal Diode
Snubber resistance	2000 ohms
Snubber capacitance	0.1e-6 F
Ron	1 e-3ohms

C. Data for STATCOM

Power Rating	4.8 MVA
Voltage (L-L)	4.16 kV
Base power	4.3 MVA
Reactive power limit	1.8e6 – 1e6
Average time delay	3.9e-3
Control parameter	
Voltage ref	1.0 pu
Voltage regulator	[0 0.032]
Val control	-3.5 Mvar

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