REACTIVE POWER INJECTION CONTROL METHODS FOR FAULT RIDE THROUGH CAPABILITY IN DISTRIBUTED GENERATION

A Graduate Project submitted in fulfillment of the requirements For the Degree of Master of Science in Electrical Engineering

By

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Abstract

Reactive Power Injection Control Methods For Fault Ride Through Capability In Distributed Generation

By

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Master of Science in Electrical Engineering

Decentralized and renewable energy sources are being very popularly used in the modern power system and have become very supportive and useful for the stabilization of the power system. In the past, decentralized and renewable energy sources were disconnected by utility companies during abnormal conditions such as faults and under voltage conditions. In the event of fault it was necessary to remove decentralized and renewable energy source so that such sources do not provide or contribute in increase of fault current. This paper shows the methods of reactive power injection by capacitor banks and use of IGBT based inverter with PI controller. By using these methods, decentralized and renewable energy sources can stay connected to the local network or grid, along with helping the system voltage to remain at 1.0 p.u. by injecting reactive power.
1. Introduction

As there is a trend to supply electrical energy using decentralized and renewable energy source, these sources have become very important part of the power system nowadays. Further, it is becoming more popular to use decentralized and renewable energy in distribution and local networks, also called as distributed generation. Figure 1 shows the growth of power supported by wind energy stations which has lead to increase in wind energy production within the last few years of span. We have different types of renewable energy sources available such as Wind, Solar, Geothermal plants etc. Now we also have the technology to distribute (add) electrical power in the power system or a small network for utilization [2]. This small or medium sized decentralized and renewable energy sources are often connected to the local network or distribution line to supply electric power and maintain the healthiness of the system. These generators (decentralized and renewable energy sources) are connected to medium or small size voltage level network and a typical example of that is shown in Figure 2, which shows the wind farm having wind power generators connected with the local network [2].

![Figure 1: Growth and installed capacity of wind energy sources in the world. [18]](image)

The increased penetration of wind energy into the power system is directly reflected in the requirements for grid connection of wind turbines over the last few years. These codes are becoming more demanding, requiring the wind farm to behave more as a conventional power plant in the power system. Therefore, it is essential to analyze the characteristics of wind generators during the network disturbances [2].
When faults occur in a local network or distribution system, the decentralized and renewable energy sources connected to it provide power to the fault and give an excessive increase in amount of fault current, which can cause serious damage not only to the local distribution system but also to other healthy parts of the network. Because of this fault occurrence it becomes necessary to disconnect the supply provided by decentralized and renewable energy sources. With the increase in the number of decentralized and renewable energy sources, it is necessary to keep them connected to the power system. The conventional system is not sufficient to stabilize such abnormal conditions and may cause black out and load shedding consequences due to a fault. Decentralized and renewable energy sources are helpful to recover such sudden fault occurs and help to improve voltage quality and limits over currents [1] [2].

![Wind Farm Connected to Medium Voltage Bus bar.](image)

Decentralized and renewable energy sources are very important due to the amount of power connected to the system. Therefore a new approach is introduced by grid operators for the protection of such decentralized and renewable energy sources and to keep them connected during the fault. In the event of fault, these sources receive reactive power instead of feeding. Therefore the directional reactive power and under voltage protection system is used [2]. This protection system disconnects the decentralized and renewable energy sources (generators) in the event of a network fault as they receive reactive power under faulty conditions. As long as they supply reactive power to the system, they can stay connected to the network and stabilize the network [1] [2] [3].
This paper will illustrate the requirements according to safety and reliability to connect decentralized and renewable energy sources to medium or small voltage network. It is important to keep these sources connected even during the fault because they give stabilization and feed reactive power back to the local distribution network [1]. This paper will show the method of controlling reactive power and fault ride through capability, thereby preventing the disconnection of the renewable energy sources against under voltage and directional reactive power for protection during fault [1] [2] [3] [6] [7] [8].

In short, such sources can stay connected during the fault, only if they feed reactive power back into the system to stabilize the system, and they do not receive any reactive power during the system fault, and to satisfy this condition, directional reactive under-voltage protection and reactive power injection method is proposed.

The main objective of this paper focuses on the control methods of reactive power injection using converter/inverter circuit, transformer and capacitor banks to provide reactive power support in case of grid/local network faults. This control strategy can improve the voltage quality during the fault and satisfy the FRTC (Fault Ride-Through Capability) requirement (see in requirement section “section 3”). This paper will be highly concentrated on Fault condition improvement by reactive power injection [1]. For strong grids, there is a decoupling between the active and reactive powers. Thus the injection of reactive power during a fault is a good solution for this control strategy without compromising the power system transient stability [2]. However if the wind farm is connected to a weak electrical system (i.e. Voltage and frequency fluctuation conditions), there might be some power surge problems due to technical constraints related to the weak electrical networks. In this case, the control strategy proposed is based on the reactive injection curve, defined by the grid code requirement for improving the transient stability of the power system [2]. To reach this aim, Tap changing Transformer, PI controlled IGBT inverter and capacitor banks are used. The wind park is modeled as a reactive power injection source with the current limiting capability. The control of reactive power is done with the help of power electronics. The directional reactive power and under voltage protection will be used to protect the system [1] [2] [3] [5] [7] [9].

In this report, for the reactive power injection technique are taken from reference number [1], [3], [4] and [5]. Concept for detections and protection against low voltage/zero voltage due to fault are taken from reference number [1], [6], [7] and [8]. The concept for the requirement during Fault Ride Through Capability is taken from [6], [7], [8] and [9].
2. Regulations

In the process of connecting a new or old plant, all decentralized and renewable energy sources and it's each unit has to be regulated according to the IEEE 1547 standards to keep the system healthy. These sources must be under control of the utility company or network operator and must guarantee the injection rate of electrical power in the network for a specific time period. Also the type of decentralized and renewable energy sources (For example: Wind farm, Geothermal plant, solar cell plants, etc.), the capacity of the plant and the time period for reactive power injection should be taken into consideration. For example, A Solar cell can provide power during the day time only, but solar cell plant has to ensure the value of power being injected during the day time [6] [7] [8].

The decentralized and renewable energy sources must be able to satisfy the following conditions [6-8]:

a. Support and stabilize the system during voltage dip in the system.
b. Support system voltage during fault by supplying reactive power to the system and act like capacitive element for the system [2].
c. Stay connected to the grid or network during the fault in the system [6].
d. Supply same or lesser amount of reactive power after the fault is cleared or during healthy system [2].
e. All the decentralized and renewable energy generating units and whole plant must be certified for all above points and given to the utility company [2].
f. All the decentralized and renewable energy sources must provide dynamic grid support during voltage dips and faults in the high voltage networks [1].
g. If any unit fails to supply reactive power to the system after the fault occurrence, that unit or whole plant must be disconnected by a directional reactive power and under voltage protection system.

In general, renewable energy sources connected to the network must support the system voltage during voltages dips and faults, but if it is not able to do so, such decentralized and renewable energy sources must be disconnected from the system. As we know, It is very important to keep them connected to small and medium voltage networks to stabilize the system, for the improvement in power quality and to decrease the use of conventional power sources [6] [8] [9].
3. Requirements

In this section, a set of minimum technical requirements concerning the installation of new wind farm is suggested. In Figure 3, each point on the graph (i.e. The heavy black line) represents a voltage level associated with time duration which connects the generating units or power park modules to withstand or ride through. The profile is not a voltage-time response curve obtained by plotting the transient voltage response at a point on a transmission or local network system or user system to a disturbance. Figure 3, shows a requirement of the plant to stay connected into the system and to obtain a fault ride through capability [7]. The interconnection requirements, active and reactive power control, fault ride through capability requirements depends upon the country and state wise requirements, some general requirements for interconnection and directional reactive power are listed below.

The wind farm or any renewable energy source must have a fault ride through capability in order to stay connected to the grid. In the event of a subsequent fault or system disturbance the Wind Farm’s PCC voltage should be above the value defined in the Time-Voltage characteristic curve defined in Figure 3. Below the line, the wind park is allowed to trip [1].

It is necessary during faulty condition that, a demand of reactive power injection must follow a specified curve. This requirement, besides improving the voltage levels in the electrical network in a defect condition, allows the wind farm not to be removed from the system by the trip of the under voltage relay, increasing the ride through capacity [2].

The generating plants have to support the network voltage level with additional reactive current during a voltage dip and fault, the voltage control must be activated and must follow the voltage requirement as per figure 4.
The voltage control and reactive power injection must be done within 20 ms after the fault is detected, by providing a reactive current on the low voltage side of the generator transformer equal to at least 2% of the rated current for each percent of the voltage dip [6-2].

The wind farm must produce a reactive power output of at least 100% of the rated current as per the reactive injection curve [6-2-1].

When the voltage level gets below 10% of the rated generator voltage, the control action should act within 20 ms after the identification of the fault, and should supply reactive power on the low voltage side of the generator transformer for at least 2% of the nominal current for each 1% of voltage dip [2] [1] [6].

If the voltage at the network’s common connection point drops and stay below 90% of its rated value then the directional reactive power and under voltage protection system must trip and disconnect the generators or any renewable energy sources after 0.5 second. Such situation occurs when the generating plant starts taking reactive power. This problem can be solved by injecting more reactive power and bringing the voltage level back to normal or more than 90% during the fault [1-2].

Figure: 4. The Principle of Voltage Support in Event of Low voltage [2].
4. Concept of reactive power and how reactive power helps to the stabilization of voltage during low voltage situations and voltage Dips.

The power produced by generators is usually an AC power. This power goes up and down around some “average” value, which is called the “real” power and it is measured in kilowatts. If this average value is zero, then all the power being transmitted is called “reactive” power. Such reactive power does not contribute in load consumption and only active power is consumed by the load, but reactive power is very important to deliver active power to the load and to increase voltage stability. By increasing reactive power, system stability can be increased. [6] [7] [9]

Apparent power $S$ is a summation of active power $P$ and reactive power $jQ$,

$$S = P + jQ$$  \hspace{1cm} (1)

And Active Power is

$$P = V I_p \cos \phi$$  \hspace{1cm} (2)

Which can also be expressed as

$$P = E V \sin \theta / X$$  \hspace{1cm} (3)

And Reactive Power is

$$Q = V I_q \sin \phi$$  \hspace{1cm} (4)

Which can also be expressed as

$$Q = E V \cos \theta / X$$  \hspace{1cm} (5)

Here,

$S$ = Apparent Power in KVA

$P$ = Active Power or True Power in Watts

$Q$ = Reactive Power in KVAR

$V$ = On Load Voltage in Volts

$I$ = Current in Amperes, $I_q$ = Reactive current, $I_p$ = Active current

$E$ = No Load voltage in Volts

$X$ = Circuit Reactance in Ohm
Here we can see from the above equation number (5) that, if the reactive power injection is done, voltage increases proportionate to the reactive power injection. In reference to the equation (5) and (6), the On load voltage “V” is varied with respect to the corresponding change in the reactive power “Q”. Hence a tap changing transformer is used to adjust the voltage according to the requirement of reactive power.

\[ Q \propto V \]  \hspace{1cm} (6)

And from the equation number (4) and (7), the reactive power Q is varied with respect to the corresponding change in current I. Hence, by injecting current into the circuit, reactive power can be increased which can increase the voltage level of the system. For this purpose a PI controlled IGBT inverter is used.

\[ Q \propto I \]  \hspace{1cm} (7)

\[ Q \propto \sin \varphi \]  \hspace{1cm} (8)

More to mention that, by improving the phase angle \( \varphi \) from the equation (4) and (8) reactive power can be adjusted. A capacitor bank is used to correct the power factor and to inject reactive power kvars.
5. Brief Explanation For Main Components Of The Control System.

In this section, different control systems are used and the significance of capacitance in each system is explained. To increase FRTC and for injection of reactive power, PWM based voltage regulator is used. Here PI controlled IGBT inverter is used to provide voltage regulation and to inject reactive power into the system. The transformer is implemented for injection of reactive power and voltage improvement followed by a capacitor bank to improve power factor with voltage quality. The analysis of the proposed control system and the need for a capacitor is explained briefly and type of relays used are detailed below [1] [2] [3] [6] [7] [8].

5.1 Relays:

The main purpose of the relay is to measure voltage, sense voltage dips and to keep check on abnormal conditions such as faults and under voltage. IEEE defines relays as ‘‘an electric device that is designed to respond to input conditions in a prescribed manner and, after specified conditions are met (Ex: pickup value), it causes contact operation.’’

In electrical network, when the voltage level drops down due to faulty condition or there is a sudden increment in current, it is sensed by the under voltage relay and over current relay respectively. When the voltage level goes below the pickup value of the relay, it performs trip operation. Here pick up the value of the relay is set to 0.9 p.u. of voltage. The control is designed in order to balance the voltage level irrespective of which abnormal conditions has occurred. Directional relays are also applied to check that reactive power is being fed to the system or being consumed by the generating plant. For this purpose fast acting relays like Numerical Relays and Microprocessor type relays can be implemented [1] [2].

The following relays may be used for different purposes:

- Over Voltage Relay (IEEE device number - 59),
- Under Voltage Relay (IEEE device number - 27),
- Over Current Relay, (IEEE device number - 51),
- Directional Relay, (IEEE device number - 92).

The measurement of active power and reactive power being delivered is also important, along with the record of voltage, current and frequency. For that purpose “SEL-751” can be used, which provides complete protection, with over-current, over-voltage, under-voltage, directional power, load encroachment, and frequency elements [19]. And for the protection of the system “SEL-547 distributed generator interconnection relay” can be implemented [20].
5.2 IGBT based Inverter and Voltage regulator:

The application of power electronics has created a revolution in the field of power system to reduce complexity. In this paper the goal of stabilizing the voltage to 1.0 p.u. is achieved using power electronic devices. Insulated Gate Bipolar Transistors (IGBT) with a technique of pulse width modulation is used along with a PI controller to achieve stability of the system. Such PI controllers have high efficiency in regulating the voltage to 1.0 p.u during faults as it work on proportional and integral. Here the PI voltage controller along with inverter produces controlled sinusoidal AC power at the output. [1][2][3][4]. PI and PID controller are being used in many control operations and PID controllers are the best feedback type controllers.

5.3 Capacitor Bank:

The main purpose of capacitor bank is to provide good power factor and to inject reactive power for the voltage stabilization purpose. Capacitor banks are very useful for improvement in power factor and voltage stabilization because they are good sources of reactive power. For better efficiency of the system, power factor is considered to be a major factor [3] [7] [8]. But capacitor banks have a limitation that they improve stability of voltage up to certain limits only and therefore IGBT type PWM voltage regulator and transformers are needed.

\[ Q = C \times V \]  

\[ C \] is a capacitance of the capacitor.

5.4 Transformer or Tap changing Transformer:

Transformer unit changing or tap changing transformers is very useful for injection of reactive power. By increasing the voltage of the transformer of the system, reactive power of the system can be improved. As we know \( Q \) is proportional to \( V^2 \). Therefore as voltage increases, the reactive power increases. Thus such increase in voltage can provide good reactive power injection at the sending end and receiving end too, which helps to stabilize the system voltage. [5][6]

\[ Q = \frac{V^2}{X} \]  

When decentralized and renewable energy sources are connected through such reactive power injecting devices, it helps system network to stabilize and also limits the over current during fault conditions.
6. Generators used in wind generation

6.1 Types of Generators:

There are different types of generators used in wind generation, such as Fixed speed induction generator (FSIG) wind turbines, doubly fed induction generators (DFIG) wind turbines and permanent magnet synchronous generator. In the past FSIG and DFIG were mostly used.

6.1.1 Fixed Speed Induction Generators (FSIG) Wind Turbines:

The FSIG wind turbine is a simple squirrel cage induction generator coupled directly to the electricity supply system. Rotational speed of the magnetic field of stator determined from the operating frequency of the network. The operating range of the generator is very limited due to well known steep torque-slip characteristics of the induction machine. Hence, this type of wind turbine is with fixed speed. The main disadvantage of FSIG is that, it does not have the capability to control active and reactive power independently. Its huge advantage FSIG is, having a simple and robust construction with low cost. In contrast to other generator topologies, FSIG provide no inherent means of torque oscillation damping because of this greater burden and cost occurs on gearbox. [3] [2]

6.1.2 Doubly Fed Induction Generators (DFIG) Wind Turbines [3]:

The DFIG has wound type rotor with slip rings and this slip rings are fed by frequency converter. The electrical supply system is directly connected with stator of DFIG. By using frequency converter, the network frequency can be decoupled from the mechanical speed of machine and variable speed operation is possible, which permits maximum absorption of wind power. As power rating of DFIG is a function of slip, it operates over a range of speeds between about 0.75 and 1.25 p.u. of synchronous frequency, which requires converter power ratings of approximately 25%. The DFIG wind turbine has a capability to control active and reactive power independently, which is a huge advantage of its own. Moreover, DFIG has very less mechanical stresses compared to FSIG. In this type of generator there is a decoupling between mechanical speed and electrical frequency, due to that the rotor can act as an energy storage system, absorbing torque pulsations caused by wind gusts. DFIG also have low flickering and acoustic noise. DFIG wind turbines have a major disadvantage that it needs periodic slip ring maintenance which increase its maintenance cost and also have a greater capital cost. [3] [2]
6.1.3 Synchronous Generator:

Multi pole synchronous generator is a good alternative to the much-used induction machine generator, which is fed through a power electronic converter/inverter stage. The field of synchronous generator can get excited by an electrical excitation system or by permanent magnets. The grid can be decoupled from the generator by AC/DC/AC converter and also acts as a frequency converter. It consists of two back-to-back voltage source converters, usually with IGBT switches, which can independently control the active power transfer through the DC link and the reactive power output at each converter terminal. The speed range is generally similar to that of DFIG. Synchronous generator has multi construction which leads to low mechanical rotational speed of the rotor which permits direct coupling to the wind turbine. Direct drive synchronous generator wind turbines reduces the number of stages in the gearbox or elimination of gearbox can be done. However, the greater VA rating of the power electronic converter is needed to compare to DFIG and the larger physical generator size, are the disadvantages of synchronous generator. All present commercial models for multi-MW wind turbines in the range above 3MW are either DFIGs, or synchronous generators coupled to the network through back-to-back converters. [2-3].

When a comparison made between the variable speed wind turbine and the constant speed wind turbine, the generator with shows variable speed reduces mechanical stresses. Gusts of wind can be absorbed and dynamic compensation can be achieved for torque and power pulsations caused by back pressure of the tower. This backpressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor blades. Following are advantages to use a doubly fed induction generator in WECS with the rotor connected to the electric grid through an AC/DC/AC converter [2-3]

Advantages:

- Only electric power injected by the rotor needs to be handled, implying a less cost AC-AC converter. [2]
- Improved system efficiency and power factor control can be implemented at lower cost, the converter has to provide only excitation energy. [2]

Hence, WECS equipped with doubly fed induction generator systems for variable speed wind turbine via power electronics is an efficient configuration for wind energy conversion.
6.2 Why direct drive PMSG wind generator is better than other generators?

Synchronous generator is a better option if speed of wind is constant or gear train is used to keep constant speed of the generator shaft connected wind turbine. The permanent magnet synchronous generator is very advantageous over separately excited synchronous generator. The advantages of PM machines over electrically excited machines can be summarized as follows according to literatures; [1] [3]

Advantages [1]:

- Higher efficiency and energy yield,
- No additional power supply for the magnetic field excitation,
- Improvement in the thermal characteristics of the PM machine due to the absence of the field losses,
- Higher reliability due to the absence of mechanical components such as slip rings,
- Lighter and therefore higher power to weight ratio.

But PMSG has some of the disadvantages which are stated below [1]:

- High cost of PM material,
- Difficulties to handle in manufacture,
- Demagnetization of PM at high temperature.

Even after having these disadvantages, the use of PMs is more than others, because the cost of PM is decreasing and the performance of PMs is improving. Nowadays, PM machines with a full-scale power converter is more acceptable for direct-drive wind turbines, in addition to that the cost of power electronics is decreasing in recent year. For offshore wind farms, variable speed direct-drive PM machines with a full-scale power converter is becoming more attractive [1] [3]. More to mention that by using gearbox system is a better solution for annual energy yield per cost and also with respect to the total weight. For example, the market interest of PMSG system with a multiple-stage gearbox or a single-stage gearbox is increasing. [1-3]
7. Modeling and Analysis Reactive Power Injection Control

In this part, working of PI controller type voltage regulator using a PWM based inverter and working of the circuit during fault and its fault ride through capability is explained. In this circuit voltage regulator, tap changing transformers and capacitor banks are used to stabilize the voltage.

7.1 Reactive power control using IGBT type PWM voltage controller:

![Diagram](image.png)

Figure 5: Simplified Model for Reactive Power control using IGBT type PWM voltage regulator. [From Simulink Simulation] [14]

In above figure 5, a simplified model of the reactive power control using IGBT inverter controlled by PI controlled PWM voltage regulator is shown. As shown in figure 5, rectifier delivers DC power to the inverter, and this DC power is smoothen by LC circuit. The inverter circuit gate signal is given by PWM generator. PWM generator generates the gate pulse according to the output PI controller signal and this signal is proportional to the feedback signal from grid side voltage. The three phase output of the inverter is given to the series inductor and capacitor which works as an LC filter and output of this LC filter circuit is directly fed to the load or grid. Figure 6 shows more details of control for gate signal using the PI controller and PWM. [3][4][5].
Figure 6 shows a block for PI based voltage regulator. In PI based voltage regulator two inputs are available. One of them is Input 1(In1), which provides three phase voltage feedback signal Vabc of the load side to the PI controller and the other one is Vref which give reference voltage for the controller. In voltage controller proportional gain Kp is set to 0.5 and integral gain Ki is set to 500. Two inputs Vabc and Vref are compared with each other and its proportional output is provided by Vabc_inv. Output Vabc_inv is given to the input of gate pulse width module generator. PWM generator is set to operate at 24KHz pulse output. This controlled gate pulse is given to the IGBT based inverter, which will provide 60Hz output from the IGBT type inverter. [1][3][5]

Calculation of Kp and Ki PI based voltage controller [5]:

\[
K_p = \frac{\tau f_{sw}}{V_{dc}} \quad \text{(11)}
\]

And

\[
K_i = \frac{\tau f_{sw}^2}{2 V_{dc}} \quad \text{(12)}
\]

\(\tau = L/R\) is grid time constant.
\(L\) is the coupling inductance between the GCI and the grid.
\(R\) is the coupling resistance.
\(V_{dc}\) is the DC-link voltage.
\(f_{sw}\) is the switching frequency.
Kp is proportional gain.
Ki is integral gain

The main purpose of this voltage regulator is to inject reactive current Iq during faults and abnormal conditions to give dynamic VAR control. The generated voltage here is a sinusoidal and controlled voltage which remains at 1.0 p.u. Hence during faults such as three phase fault and line to ground fault, this system is efficient to provide rated and pure sinusoidal voltage output through an LC filter to the local grid and load. A concept taken from [1][2][3][5].
7.2 Reactive Power injection and voltage control using Transformer:

As discussed above, it is known that by increasing the voltage of the system, reactive power delivery can be improved and reactive power injection can be done. To utilize this characteristic here, the transformer voltage stepping up technique is used. As shown in Figure 6, it can be seen that one autotransformer is used for step up and step down the voltage. Here two relays, over voltage and under voltage relay are used to sense the three phase voltage of grid side or load side. Three phases of the generators are directly given to the transformer and output of this transformer is given to the rectifier. A concept taken from [1] [2] [6].

![Simplified Circuit for Reactive Power injection and control using transformer.](figure6.png)

As per the circuit shown in figure 6, when the system is working under normal condition, the transformer tap remain on its first tap to provide normal rated voltage to rectifier. But when the faulty condition or under voltage condition arises, the transformer tap is stepped up to appropriate voltage level tap and injects reactive power to step up the voltage. Voltage of grid side is monitored by the relays. Over voltage relay senses the increase in three phase voltage $V_{abc}$ from the Grid side and gives the signal to transformer to step down the transformer tap. In the same way when there is an under voltage condition, it is sensed by under voltage relay and relay gives the signal to transformer to step up the tap voltage. Even though, this is a very efficient technique, transformer taps have limitation to provide reactive power due fixed number of taps. A concept taken from [6] [15] [1].
7.3 Capacitor Banks with synchronous generator:

The main use of capacitor banks in a power system is to make power factor correction and to provide the necessary reactive power kvar. By providing such capacitor banks, need of reactive powers can be fulfilled to increase the voltage and stabilize the system. As shown in Figure 7, capacitor bank of 100kvar in connected to three phase synchronous generator and bus. Such capacitor banks have limited efficiency to provide PF correction and reactive power injection. For more stabilization of voltage other two methods discussed above are needed.

![Figure 7: Circuit connections for connecting the capacitor bank with Synchronous Generator](From Simulink Simulation)

By using these three methods, powerful and efficient reactive power injection can be achieved, resulting to lift up the voltage level up to systems voltage in 1p.u. or up to system’s rated voltage.
8. Simulation and Results

In this paper, MATLAB Simulink is used which includes simpowersystems, simelectronics and simmachines. Matlab and Simulink are easy and helpful to user for doing even complex simulation [14].

8.1 Simulation of Wind, Wind turbine and Generator:

Here for simulation of Wind speed Signal Builder is used to create a constant wind speed of 19 miles/Hour. The output of wind speed is given to the wind turbine which converts kinetic energy of wind into mechanical energy. The wind turbine generates appropriate output to wind speed, here wind speed is constant and therefore rotation per minute of turbine shaft is constant and provides about 1800 RPM. The output of wind turbine is given to Synchronous Generator which converts mechanical energy into the electrical energy. This is a three phase generator with 280KVA capacity and also a capacitor bank is connected across the generator’s three phase output for power factor correction.

8.2 Converter/inverter circuit and control circuit for voltage controller:

In this block a transformer, rectifier, IGBT inverter with PWM and PI based voltage regulator are provided. In this block, at first three phase voltages coming from the Synchronous Generator is given to the transformer through a circuit breaker and this circuit breakers are connected to under voltage and over voltage relays. These relays compare voltage of the grid side voltage Vabc with voltage 0.9p.u. If the voltage level goes below the set value of voltage, the under voltage relay reacts and gives enable signal to circuit breaker which disconnects transformer-1 which provides 600V output and simultaneously transformer-2 gets connected. Transformer-2 provides higher voltage with 1200v which has more voltage ratio and like this reactive power is injected into circuit and which helps to stabilize the system voltage. The voltage output coming from the transformer is given to the rectifier circuitry.

When the output of the transformer is given to the rectifier, it converts AC power into DC power. For smoothening of DC power, LC circuit is used and after that DC power is fed to the IGBT type inverter. IGBT inverter gives pure sinusoidal AC voltage output. The gate pulse input of the Inverter is given by the PWM pulse generator and this gate pulse is controlled by the PI based voltage controller. The voltage controller compares the reference voltage (Vref) with the three phase voltage (Vabc) of the grid side end. Then appropriate gate pulse is provided to the inverter. Thus inverter tries to keep voltage level to normal rated voltage. The load voltage is regulated at 1 p.u. (380 V rms) by a PI voltage regulator using abc_to_dq and dq_to_abc transformations. The first output of the voltage regulator is a vector containing the three modulating signals used by the PMW Generator to generate the 6 IGBT pulses. The second output returns the modulation index [14]. Here two types of faults are simulated, three phase to ground fault and single phase to ground fault, which are discussed below with the simulation results obtained from Simulink.
8.3 Three phase fault:

Figure 8: Output of load side voltage during three phase to ground fault.

Figure 9: Zoomed output of load side voltage during three phase to ground fault.
Figure 10: Output of load side current during three phase to ground fault.

Figure 11: Zoomed output of load side current during three phase to ground fault.
Figure 8 shows the output of load side voltage during three phase to ground fault. From figure 8 it can be seen that in 0.057 seconds, voltage level falls down to 0.0 p.u. from 1.0 p.u. due to effect of (three phase to ground) fault. More details can be seen from Figure 9. Figure 9 shows that when voltage drops down to 0.0 p.u. as an effect of three phases to ground fault, this is sensed by relays and relay sends the reference voltage signal $V_{abc}$ to the PI voltage controller input. The PI controller controls PWM pulse for gate inputs of IGBT inverter and due to that reactive power is injected by IGBT inverter. Simultaneously under voltage due to fault is sensed by under voltage relay and it sends signal to step up the voltage of a transformer. This causes injection of reactive power and because of that, reactive power increases after some delay.

As shown figure 9, due reactive power injection the voltage comes back to its normal voltage level of 1.0p.u.. Figure 10 and Figure 11 shows outputs of the current during three phases to ground fault. It can be seen from both the figures that, there is a huge amount fault current flow during three phase fault to ground fault, but due to reactive power injection, fault current comes back to its normal rated value.

### 8.4 Single Phase to Ground Fault:

![Figure 12: Output of the load side voltage during a single phase to ground fault.](image)
In this part, single phase to ground fault simulation results are discussed. Figure 12 shows the output of the load side voltage during a single phase to ground fault and Figure 13 shows zoomed output of the load side voltage during a single phase to ground fault.

As it can be seen from figure 13, when the fault occurs, voltage of one phase goes to zero because of single phase to ground fault and as an effect other two phase voltages increase upto 2.0p.u. Figure 15 shows that during a fault, value of the current increases. Here Figure 16 shows that, the value of current increases more in the phase which is under fault and increases in the other two phases also. But as soon as the reactive power injection increases, the value of voltages comes to normal rated voltage and at the same time the current of the system comes back to its normal rated current.
Figure 14: Output of the load side current during single phase to ground fault.

Figure 15: Zoomed output of the load side current during single phase to ground fault.
Figure 16: Output of Active and Reactive power during a single phase to ground fault.
9. Conclusion:

The availability of renewable energy sources and the right technique to connect decentralized and renewable energy with electrical network has created a revolution in modern power systems. This paper proved to be an epitome for improving the efficiency and reliability of the power system. The method of controlling reactive power injection and fault ride through capability can give the ability to renewable energy sources to stay connected during faulty conditions and helps to stabilize system voltage of connected connected system. The results produced through Simulink simulation not only satisfies the goal to keep the system voltage at 1.0 p.u. but also helps to limit the current.
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Appendix:

IGBT Data:-

PWM Generator Data:-
Voltage Regulator (Voltage Controller using PI controller) Data:

- **Proportional gain (Kp):** 0.5
- **Integral gain (Ki):** 500
- **Sample time (s):** Ts