1. INTRODUCTION

Distributed generation includes the solar panels, photovoltaic cell, micro turbines, wind turbines, combustion gas turbines, biomass gasification, and various other small generation units which are based on renewable energy sources. The distributed generation is a technology which has evolved in the present time and has become one of the major fields of interest for the researchers. The distributed generation has the advantage over the conventional methods of power generation that they can be installed at the sites where the power requirement has increased and also it is not possible to set up a new power generation station at every few kilometer distance. Other advantage which it possesses is that this technology is environment friendly which means it does not produce harmful by-products which in a direct or indirect way affects the environment.

Third advantage of Distributed Generation is that it is not costly and it works on the non-conventional sources of energy like wind energy, solar energy, increases the reliability, reduces the losses etc. A distributed generation offers several advantages but to make the full use of the Distributed generation potential it is necessary that we should again think on our power generation methods. Today Distributed generation has become an essential part of distributed energy resources including storing of energy. Much work has already done in the past about the sizing and location of distributed generation into the network so that the transmission and distribution losses are minimized.

Disadvantages of distributed generation are that it disturbs the power flow in the network which in turn disturbs the voltage profile and reduces the stability of the power system.

Also if the distributed generation is not connected to the optimal location and is of optimal capacity as required by the particular location it will increase the losses thereby degrading the quality of the voltage [94].
Methods such as ant colony optimization [2], particle swarm optimization [3 - 4], monte-carlo simulation methods [5] genetic algorithm [6] and optimal power flow method [7] have been discussed. A method is being introduced that four types of Distributed generation are considered with one Distributed generation installed to minimize the total real and reactive power losses. The main aim of this methodology is to calculate size and to identify the corresponding optimum location for Distributed generation, placement of DG to minimize the total real and reactive power losses and to improve voltage profile [8].

The IEEE 30 bus network consists of PV and PQ busses. PV bus is the bus where we put the values of active power and magnitude of voltage and DG is connected to the distribution grid through the synchronous generator with excitation mode of control for voltage control, the PQ bus is the bus at which input values of active power and reactive power inserted. On the other hand in PQ bus the DG is connected to the distribution grid through synchronous generator with excitation control mode for power factor control [9]. S.P. Rajaram et al. suggested that the optimal location of connecting Distributed generation in any network is the weakest node at which the maximum voltage drop occurs [10].

In our test network PV buses are bus no. 1, 2, 5, 8, 11, 13 and the remaining are PQ buses. Slack bus is connected to the bus 1 whose voltage magnitude is set to 1 p.u. It consists of four transformers of 100 MVA rating. The network is designed for 11kV transmission line [94].
1.1. MOTIVATION

For global climate change problem, renewable energy technologies are an important role in regard to and energy security for the future. The evolution of present conventional or centralized generation in the form of distributed generation and Smart and micro Power Grids has great potential to remove several issues linked with green energy, energy efficiency; energy security and the drawback of old power system infrastructures. These phenomena also become major options to fulfill the present high power demands and build flexible power system networks where both customer and power operator can mutually interact on a real time basis.

Power system operation is very challenging from system security, reliability and efficiency points of view. The demand of electrical power is increasing continuously and existing power system networks are very complex, large scale, centralized and far from load centers to make energy supply to all customers must be continuously stable and reliable. Integrated distributed generation and existing power systems are capable of supporting energy security, such as during peak demand or power shortages.

Integration of distributed generation to power systems causes some technical issues, such as stability of power system and power quality. However, with the help of compensation technics, there are high possibilities that these issues can be minimized.

A power electronics voltage-source converter device is used to maintain reactive power within limit is called static synchronous compensator (STATCOM). This device is used in AC electrical power transmission grids. This device is a member of the FACTS family.
STATCOM is connected to support the electricity network which has a poor power factor, poor voltage regulation and the most common use is for voltage stability. A STATCOM is simply voltage source converter (VSC)-based device and it has a voltage source behind a reactor. The voltage source is formed from a DC capacitor so that a STATCOM is very less active power capability. The active power capability may be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the magnitude of the source voltage.

For example, if the value of AC voltage at the point of connection is less than the value of terminal voltage of the VSC, then STATCOM will generates reactive current. The STATCOM absorbs reactive power when amplitude of the voltage source is lower than the AC voltage. The STATCOM is fast switching device and response time less as compared to SVC the fact the fast switching times provided by the IGBTs of VSC. At low Ac voltages STACOM can provide better reactive power support than SVC.
1.2. BACKGROUND

Distributed generation technology has impact on power systems, still some of the attempts made to overcome these impacts. Distributed generation shows both positive and negative impacts on power systems, such as improving system reliability, preventing under-voltage drop, influencing transient stability and harmonic distortion during connection or disconnection.

Also, a comprehensive analysis of impact of distributed generation on modern power system concepts has been made as well as some basics of Distributed generation is a new concept for future power system generation involves broadening knowledge and technologies, which requires standard and interoperability features for operation and implementation. The realization of impacts and compensation techniques of distributed generation frameworks will take gradual stages and possibly many years. This also provides an overview of FACTS based technology, especially STATCOM as a compensator device controller with an elaborate discussion on the fundamentals of power compensation, as well as each model of power compensation for system stability.

In view on the fact that the capabilities of the STATCOM device to provide reactive power support, voltage enhancement, reduce voltage variations and enhance system stability, the STATCOM makes an ideal choice as a compensation device.

In addition to this, a few papers have been reviewed which stand in support of the fact that STATCOM suits better than the other set of power semiconductor FACTS devices like the Static VAR Compensator (SVC) etc.
1.3 OVERVIEW OF DISTRIBUTED GENERATION

1.3.1 DEFINITION OF DISTRIBUTED GENERATION

A distributed generation is simply defined as a small-scale generation of electrical energy. It often acts as an active unit of power generation and connected at distribution level. Some of the standard definitions of the Distributed Generation are also given as follows:

1.3.2 IEEE DEFINITION

As per the IEEE standards, a distributed generation can be defined as the generation of electrical power smaller than central power plants, usually 10 MW or less, so as to allow interconnection at any point in the power system, also called as Distributed Resources or Distributed Generators.

1.3.3 ELECTRIC POWER RESEARCH INSTITUTE (EPRI) DEFINITION

EPRI define distributed generation as implicit in an overview of the integrating distributed energy resources. According to this definition the new system would also be able to seamlessly integrate with locally installed, distributed power generation as power system quality. Less than 20 MW / unit could be deployed on both the supply and consumer side of the energy and information portal as essential assets dispatching reliability, capacity and efficiency in distributed generation sources.

1.3.4 IEA DEFINITION

International Energy Agency (IEA) defines Distributed Generation as “Power generation equipment and system used generally at distribution levels and where the power is mainly used locally on site”.
1.3.5 CIGRE DEFINITION

The International Council on Large Electricity Systems (CIGRE) defines Distributed Generation as a kind of generation which is not centrally planned and centrally dispatched at present. It is connected to the distribution system smaller than 50-100 MW.

1.3.6 DISTRIBUTED POWER COALITION OF AMERICA (DPCA)

Distributed generation is a small unit of power generation based on renewable sources that provides electrical power at a site nearest to consumers than central power station. A distributed generation can be connected directly to the consumer or to a transmission or distribution System.

1.3.7 US DEPARTMENT OF ENERGY (US. DOE)

Distributed generation is a small unit of power generation based on renewable sources which is at a site nearest to load center. Up gradation cost is very high in transmission and distribution system and to eliminate this type of difficulties and provide customer with best quality, more reliable and clean environment distributed energy resources can prefer. The range size and capacity of distributed generation are from few kilowatts to 50 MW [22].

1.3.8 AMERICAN GAS ASSOCIATION (AGA)

The deliberate placement of small power generating units (5 kW to 25 MW) at or close to customer loads is called distributed generation (DG). Distributed generation has an ability to provide distribution grid support to fulfill the requirements of power quality and reliability located near substations [22].
FIGURE 1: DISTRIBUTED GENERATION SYSTEM [90]
Central Generation or CG is defined as the generation of electric power by central station power plants to provide bulk power and large fossil-fired gas, coal, and nuclear fuel to produce steam that drives turbine generators. In some cases, large hydro turbine is also used. These enormous plants require costly management of large infrastructures. Central generation plants are liable to unreliability and instability under unforeseeable events, and are often vulnerable to attacks.

The limitations of CG, in terms of efficiency and environmental impact as well as stability to sustain them, researchers, engineers and policy-makers should have given respond to renewable energy resource options. Centralized and distributed generated grid system has their merits and demerits. Thus, the aims of this work at enumerating both positive and negative aspects of the grids as well as addressing the challenges posed by the grids. This analysis helps to assess the best option that may improve the reliability, resiliency and sustainability of the present grid structure.
FIGURE 2: CENTRAL VS. DISTRIBUTED GENERATION [90]
<table>
<thead>
<tr>
<th>Component Cost</th>
<th>Centralized Generation (CG)</th>
<th>Distributed Generation (DG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Capital</td>
<td>Lower Cost per unit</td>
<td>Higher cost per unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saved cost of system design due to reduced capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saved cost of system design due to use of waste heat in cogeneration</td>
</tr>
<tr>
<td>Fixed Operation and Maintenance Cost</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Variable Operation and Maintenance Cost</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Fuel</td>
<td>Same as DG</td>
<td>Same as CG</td>
</tr>
<tr>
<td>Transmission</td>
<td>High voltage transmission is mandatory</td>
<td>Only distribution required</td>
</tr>
<tr>
<td></td>
<td>High losses and transmission failure</td>
<td>Reduced capital cost</td>
</tr>
<tr>
<td>Expense for Unserved Energy</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
1.4 CONDITIONS FOR DISTRIBUTED GENERATION CONNECTION

It is found that the connection of distributed generators to a distribution network is based on their bad impacts on the distribution power system. This process is totally depends on the impedance of system at the point of common coupling (PCC), short-circuit power, resonance and the type of distributed generators which usually includes renewable energy sources. The requirements of the connecting distributed generators to the distribution network are discuss below.

1.4.1. SIZE OF THE CONNECTED POWER

The voltage level is determined the size of the connected power to particular distribution system. **For low voltage systems:**
The total rated power of the distributed generators to be connected should not exceed 10 % of the distribution transformer rated power.

**For high voltage systems:**
The total rated power of the distributed generators to be connected should not be higher than 10% of the supply transformer 110/22 kV rated power.

1.4.2. INCREASE IN VOLTAGE

When the distributed generators are to distribution system the voltage increase in the MV systems should not more than 2 % in comparison with the voltage before their connection, similarly distributed generators connected to the LV systems the voltage level should not increase by more than 3 %.
1.4.3. VOLTAGE CHANGES DURING SWITCHING

At time of switching, individual generators changed voltage at PCC. In the MV system, these changes do not cause excessive negative impacts provided that the highest voltage change at PCC does exceed 2 %, and for LV systems the voltage change limit is 3 %.

1.4.4. LONG-TIME FLICKER

When analyzing various distributed generators at the common coupling point. It is very important to consider the voltage fluctuation because fluctuations are the responsible for flicker. It is therefore necessary to manage the long-time flicker perception rate \( P_{lt} \) and for the long-time flicker factor \( A_{lt} \) as follows:

\[
P_{lt} \leq 0.46,
\]

\[
A_{lt} \leq 0.1. \tag{1.1}
\]

The long-time flicker perception rate \( P_{lt} \) is determined using the following equation:

\[
P_{lt} = c \frac{S_{nE}}{S_kV} \tag{1.2}
\]

Where:

\( c \) = flicker factor

\( S_{nE} \) = load rated power [MVA],

\( S_kV \) = system short-circuit power [MVA].

If we consider more than one generating unit than \( P_{lt} \) should be calculated separately for each device.

\[
P_{lt\text{res}} = \sqrt{\sum_{i} P_{lt\ i}^2} \tag{1.3}
\]

\[ \]
The allowable higher harmonic currents of the individual equipment connected at PCC can be computed using the following equation:

\[ I_{v\, pri} = I_{v\, pr} \frac{S_A}{S_{AV}} = i_{v\, pr} \cdot S_{kV} \cdot \frac{S_A}{S_{AV}}, \]

Where, \( S_A \) = single device apparent power [MVA],
\( S_{AV} \) = total connected power [MVA],
\( i_{v\, pr} \) = relative current [A/MVA],
\( S_{kV} \) = distribution system short-circuit power [MVA],
\( I_{v\, pr} \) = higher harmonic allowable current [A].

If the allowable harmonic currents are exceeded, then connection at PCC is not possible.

1.5 DISTRIBUTED GENERATION ISSUES

As per the literature review conducted and study of various research papers as presented by the different authors we have seen that following are the major issues rises among the researcher, designer and the planner when the distribution generation is connected to the power system:

- Voltage Regulation
- Operation and Control
- Grounding Issue
- Harmonic Distortion
- Change of Short Circuit Capacity
- Flicker
- Islanding
- Protection System
- Voltage Unbalance
- Sustained Interruptions
1.5.1 VOLTAGE REGULATION

The voltage regulation problem can arise to introduction of Distributed generation into Distribution Network for any of the following reasons:

- Discontinuous nature of the wind turbine, fuel cells and combined heat and power plants
- Interference of the synchronous generators capable of supplying active and reactive power with the utility voltage regulating equipment, i.e., with static voltage regulators (SVR) and with load tap changers (LTC)
- The induction generators and inverters are used for grid connection which are not suitable for voltage regulation and generate reactive power
- A small distributed generation unit is used which lacks the capacity to regulate the voltage
- Breakdown of a large distributed generation unit responsible for voltage regulation in case of a fault on the feeder
- The coordination between multiple distributed generation units is very less
- Frequent switching of a large number of small distributed generation units working at a constant power factor.
- Reverse power flow that occurs when distributed generation output is in excess of downstream feeder load
1.5.2 OPERATION AND CONTROL

Distributed generation output is varied according to the local load variation. Distributed generation power output can also be controlled autonomously of the local loading of the area. This control mode is implemented if distributed generation operation follows price signal, which might or might not correspond to the local load variations, or distributed generation follows the availability of natural resources, like wind or solar power. In this case, distributed generation might adversely affect the voltage control. Due to this increasing the variations between the maximum and minimum voltage level, the minimum voltage level could remain (usually at a high load, no distributed generation situation) but the maximum voltage level could increase, e.g. in low load condition with distributed generation operating at maximum production and at a unity power factor. Generally speaking, distributed generation can provide some Challenges to the traditional voltage, frequency and power control [22].

1.5.3 GROUNDING ISSUE

A grid-connected distributed generation must provide an actual ground to prevent un-faulted phases from over-voltage during a single-phase to ground fault, whether it is connected through the transformer or directly. It is more important challenge in the distributed generation. Grounding analysis of distributed generation must consider not only the generator- winding configuration (or inverter arrangement), but also its grounding points and interface transformer configuration. Grounding analyses consider the grounding of both the primary and secondary electrical power systems to which the DR is connected.
Voltage harmonics are always present on any utility grid. Nonlinear loads, power electronic loads, rectifiers and inverters in motor drives can be regarded as some of the sources that produce harmonics. The harmonics are the main causes of overheating, equipment failure, faulty operation of protective devices, nuisance tripping of a complex load and interference with communication circuits. All power electronic equipment creates current distortion that can impact neighboring equipment. Distributed Generators like wind turbines, Photo Voltaic cells, fuel cells etc.; are likely to introduce the problem of harmonics in to the power system. The generation of harmonics with the introduction of distributed generation is most common and it depends upon the interconnection technology and power converter technology. However this issue of harmonic generation is very much significant in line commutated inverters as they are mostly of SCR based. But with the introduction of IGBT type inverters the generation of harmonics has been reduced to a considerable level. However the problem of harmonic is not much crucial as some of the other problems discussed in this research work.

When new distributed generators are connected in the power system, increases the level of short circuit capacity (SCC). Although sometimes, it is necessary to have a high SCC at the point of connection of the line commutated inverter in a HVDC station or in the presence of large loads with rapidly varying demands, in general the increase of the SCC potentially indicates a problem [22].
1.5.6 FLICKER

Voltage level of the feeder line which may be because of the start of a machine or a step change in the output of the distributed generation. If the generator starts or its output changes frequently, flicker can be observed. Flicker can be determined by observing the magnitude and the number of changes of voltage occurring per unit time and see if this is above the threshold level. If complaint is received from the customer then its minimization must be done. Minimization technique includes reduced voltage start on induction generators as well as speed matching. Synchronous generator requires good synchronization and Flicker is a sudden change in the voltage matching, also the inverters must be controlled to limit the incoming current and voltage level fluctuations.

1.5.7 SUSTAINED INTERRUPTIONS

Induction generator and uncontrollable inverter are not suitable to operate in standalone mode because they have lacking proper storage might not be able to base on the technologies of distributed generation in case of failure in the main power system are not capable to provide backup generation in all the distributed generation technology.

1.5.8 VOLTAGE UNBALANCING

Several distributed generators are available which supply electricity to the network in single phase. If they exist, the voltage unbalancing of the system will occur and should not increase beyond the threshold level. Distributed generation also suffer with the unbalancing of the loads in the phase their performance deteriorates due to unbalancing [22].
The purposeful division of the utility power network during widespread disturbances to create power islands is called Intentional islanding. To maintain a nonstop supply of power during disturbances in the main distribution system, these islands may be designed. As in the given diagram when disturbances are present on a distributed utility system, the grid sectionalizes itself. Now the distributed energy resources supply the load power demand of the islands by creating reconnection with the main power network [92].
However, the major issues related with this islanding are:

- The voltage and frequency provided to other customers connected to the island are out of the utility’s control, yet the utility remains responsible to those customers.
- Due to the drastic change in short-circuit current; protection systems on the island are likely to be uncoordinated.
The effect of distributed generation on system protection depends upon the characteristics, location and configuration of the distributed generation. If the distributed generation’s unit are so designed that it can very rapidly detect the fault and disconnect from the system then distributed generation’s will not interfere with the working of the protection system. So most of the modern distributed generation unit requires the detection of the fault if it occurs and automatically isolates themselves from the distribution generation and can reconnect when the fault is repaired. But, depending on features of the network and the distributed generation, the following protection problems can arise.

- False tripping of feeders (sympathetic tripping)
- Fuse coordinate with re-closure fast-trip varies with distributed generation operation
- Nuisance tripping of production units
- Blinding of protection
- Increased and decreased of fault levels
- Unwanted islanding
- Prohibition of automatic reclosing
- Unsynchronized reclosing
The technologies related with distributed generation are becoming more sophisticated, hence widening applications distributed generation systems. The discussion about the impacts of distributed generation in this work is mainly based on the following types of distributed generation systems.

- Wind turbines
- Small-hydro turbines
- Small diesel generation.
- Photovoltaic power generation
- Reciprocating Engines.
- Micro turbines
Wind energy systems can contribute to the distribution network voltage distortion along with the voltage sag because of its rotating machine characteristics and the design of its power electronic interface. This type of the distributed generation can in fact cause harmonics in the line current, leading to harmonic voltages in the network.

Figure 4: Power conversion in a wind turbine system [1].
The Power Quality problems arising from small hydro energy systems are far less in comparison to the wind energy systems. Actually they have a less amount of harmonic content injected in to the system. However, the percentage of this amount of distortion increases considerably, when the number of hydro turbines connected to the system also increase.
In most networks, voltage fluctuations due to Photovoltaic systems are not creating problems because network is enough strong to power changes in Photovoltaic systems. But in weaker grids, in during islanding operation in which large amounts of PV systems are connected, voltage fluctuation has been creating some problems.
Even though the small diesel systems never cause a major threat to the overall power system, one of the problems related with small diesel generator sets recognized with wind energy systems is the slow response of the governors. As a result, a stable frequency may not be maintained and the voltage regulation may also degrade from its desirable value.
1.6.5 MICRO TURBINES

Micro turbines are simple construction, compact design and robust instrument used as electric generators in distributed generation systems. It has a compressor, combustor, turbine, and a generator. These turbine units have efficiencies and designed for continuous operation. Micro-gas turbine systems are equipped with air bearings to achieve speeds between 50,000 - 90,000 rpm. These systems can be mass-produced at low cost in the range of 25 - 100 kW.

FIGURE 6: MICRO TURBINE ELECTRICAL SYSTEM [46].

The following is a simple block diagram showing the various impacts of each of the above mentioned types of distributed generation systems.
FIGURE 7: POWER QUALITY ISSUES CAUSED BY VARIOUS DGs IN A POWER SYSTEM
1.6.6 DETERMINING THE LOCATION OF DISTRIBUTED GENERATION AND STATCOM

Authors of [11] have suggested that the optimal location of distributed generation is the weakest bus in the power system. The weakest bus is simply defined as the bus at which the magnitude of voltage drop is maximum. The weakest buses in our test system are the bus no. 26, 29 and 30 with bus no. 30 being the most sensitive bus therefore a distributed generation has to be necessarily installed at bus no. 30 whereas it can also be connected to bus no. 26 and 29 it depends on the system planner. The optimal position of a STATCOM is the bus where the reactive power loss is maximum. In our test network bus no. 8 has maximum loss therefore we have connected the STATCOM at bus no. 8 to minimize the losses.

1.6.7 THE SIZE AND CAPACITIES OF DISTRIBUTED GENERATION

The placement of distributed generation in a power system improved the voltage profile with reduced losses. However, the placing of distributed generation only at optimal location is not sufficient wherein the size of the distributed generation should also be determined for its effective working. Wind based distributed generation of 50 MVA, 68 MVA and 11kV has been connected in our test system.
(DISTRIBUTED GENERATION -1,  50 MVA, 11kV, 50Hz)
Stator Resistance 0.01pu
Stator reactance 0.1pu
Rotor Resistance 0.01pu
Rotor Reactance 0.08pu
Magnetization Reactance 3pu
No. of poles 4
Gear box ratio 1/89
Blade length 75 meters
No. of blades 3

(DISTRIBUTED GENERATION -2,  68 MVA, 11kV, 50Hz)
Stator Resistance 0.01pu
Stator reactance 0.1pu
Rotor Resistance 0.01pu
Rotor Reactance 0.08pu
Magnetization Reactance 3pu
No. of poles 4
Gear box ratio 1/89
Blade length 75 meters
No. of blades 3
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Technology</th>
<th>Typical available size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Combined cycle gas turbine</td>
<td>35-400MW</td>
</tr>
<tr>
<td>2</td>
<td>Internal combustion engines</td>
<td>5kW- 10MW</td>
</tr>
<tr>
<td>3</td>
<td>Combustion turbines</td>
<td>1-250MW</td>
</tr>
<tr>
<td>4</td>
<td>Micro turbines</td>
<td>35kW-1MW</td>
</tr>
<tr>
<td>5</td>
<td>Fuel cells, Phos. Acid</td>
<td>200kW-2MW</td>
</tr>
<tr>
<td>6</td>
<td>Fuel cells, molten carbonate</td>
<td>250kW-2MW</td>
</tr>
<tr>
<td>7</td>
<td>Fuel cells, proton exchange</td>
<td>1-250kW</td>
</tr>
<tr>
<td>8</td>
<td>Fuel cells, solid oxide</td>
<td>250kW-5MW</td>
</tr>
<tr>
<td>9</td>
<td>Battery storage</td>
<td>0.5-5MW</td>
</tr>
<tr>
<td>10</td>
<td>Small hydro</td>
<td>1-100MW</td>
</tr>
<tr>
<td>11</td>
<td>Micro hydro</td>
<td>25kW-1MW</td>
</tr>
<tr>
<td>12</td>
<td>Wind turbine</td>
<td>200W-3MW</td>
</tr>
<tr>
<td>13</td>
<td>Photovoltaic arrays</td>
<td>20W-100kW</td>
</tr>
<tr>
<td>14</td>
<td>Solar thermal, Central receiver</td>
<td>1-10MW</td>
</tr>
<tr>
<td>15</td>
<td>Solar thermal, Lutz system</td>
<td>10-80MW</td>
</tr>
<tr>
<td>16</td>
<td>Biomass gasification</td>
<td>100kW-20MW</td>
</tr>
<tr>
<td>17</td>
<td>Geothermal</td>
<td>5-100MW</td>
</tr>
<tr>
<td>18</td>
<td>Ocean energy</td>
<td>0.1-1MW</td>
</tr>
</tbody>
</table>
Distributed generation improves voltage regulation and stated as voltage support, commonly known as one of the benefit of distributed generation. However, voltage support is by no means guaranteed, and in some cases distributed generation will reduce voltage regulation. The major impact of distributed generation on the distribution system is that it causes an undesirable variation in its voltage regulation and its extent actually depends on the conditions under which voltage is degraded. It is also necessary to categorize the voltage variations based on the duration, namely, short duration and long duration variations. Obviously, more emphasis is to be made on the long duration variations because of the serious impacts it may lead to and the distortion it creates in the system.

1.6.8 LONG-DURATION VARIATIONS:

As per the IEEE standards, long duration voltage regulation variations are the RMS deviations at power frequencies which persist for a duration which is longer than one minute. Long-duration variations are usually caused due to the following reasons:

- The Inadequate voltage regulation
- Broken neutral
- Utility-initiated voltage reduction
- Sudden change of load or unusual load on a distribution circuit
1.7 BENEFITS OF DISTRIBUTED GENERATION

In spite of the several technical and economic impacts of the distributed generation systems, there are so many reasons to promote these distributed generation installations which may include the following main points:

- Reduction of greenhouse gas emissions
- Grid support
- Reduces the cost as there is no use of long transmission line
- Environment friendly
- Avoid the impact of massive grid failure.
- Better power quality and reliability.
- Independence from imported fuels
- Present Higher security of supply
- Promotion of development of certain technologies
- Establishment of new industries with additional employment.

To reach such goals are measured by the two criteria, namely effectiveness and efficiency. Efficiency can further be subdivided into the following two categories:

Static Efficiency
Dynamic Efficiency

**Static efficiency:**
This type of efficiency focuses on a certain point in time. For example, if the development in technology is being currently supported with as small resources as possible to reach a desired level.
Dynamic efficiency:

This is the second type of efficiency which measures the technological development which is induced upon in the system by a support mechanism induces, i.e., if the costs of the energy falls. One of the most interesting features of a distributed generation system is the amount of flexibility that it offers which would allow not only the market participants and changing market conditions, but also help the consumers have an access to a near uninterruptable power supply which has truly been a challenge over the past few decades, especially in a country like India. So, we would now have a look in to the various ways in which the DG offers its flexibility.

1.7.1 FLEXIBILITY IN PRICE RESPONSE

The operation, size and expandability are important aspects of distributed generation technologies. Flexibility in cost evolutions may be one of the best examples distributed to serve distributed generation against price fluctuations. The continuous use of distributed generation for maximum shaving is the major driver of the demand for distributed generation. In European countries, the market demand for distributed generation is driven by heat applications, the introduction of renewables and by potential efficiency improvements.
1.7.2 FLEXIBILITY IN RELIABILITY NEEDS

High reliable system include proper maintenance of grid and generation infrastructure due to this high investment is required and cost effectiveness that comes from the introduction of competition in generation.

However, for several industries, such as petroleum, chemical, refining, paper, telecommunication, metal, a reliable power supply is very important. Such companies are required the reliability of the grid supplied electricity is very less and thus be willing to spend in distributed generation units in order to increase their overall reliability of supply. Fuel cells and backup systems combined with an Uninterruptible Power Supply (UPS) are known as the technologies that could provide protection against power interruptions, however it has to be noted that the fuel cell technology is not commercially available.

1.7.3 FLEXIBILITY IN POWER QUALITY NEEDS

The characteristics of different distributed generation are different thereby they create various power quality issues. The addition of distributed generation on the network leads to the improved power quality with the only exception of a single large distributed generation connected to a weak network particularly during the start and stop of the distributed generations.
1.7.4 ENVIRONMENTAL FRIENDLINESS

The demand of distributed generation is increasing day by day because these are environment friendly. Distributed generation technology is clean energy source and cost efficient. The distributed generation is based on renewable energy sources by nature small scale generation from few kW to 100 MW.

Most government policies promote the use non-conventional source of energy to increase the impact of distributed generation. Generally in distributed generation we use cheap fuels, like biomass resources and landfill gases in proximity landfills.

1.7.5 SUBSTITUTE FOR GRID INVESTMENTS

The transmission and distribution losses are about 30% of electrical energy costs. If the customer requirement is less, then transmission and distribution costs in the electricity bill will be more.

Distributed generation units can be used as a substitute for investments in transmission and distribution capacity from the viewpoint of the system operators. In some cases, it can be used as an alternative to connecting a customer to the grid in a stand-alone application. Furthermore, locating the distributed generation near to the load center could also contribute to minimized grid losses.
There are so many technologies can be used to improve the power quality at a site. These technologies are very helpful to protect the customer from variations in Power Quality in utility supplied power or to mitigate these Power Quality disturbances emanating from the customer’s own equipment.

These technologies are frequently used as individual components of an overall Power Quality control approach are given below:

- Transient voltage surge suppressors
- VAR compensators
- Dynamic Voltage Restorers (DVR)
- Isolation transformers
- Motor alternator / motor-generator sets
- Various types of UPS

Any of the above mentioned facilities may be chosen for an electrical power system in order to protect its:
- Entire load - At the electric service entrance
- Sensitive sub-facilities - Individual circuit protection
- Individual operations - Controls or individual equipment protection

However, the level of protection depends on the size and type of critical load which could be categorized in the following manner:
- Small-scale equipment (up to 3kVA)
- Medium-scale equipment (from 3 kVA to 100 kVA)
- Large-scale equipment (above 100 kVA)
Keeping in view all the important aspects discussed about the distributed generation in the above sections, it is quite evident that even though there are a few issues related to the connection of distributed generation in to the power system, it is worth taking a chance because of the wide variety of applications and the kind of flexibility it offers to the smooth operation of the power system.

However, it is very essential to focus on the ways to handle the ill effects of the interconnection of distributed generation and the distortion that occurs at the time of PCC. There are a wide range of power semiconductor devices that are eligible to be used as the compensation devices especially SVC (Static Var Compensator), STATCOM (Static Synchronous Condenser) etc.

First, we would look in to the basics of these two leading FACTS based power semiconductor devices which includes a simple study of SVC and a comparison of SVC and STATCOM and finally an in detail emphasis on STATCOM considering its advantages over the SVC.

1.9.1. SVC (STATIC VAR COMPENSATOR)

It has been already discussed that integration of distributed generation (large- or small-scale) can have important effects on power system stability. To make grid more stable reactive power compensation and voltage control is required. Without this control system may collapse. Therefore, a dynamic shunt reactive power compensator is required to minimize these issues.

Keeping in view the various issues occurring at the time of PCC (Point of common coupling), the concept of smart grid technology uses the compensation system which involves the FACTS controller devices such as an SVC. The main objective of SVC (Static Var Compensation) system is to maintain the system stability, which would be vulnerable during interconnection of distributed generation in to the distribution system during the occurrence of fault by supplying reactive power or absorbing reactive power into the existing network.
1.9.1.1 TYPES OF SVC

Two most popular structure of shunt controller are consists a fixed capacitor (FC) with a thyristor controlled reactor (TCR) and the thyristor switched capacitor (TSC) with TCR. Among these two setups, the second (TSCTCR) minimizes stand-by losses; however from a steady-state point of view, this is equivalent to the FC-TCR. In this work we have FC-TCR structure is used for analysis of SVC which is shown in given figure.

FIGURE 8: STATIC VAR COMPENSATOR
A simple Line diagram of a Static Var Compensator consisting of various elements of reactive power compensation devices like Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TSC), Switched Capacitor, Inductor, and Filter Circuit etc.; is as shown below.
The response time of SVC is fast as compared to traditional mechanically switched reactors or capacitors when SVC is used as a control device. The SVC has two main components and their combination given below.

- Thyristor-controlled and thyristor-switched reactor (TCR and TSR)
- Thyristor-switched capacitor (TSC).

TCR and TSR have paired parallel back-to-back connected thyristor used as shunt connected reactor to control phase angle.

TCR generates and control constant variable inductive reactive power from zero to maximum. Conversely, TSR is controlled without phase angle control, which results in a step change in reactance and provides fixed inductive admittance. TSC and TSR have similar structure and operational characteristic. TSC cannot inject a reactive current with variable amplitude into the system. The transient phenomenon in TSC does not generate harmonics but if they appear, it is not a serious problem.

1.9.1.3 BLOCK DIAGRAM OF SVC CONTROL SYSTEM

The Block diagram describes the controlling mechanism of SVC FACT device. The SVC based TSC-TSR control system includes the voltage regulator and reactive power measurement is explained.

The main aim behind this voltage control system is to keep the voltage level within the acceptable limits especially at the point of common coupling (PCC) else the system will get collapse. The voltage regulator measure’s the input variable and produces an output signal which is proportional to the reactive power.
The measured value of voltage is compared with the reference voltage denoted by $V_{\text{ref}}$ and an error voltage is calculated as the difference between the measured and actual voltage value which is fed as an input to the controller. The output of the controller is a per-unit susceptance signal, $B_{\text{ref}}$. This is done in order to reduce unwanted signal error to zero in the steady-state operation then the signal is applied to the gate-pulse generation.

FIGURE 10: BLOCK DIAGRAM OF AN SVC CONTROL SYSTEM [91]
This derived $B_{\text{ref}}$ signal from the voltage regulator is applied to the gate-pulse generation which produces exact firing pulses for TCR-TSC of the SVC. Subsequently the unwanted susceptance signal is corrected and the desired susceptance output is available at the output of SVC.

### 1.9.1.4 V-I CHARACTERISTICS OF AN SVC

The given figure shows a graph between the voltage and current representing the V-I characteristics of a Static Var Compensator.

![FIGURE 11: V-I CHARACTERISTICS OF SVC](image)
The Static Synchronous Compensator (STATCOM) is an important shunt active power semiconductor device to control the power flow and improve transient stability on power system. The STATCOM has an ability to maintain the voltage profile within the acceptable limits by controlling the amount of reactive power in the system.

FIGURE 12: STATCOM STRUCTURAL DIAGRAM
VSC which is a part of STATCOM device converts dc voltage into a three-phase output voltage of desired phase angle, amplitude and frequency. Various techniques had been adopted for the effective utilization of electrical power using VSC. Pulse width modulation (PWM) technique is used for the minimization of harmonics and reactive power losses. Inherently, STATCOMs have a symmetrical rating with respect to inductive and capacitive reactive power.

It carries out the following two important functions:

- When system voltage is low, the STATCOM behaves as a capacitive network and generates the reactive power and is called as a Capacitive STATCOM
- When system voltage is high, it absorbs reactive power and in this case, it can be called as an Inductive STATCOM.
Variation in reactive power on the secondary side of a coupling transformer is achieved by the Voltage Source Converter (VSC) connected. VSC is a simple forced-commutated power electronic device (like: GTOs, IGBTs or MOSFETs) to produce an output voltage $V_2$ from an input DC voltage source. The principle and operation of STATCOM is explained with the help of the figure. In this figure $V_1$ represents the system voltage to be controlled and $V_2$ is the voltage generated by the VSC. The active and reactive power transfer between a source $V_1$ and a source $V_2$.

$$P = (V_1 V_2 \sin \delta) / X, \quad Q = V_1 (V_1 - V_2 \cos \delta) / X$$

**FIGURE 13: OPERATING DIAGRAM OF A STATCOM**
Symbol Meaning

$V_1 = $ Line to line voltage of source 1
$V_2 = $ Line to line voltage of source 2
$X = $ Reactance of interconnection transformer and filter
$\delta = $ phase angle of $V_1$ with respect to $V_2$

The overall operation of a STATCOM can be summarized into the following three modes:

- Under steady state operation, the voltage $V_2$ generated by the VSC is in phase with $V_1$ (i.e. $\delta=0$). This means that only reactive power is flowing into the circuit and the active power is zero ($P=0$).
- If $V_2$ is lower than $V_1$, reactive power $Q$ flows from $V_1$ to $V_2$ which indicates that the STATCOM is absorbing the reactive power.
- If $V_2$ is higher than $V_1$ then the reactive power $Q$ flows from $V_2$ to $V_1$ and STATCOM in this case acts as a generator of reactive power.

Total reactive power ($Q$) = $V_1 (V_1 - V_2) / X$

A capacitive network connected on the DC side of VSC work as a DC voltage source. Under steady state operation the voltage $V_2$ lags behind $V_1$ in order to compensate for the transformer and VSC losses in order to keep the capacitor charged.
1.9.2.2 VOLTAGE SOURCE CONVERTER TECHNOLOGIES

The operation of voltage source converter had been controlled with the help of switching devices using various control methods. There are two different control methods for the operation of VSC which are as follows.

1.9.2.2.1 VSC USING GTO-BASED SQUARE-WAVE INVERTERS

In this type of circuit, four three-level inverters had been used to generate a 48-step voltage waveform to minimize the harmonics present in the square wave generated by individual inverter and special interconnection transformers are used. In this type of VSC, the fundamental component of voltage $V_2$ is proportional to the voltage $V_{dc}$, the variation in which controls the reactive power flow into the distribution network.

1.9.2.2.2 VSC USING IGBT-BASED PWM INVERTERS

This method produces a sinusoidal waveform from a DC voltage source with a chopping frequency of a few (kHz). Harmonic voltages are eliminated by the use of filters on the AC side of the VSC. The VSC uses a fixed DC voltage $V_{dc}$ and voltage $V_2$ is varied by changing the modulation index of the PWM modulator.
The V-I characteristics of the Static synchronous compensator (STATCOM) are shown in the below figure and these characteristics can be described by the following equation:
\[ V = V_{ref} + X_s I \] .................................1.9.1

Where,

\[ V = \text{Positive sequence voltage (pu)} \]
\[ V_{ref} = \text{Reference Voltage} \]
\[ I = \text{Reactive current (pu/Pnom)} \]

Also, \( I > 0 \) indicates an inductive current

\[ X_s = \text{Slope or droop reactance (pu/Pnom)} \]

If the value of reactive current is within the limit \((-\text{Imax}, \text{Imax})\) imposed by the converter rating, the output voltage is regulated w.r.t. reference voltage \( V_{ref} \). However, a voltage drop 1% to 4% had been used at maximum reactive power output indicated the slope in the figure.

1.9.3. DISCUSSION ON STATCOM AND SVC

Mainly two type of shunt reactive power generator were used as a controller (SVC and STATCOM). SVC is a shunt connected admittance device whose output had been adjusted discontinuously to generate or absorb the reactive current. On the other hand, STATCOM is a shunt connected synchronous voltage source whose output had been adjusted continuously to generate or absorb the reactive current.
A static synchronous compensator (STATCOM) performs the same function of reactive power compensation as static VAR compensator (SVC). However, the following points would justify the fact why STATCOM is better than SVC.

### 1.9.3.1 Generation of Reactive Power

The STATCOM can generate more reactive power than SVC when voltage is lower than the normal voltage regulation range because maximum capacitive power generated by an SVC is proportional to the square of the system voltage (constant susceptance), while the maximum capacitive power generated by a STATCOM decreases linearly with voltage (constant current). During fault the STATCOM generates more capacitive reactive power which is an added advantage of STATCOM over SVC.
1.9.3.2 FASTER RESPONSE

In addition to the above mentioned advantages, the STATCOM has a faster response than SVC which means that the STATCOM will produce output much faster than SVC as soon as the input is applied.

1.9.3.3 NO DELAY TIME

With the presence of Voltage Source Converter (VSC) in STATCOM there is no delay associated with the firing of SCR unlike SVC whose delay time is usually in the order of 4 ms (milliseconds).

1.9.3.4 BETTER CHARACTERISTICS

A static synchronous compensator (STATCOM) has better input-output characteristics as compared to SVC indicated when the system voltage drops sufficiently to drive the STATCOM output current to its maximum value so that the maximum reactive output current of STATCOM is not affected which shows constant current characteristics when voltage is below the minimum limit.

1.9.3.5 BETTER STABILITY

In contrast to a STATCOM, the reactive power output of SVC is proportional to the square of the voltage magnitude as a result reactive power decreases rapidly with the decrease in voltage magnitude thus reducing its stability.
The harmonics present in STATCOM are much lesser than SVC which makes it a better choice over SVC. The basic concepts related to the distributed generation viz. advantages and disadvantages of DG technology, need of power control strategies to minimize the distortion arises in the active as well as reactive power flow balance with the integration of DG into the DS, comparison of STATCOM and SVC as the compensation devices and so on. From the above discussion, we select STATCOM as a compensating device for minimizing the distortions which arises in the distribution system after the integration of a wind turbine distributed generation.