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Grid integration of renewables: challenges and solutions

Exponential growth in the energy demand on account of rising population and economic growth, increasing apprehensions of energy security coupled with climate change and global warming concerns are some of the major drivers for pushing the renewable energy (RE) to the top of the energy portfolio. Among various renewable energy resources, wind and solar PV systems are experiencing rapid growth since 2010. By the end of 2016, the world total capacity of wind power generation was 487 GW and that of solar PV was 303 GW, aggregating to a penetration level of 4.0% and 1.5% respectively. Global renewable energy penetration till December 2016, excluding conventional hydro share (of 16.6%) was only around 8.0%. However, many countries have set target of 30% RE based electricity generation by 2030. India has an ambitious target of achieving 175 GW of RE power by 2022, with 100 GW from solar, 60 GW from wind, 10 GW from biomass and 5 GW from small hydro.

Power generation from renewables often takes place through distributed generation (DG). These units, mostly located in remote locations, are not centrally planned or dispatched, and are usually connected to distribution grids at LV or MV levels. In few cases, large capacity RE generation are also connected to transmission networks. As a result, the power generation structure is moving from the large, centralized plants to a mixed generation pool consisting of traditional large plants and many smaller DG units. Most of the RE generators have electrical characteristics that are different from the synchronous machines. Since a large group of DG technologies use power electronics converters for grid connectivity, they introduce many technical issues related to the operation, control and protection of the power system, impacting generators, transmission system and consumer devices.

This paper presents some of the technical issues and challenges that need to be addressed for the effective grid integration of RE based power generators so that eventually, our reliance on polluting and expensive fossil based hydro-carbon driven power generation can be reduced substantially.

Keywords: distributed generation, energy storage, power quality, solar PV, wind energy.

1.0 Introduction

The share of renewable energy in the world power system is growing rapidly. During the past 50 years since 1965, global power generation from renewables has increased by more than 500%. In 2016, renewable power (excluding hydro) grew by 14.1%, and represented almost two-third of new net electricity capacity additions with almost 165 GW. The RE power addition, which was 34% less than coal power addition in 2016, is going to increase further so that by 2022 the gap is expected to be halved to just 17% [1]. By the end of 2016, total global renewable power generation capacity (including conventional hydro) was nearly 2,017 GW, as shown in Table 1. This was almost 30% of the world's power generating capacity sufficient enough to supply nearly 24.5% of global electricity, with hydropower contributing to about 16.6% and other modern RE providing nearly 8% [2].

TABLE 1: RE BASED POWER GENERATION CAPACITY BY 2016

Resource type	Capacity (GW)
Hydro power	1,096
Wind power	487
Solar PV	303
Bio-power	112
Geothermal power	13.5
Concentrating solar thermal	4.8
Total RE generation capacity	2017

The increasing share of renewables in the power grid will bring both positive and negative consequences. The positive aspects include relief in line congestion, reliable power in remote locations, energy security, reduction in pollution and global warming. However, the issues arising from RE power in grid is much more challenging and thus needs more considerations. Renewables can be embedded into all types of electric networks, from small to large capacity grids. But,

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due to the relatively small capacity and the remoteness from HV transmission lines, these generators are usually grid connected at the distribution level, either at LV level or MV level.

The grid integration of RE power depends on a number of factors. These include: the share of RE power, size and location of network in which it is connected, energy conversion technology, the effect on system inertia, droop, power quality, system protection etc. [3], [4]. Addition of renewables alter the power flows in distribution networks and changes the traditional one-way power flow from the high to the low voltage levels of the power system.

Frequency and voltage are two important parameters that ensures stable operation of the power grid. More the number of generators participating in frequency and voltage regulation, more smoothened frequency and voltage excursions result after system events. Currently, majority of RE systems do not participate in system frequency and voltage regulation functions. This is mainly due to the facts that RE in general are highly intermittent and fluctuating and these units do not increase or decrease their MW/MVAR outputs when frequency/voltage deviates from the respective nominal values. Since frequency and voltage firmness is essential for maintaining system stability, this inadequacy of RE will pose a limit to the level of penetration of these technologies into the grid.

The standard practice generally followed with renewable resources is to disconnect them during contingencies and reconnect when normalcy is restored. The active power (MW) and reactive power (MVAR) support required by the system during that period is usually provided by conventional units. This is acceptable as long as RE share is low. However, with the increasing share of RE, they must also contribute to frequency and voltage regulations exactly like traditional units. Besides, the practice of disconnecting RE during system contingencies is no longer permitted as this will aggravate the situation because of loss of more power.

The paper is organized as follows: overview of RE technologies and their grid connection is discussed in Section 2, issues with grid integration of RE is covered in Section 3, possible solutions to address RE integration challenges are outlined in Section 4 and conclusions are presented in Section 5.

2.0 Overview of renewable energy technologies and their grid connection

Though a large number of renewable technologies are currently available for bulk generation of power, only two RE systems are considered in this work: a. wind turbines (WT) and b. solar photovoltaic (PV).

A. WIND TURBINES

A wind turbine generator (WTG) converts kinetic energy of wind into electric power. WTGs are generally classified as vertical-axis wind turbines (VAWT) and horizontal-axis wind turbines (HAWT). In VAWTs, turbine blades circle around a vertical axis and in HAWTs, blades rotate around a horizontal axis. Modern large capacity WTGs use horizontal-axis design. The maximum power (Pm) extracted from the wind by a WTG is given as [5]

$$\Delta V = \frac{PR + XQ}{V} \quad \text{... (1)}$$

where, ρ: air density, A: rotor sweep area, U_w: wind speed, C_p: power coefficient, λ: tip speed ratio, β: pitch angle.

It can be seen from (1) that in order to increase the output of a wind turbine, (a) it requires a higher wind speed, and (b) a longer blade length. As the WTG's power output is proportional to the cubic power of the wind speed, a small variation in wind speed can result in a large change in its output. WTGs can be of fixed speed (FS) type or variable speed (VS) type. VS-WTGs are more efficient than FS-WTGs. FS-WTGs use cage induction generators, which are directly grid connected. For wider speed control range, WTs are coupled with Doubly-Fed Induction Generator (DFIG), shown in Fig.1a, or multi-pole Permanent Magnet Synchronous Generator (PMSG), shown in Fig.1b. Power output of a WTG as a function of wind speed is shown in Fig.1c.

i. DFIG based WTGs

DFIG is a wound rotor induction generator with the three-phase stator winding is directly connected to the three-phase grid and the three-phase rotor winding is fed from the grid through sliprings, linking the rotor and grid through a bi-directional ac-dc-ac converter. Since the DFIG rotor voltage is less than the stator voltage, the transformer connecting the machine to the system has two secondary windings; one for the stator and the other for the rotor.

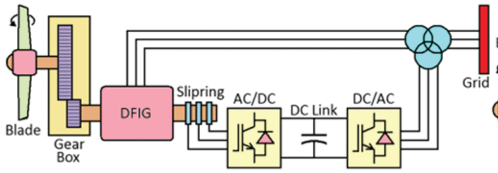

Fig.1a: DFIG based wind turbine

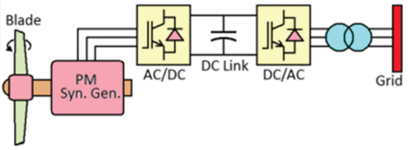

Fig.1b: PMSG based wind turbine

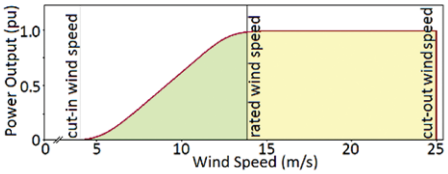

Fig.1c: Wind speed vs. WT power output

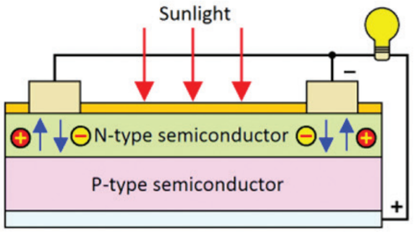

Fig.2a: Block diagram of a PV cell

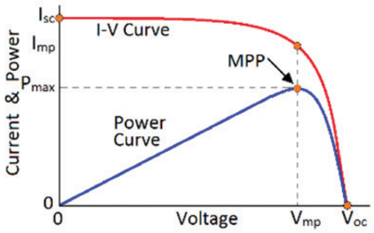

Fig.2b: I-V and power curves

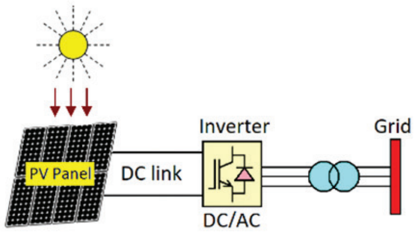

Fig.2c: PV based power generation

ii. PMSG based WTGs

A PMSG wind turbine uses full scale power electronics converters in their stator circuit for grid connection. Permanent magnets are used in the rotor for providing excitation. Because of the full-scale converters, speed control range of these WTGs is much wider than partial scale converter based DFIG-WTGs. By using large multi-pole rotor, these wind turbines can be direct coupled with the electric generators without a step-up gear.

B. Solar photovoltaic (PV)

A photovoltaic cell is a semiconductor device that converts visible light into electricity. PV cells are made up of one or many p-n junctions. When light falls on the PV cell, it produces a voltage as a function of the light intensity. The cell is the basic building block of a PV power system with an output voltage of around 0.5 V at a current level of 8 A to 9 A. To obtain higher power output, many such cells are connected in series and parallel to form a module. A photovoltaic array is the complete power-generating unit, consisting of many number of PV modules. The working of a solar PV cell is shown in Fig.2a, its current-voltage (I-V) and power-voltage characteristics are shown in Fig.2b and the PV based power generation system is shown in Fig.2c. Solar panels are usually operated along the MPPT (maximum power point tracking) curve for capturing optimum energy from the sun light.

3.0. Issues with grid integration of renewables

An electric power system is a network of electrical components comprising generators, transformers, feeders, protection devices and loads; used to generate, transmit, protect and use electric power. Traditionally, power system networks are designed in such a way that both active power (P) and reactive power (Q) flows from the higher to the lower voltage levels, that is, from the transmission network to the distribution system; and from there it is distributed to the customers. This is the conventional radial system, represented by a single voltage source on each distribution feeder. Due to the absence of generators connected, distribution systems are called passive circuits. However, with the introduction of renewable based generators, the situation will reverse. There will be many voltage sources in a single feeder. With significant level of RE based generators connected at distribution level, the power flows in the circuit may become reversed and the distribution network is no longer a passive circuit supplying loads. Depending up on the generation capacity, grid integration of renewable systems can be done at the transmission level (large capacity) or at the distribution level (small capacity). At present, majority of the RE systems are connected at LV distribution level. This is represented in Fig. 3.

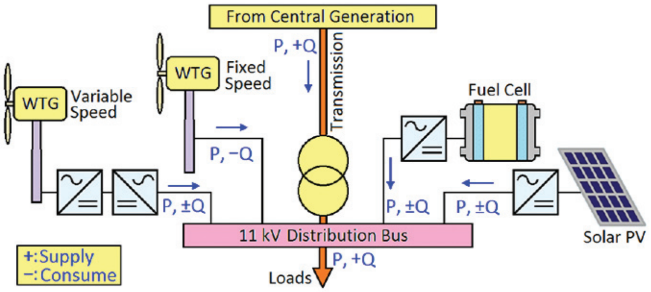

Fig.3: Grid connected distributed resources

The technical issues that need to be addressed while integrating RE resources on the distribution system are:

1. Point of common coupling (PCC) and voltage level
2. Voltage variations and power quality
3. Voltage ride-through capability
4. Reactive power compensation capability
5. Frequency regulation capability
6. Protection issues

A. Point of Common Coupling (PCC) and voltage level

The PCC is a point in the grid where multiple generators and loads are connected. The importance of PCC is that it is the point on the network at which the generator will cause most disturbances.

According to IEEE Std. 519, PCC should be a point which is accessible to both utility and customer for direct measurement [6]. The variations in RE results in voltage variations at the PCC. A basic requirement for connecting a generator to the power grid is that during faults, it should not adversely affect the quality of power supplied to the customers. The strength of a grid is measured at the PCC by the short circuit faults that it can absorb without disturbing the rest of the system.

The strength of the grid characterized by its short circuit ratio (SCR) is defined as [7]

$$SCR = \frac{S_{sc}}{P_g} \quad \text{... (2)}$$

where, S_{sc} = short circuit capacity (MVA) at the bus where generator is located, P_g = rating of generator (MW).

The short circuit capacity (S_{sc}) is the maximum power that can flow in a network in case of a short circuit. It represents the node strength to transfer power in a stable condition. It is represented as

$$S_{sc} = I_f V_s = \frac{V_s}{Z_s} V_s = \frac{{V_s}^2}{Z_s} \quad \text{... (3)}$$

where, I_f = fault current, V_s = grid voltage, and Z_s = grid impedance.

Substituting (3) in (2),

$$SCR = \frac{{V_s}^2}{Z_s P_g} \quad \text{... (4)}$$

A network may be considered strong with respect to the RE integration, if SCR is above 10 and weak if SCR is below 10. It is obvious from (4) that a network will be strong if the operating voltage is higher and the effective impedance is smaller. From a stability point of view, a new generator connected to a strong point in the grid (i.e. bus with a high fault level) will have less trouble exporting power, than the connection of the generator to a weak point (low fault level) in the network. In case of a weaker grid, the flow of active and reactive power into and out of the network causes significant changes in the system voltage. A weak system will also be affected considerably due to the disturbances caused by the addition of new elements such as loads or generators. If SCR value of a bus is less than 5, it is usually not recommended to connect RE to that system [8]. A high short-circuit power capability at the connection buses, about 20 times more than the wind or solar PV capacity will be needed to ensure reliable system operation. This will restrict the possible integration of the RE to the distribution system. If the RE based generator is far away from the network bus, long feeders will be required to connect them, and this will reduce the fault level due to increased line impedance. The impact of a renewable energy generator on the network is therefore very dependent on the fault level at the point of connection as well as on the size of the proposed generator. Accordingly, the point of common coupling for connecting a distributed generation must be carefully chosen. It is obvious from (4) that for grid integration of large amount of wind or PV, the PCC voltage level has to be as high as possible to limit voltage variations. The suitable voltage level at which a renewable based generator is to be connected with the power grid dependents on its capacity as well.

Table 2 gives the maximum capacity of renewable based distributed generators that can be connected at different low voltage networks [9]. Connecting at a higher voltage is usually more expensive because of the increased costs of transformers and switchgear and most likely because of the longer line required to make connection with the existing network. Connecting at too low a voltage may not be allowed if the generator influences the local network considerably.

TABLE 2: LIMIT OF RENEWABLE GENERATION ON DISTRIBUTION GRID

Network voltage	Max. Limit of Ren. generation
400V feeder	50kVA
400V busbars	200-250kVA
11kV feeder	2-3 MVA
11kV busbars	8 MVA
63kV to 90kV feeders	10-40 MVA

B. NETWORK VOLTAGE VARIATIONS

In conventional distribution system, the bus voltage is so set that during load variations, voltage along the feeder will be usually maintained within an acceptable range around the nominal value. The presence of generating units at distribution bus will change the voltage in all the feeders connected to that bus. In passive feeders, voltage may exceed both upper and lower limits, and in the distributed resource (DR) feeder, voltage will go beyond the upper limit. The amounts of voltage variations depend on the load and local generation. The rise in distribution system voltage (ΔV) caused by a generator supplying active power (P) and reactive power (Q) is given by [10]

$$\Delta V = \frac{PR + XQ}{V} \quad \text{... (5)}$$

where, R = line resistance, X = line inductive reactance, and V = nominal voltage of the circuit.

The rise in feeder voltage is a function of X/R ratio of the line. For HV transmission lines, X/R ratio is higher (i.e. $X>>R$) due to the geometry and low resistance of the conductors. Distribution feeders are characterized by low value X/R (i.e. R is comparable with X). As an example, for a 400kV line, X/R=16, and for an 11kV line, X/R=1.5 [11]. The voltage profile of a distribution system with and without the presence of DG is shown in Fig.4.

Another issue that affects the operation of distribution system is the unbalanced voltage. At distribution level, both loads and renewable generators can be either three-phase or single-phase. Interconnection of single phase source, such as small PV source, will increase the system unbalance. Similarly, the inherently unbalanced distribution systems can pose problems for the three-phase RE connected to it, as the resulting unbalanced currents in the generators can cause overheating and frequent shutdowns.

C. POWER QUALITY (PQ)

The quality of electric power may be described as a set of values of parameters, such as continuity of service, variation

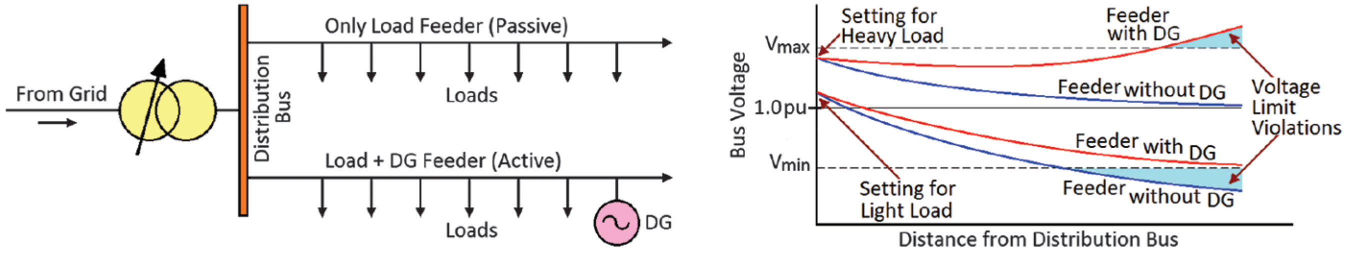

Fig.4. Voltage profiles along the distribution feeder

in voltage amplitude and frequency, transient voltages and currents, and harmonic content. The power quality problem is defined as any deviation in magnitude, frequency, or waveform shape of the voltage and current that results in failure or malfunctioning of customer equipment [12]. The increased share of WTGs and PV systems in the power grid results in many power quality issues. In case of PV systems, PQ problems arise due to variations in solar radiation, cloud shadow, power electronic modules such as inverter and filters due to their non-linear mode of operation. In case of wind turbines, PQ problems arise due to variations in wind speed, tower shadow, yaw error due to the misalignment between wind direction and turbine facing direction and power electronics devices. Accordingly, the power quality related phenomena can be divided into two main groups: (a) those caused by the fluctuating nature of energy resource and (b) the power electronic interface with the power system.

PQ issues due to fluctuating resources are:

- Over voltages during feed-in
- Long and short time voltage fluctuations
- Unbalance
- Frequency deviations

PQ issues due to the power electronics interface

- Harmonic injection
- Resonance phenomena
- Inrush currents
- Decreased damping of the grid due to nonlinearities

The voltage variations related issues include over-voltage, under-voltage, sags, swells, spikes, surges, flicker, unbalance and voltage interruptions.

Voltage sag is a reduction in the voltage magnitude (10-90%) followed by a voltage recovery after a short period of time. These are caused by short-circuit faults in the system or by starting of large motors. Over voltages of very short duration and high magnitude, is called voltage spikes (duration: µs).

Flicker is a periodic or a periodic fluctuation in system voltage that can lead to noticeable changes in light output. Slow fluctuating flickers, in the 0.5–30 Hz range, are noticeable by humans. In case of PV systems; flicker is resulted due to the power variations caused by passing clouds. In case of WTGs, flicker is caused by fluctuations in the output power due to wind speed variations, wind shear, and the tower shadow effects. Variable-speed WTGs have shown better performance related to flicker emission in comparison with fixed-speed WTGs.

Harmonics are sinusoidal voltages and currents with frequencies that are integral multiples of the fundamental frequency. Harmonics are associated with the distortion of fundamental sine wave and are produced by non-linearity of electrical equipment. Harmonics results in increased currents, power losses and overheating in devices leading to premature ageing of devices. Service life reduction of equipment has been reported as 32.5% for single-phase machines, 18% for three-phase machines and 5% for transformers. Harmonics may also lead to flickering in displays and lighting, spurious tripping of circuit breakers, malfunctioning of sensitive equipment etc.

PQ problems can be mitigated by two ways, either from the customer side or from the utility side. The first approach, known as load conditioning, ensures that the connected equipment is less sensitive to power supply disturbances, allowing the operation even under significant voltage distortions. The second solution is by installing line conditioning systems that suppress or offset the PQ related disturbances. Energy storage systems (fly wheels, super-capacitors etc.), and other devices such as constant voltage transformers, harmonic filters, noise filters, surge suppressors, isolation transformers etc. are used for the mitigation of specific PQ problems. Recently, many FACTS (flexible AC transmission system) devices such as DVR (dynamic voltage restorer), STATCOM (static compensator), DSTATCOM (distribution-STATCOM), SSSC (static series synchronous compensator), SVC (static var compensator), TCSC (thyristor controlled series compensator), and UPFC (unified power flow controller) etc. are also being used for PQ mitigation.

D. Voltage Ride-Through (VRT) capability

DFIG based wind turbines are the main technology used in wind generation systems. These WTGs are very sensitive to the voltage variations in the connected grid. During abnormal voltage conditions, continuous operation of DFIGs may lead to destructive over currents in the rotor winding or large over-voltages in the dc-link capacitor. Identical situations also arise with converters used in PV systems.

In the initial periods of renewable grid integration, for the safety reasons; during abnormal voltage periods, converter based generators used to be disconnected from the faulty system. However, with the increasing renewable penetration, such practices are not more permitted and therefore, wind and PV generators should remain in service during grid events. To enable wind and PV systems stay connected during abnormal voltage conditions, they need a voltage ride through capability [13], [14]. VRT capability helps to produce reactive power in an effort to stabilize the grid. Without VRT capability, DRs must trip for voltage deviations more than ± 10%.

Faults in the power grid result in voltage depression over a large area, both during the fault and during post-fault dynamic behaviour. In conventional system with synchronous generators, field forcing will help to keep the unit in synchronism. As this feature is not available in distributed generators, terminal voltage will dip severely during faults. If one-unit trips due to under-voltage, that will trigger cascade tripping of other units, which in turn may lead to a bulk grid event that stresses the grid further. To avoid this, DRs should not get isolated from the network during low system voltage levels. Such requirements are called low voltage ride through (LVRT) capability.

During the post-fault period, high voltages may occur over a wide area due to dynamic backswing. These voltage variations at the transmission level tend to propagate to the distribution systems to which DRs are connected. Over-voltage may also arise due to load shedding or unbalanced faults. The magnitude and duration of high voltage will depend on the fault scenario. To support the system during the short periods of such over-voltages, the DRs should not get isolated. This requirement is called high voltage ride through (HVRT) capability.

In many countries, LVRT capabilities are now mandatory for grid integration of DRs. Fig.5a shows LVRT and HVRT requirements as per IEEE Std. 1547, and LVRT requirement specified by few renewable rich countries, including India. As per IEEE Std. 1547, grid connected wind and PV plants are expected to remain online and ride-through zero-voltage faults, i.e. 100% drop in voltage, for up to 150 ms. The no-trip zone is set by voltage recovery for up to 2s. The HVRT requirement is 140% for 150ms and 120% for 2s. In India, wind plants connected to buses at 66kV and above, ride-through is 85% drop in voltage for up to 300ms and voltage recovery is for up to 3s [15]. These generators are required to maximize reactive power till the time voltage starts recovering or for 300ms, which ever time is lower.

There are two methods to enhance LVRT capability of induction generators based wind turbines during faults: (a) by reducing input to wind turbine and (b) by increasing output of WTG. Turbine mechanical input can be reduced by blade pitch control. The generator output can be increased by using switched capacitors, SVC, STATCOM, unified power quality conditioner (UPQC), DVR, and series braking resistor etc. In case of DFIG based WTGs, LVRT capability can also be improved by using active crowbar and series antiparallel thyristors.

E. Reactive power compensation capability

Unbalance in reactive power (VAR) is one of the major causes of voltage instability in an electric network, leading to voltage drops in the buses and lines. Induction generators used in wind turbines of Type-A (fixed speed) and Type-B (limited variable speed) needs reactive power support. At no load, these WTGs consume reactive power about 35-40% of the rated active power, and at full load, VAR requirement increases to around 60%. Capacitor banks are normally used for compensating the VAR requirements. That means, these types of WTGs do not participate in system voltage control.

For variable speed WTGs and solar PV systems using self-commutated power electronic devices, the VAR can be controlled to minimize losses and to increase voltage stability. These systems can have unit power factor and can also be used for voltage regulation. For large capacity systems, a central reactive power compensation device, such as SVC or STATCOM may be used for improving the reactive power regulation capability. As an example, German utility requires reactive current injection according to the droop line shown in Fig.5b, with a minimum of 2% positive sequence reactive current for every per cent of voltage drop below 100%. This implies that for faults with voltage drops of 50%

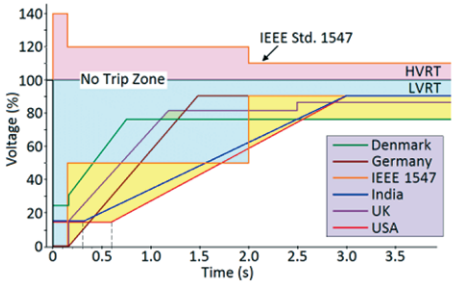

Fig.5a. Voltage ride through requirements

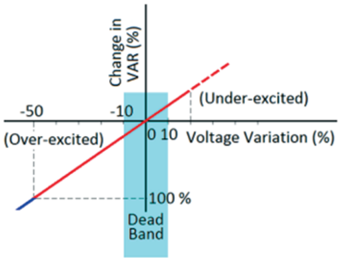

Fig.5b. VAR capability of WTGs

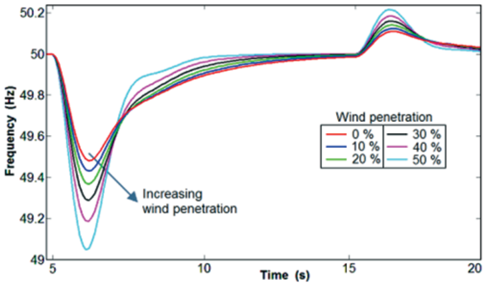

Fig.5c. Freq. profile in absence of droop and inertia

or lower, the reactive component of current goes to 100% or higher, up to 1.1-1.2pu, depending on the current rating of the converters [8].

F. FREQUENCY REGULATION CAPABILITY

Conventional synchronous generators possess two key qualities which are very essential in controlling the grid frequency. These are: (a) system inertia and (b) speed droop. Inertia is the property of a body to oppose any change in its motion. Inertia of the power system is proportional to the amount of rotating masses in the system [7]. It determines the rate of change of frequency (ROCOF) following a load event. The larger the system inertia, the less is the ROCOF following a power imbalance. The initial turbine governor action immediately following a load event, known as primary control, establishes the active power balance between generation and demand by using a proportional control action, known as droop, arrests the frequency deviations due to the change in load. The droop parameter in the governor control loop allows multiple units to share common loads.

For optimizing the energy conversion efficiency, most of the wind farms use variable speed WTG technologies. In order to prevent the reproduction of wind speed variation as frequency variation in the grid, variable speed WTGs use ac-dc-ac power electronic converters for the grid connection. The intermediate dc bus in the converter creates an electrical decoupling between the machine and the grid. Because of this ac-dc-ac decoupling, the wind turbines, though they are very heavy, appear lighter to the system. Thus, the increasing presence of WEC systems in the power system will reduce the effects of conventional synchronous generators that supply the major portion of the active power needed in the grid. The entire system will then behave as a lighter system. A lighter system will experience larger changes in the frequency even for small mismatches in the supply and demand.

The increasing penetration of wind and solar energy in the power grid increases the equivalent droop parameter of the system. The increase in droop value translates into a weaker system, less responsive to load changes and consequently, more frequency excursions result after every system event. Since the droop parameter is incorporated in the primary speed control loop of a prime-mover governor, increase in the droop value will reduce the overall frequency control capability of the generating unit. Fig.5c represents the system frequency profile after a small increase in load, in absence of inertia and droop [16].

Another requirement for a generating unit to take part in frequency regulation is the availability of sufficient reserve generation margin to meet the sudden increase in load demand or tripping of some generators. Traditionally, variable speed WTGs and solar PV systems always operate at the maximum power point tracking (MPPT) curve so as to capture optimum energy from the resource. This leaves no power reserve for frequency regulation needs. Thus, these generators provide very little or no support to the system frequency regulation.

G. PROTECTION ISSUES

The major protection issues related to the grid connection of distributed resources are: (a) change of short circuit levels, (b) reverse power flow, (c) lack of sustained fault current, (d) blinding of protection and (e) islanding.

I. Change in short circuit levels

Direct grid connected synchronous machine based DRs increase the network fault levels. Induction generators provide only limited fault currents, not in a sustainable manner. As seen earlier, a high fault level indicates a strong grid, in which the likely effects of connecting a new DG on the PCC voltage will not be very severe. However, the increase in network fault level due to the addition of DG represents another issue in terms of system protection. Short circuit current level in a network is the main parameter used in deciding the rating of CTs, CBs etc., and the coordination between overcurrent relays. Short circuit level is characterized by the equivalent system impedance at the fault point. With the connection of generators, the equivalent network impedance can decrease, resulting in an increase in the fault level. The fault current under this situation may exceed the breaking capacity of existing CBs. High fault currents can also lead to CT saturation. Further, the changed fault levels can disrupt the coordination between overcurrent relays leading to unsatisfactory operation of protection systems. The fault level contribution of a DR can be reduced by introducing impedance between the generator and the network, with a transformer or a reactor. However, this will increase losses and lead to wider voltage variations at the generator.

Distribution networks are normally radial systems and are usually protected using time graded overcurrent protection schemes. Most distribution system protections detect an abnormal situation by discriminating a fault current from the normal load current.

For demonstration, consider the distribution system shown in Fig.6. When the DG is not present, the currents seen by the feeder breaker CB-1 and the Recloser RC are approximately equal to the fault current I_F (i.e. IS$\approx I_{RC} \approx I_F$). However, when the DG is connected, $I_{RC}=I_S+I_{DG}$, and $I_{RC}>I_S$. This is a condition normally does not occur in passive radial

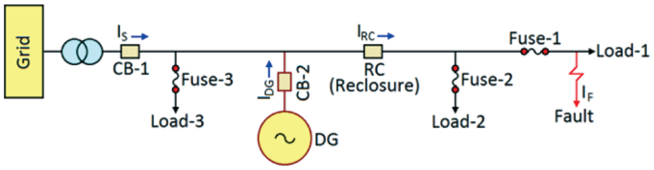

Fig.6: Change of fault currents due to DG interconnection

networks. This does not cause a problem if the recloser interrupting capacity is sufficient to handle the increased fault current. However, it is likely that coordination between the recloser and any downstream fuses (for example between RC and Fuse-1) is lost. Because both the recloser and fuses operate faster at higher fault currents, the required margins between the recloser fast curve and the fuse minimum melt curve can reduce to a level that the coordination is lost.

ii. Lack of sustained fault current

In order for the protection relays to reliably detect and discriminate fault currents from the normal load currents, the faults must cause a significant and sustained increase in the currents measured by the relays. If the fault current contribution from a DG is limited, it becomes difficult for the overcurrent based protection relays to effectively detect faults. Renewable energy based generation often employs induction generators, small synchronous generators or power electronic converters. Induction generators cannot supply sustained fault currents to three-phase faults and make only a limited fault current contribution to asymmetrical faults. Small synchronous generators are usually not able to supply sustained fault currents that are significantly greater than the rated current. Power semiconductor devices cannot withstand significant overcurrent for sustained periods and therefore power electronic converters are designed to internally limit the output current. The lack of sustained fault current compromises the ability of relays to detect faults.

iii. Blinding of protection

In presence of distributed generation, the grid contribution to the total fault current will reduce. Due to this reduction, it is possible that a short-circuit stays undetected because the grid contribution to the short circuit current never reaches the pickup current of the feeder relay. Working of overcurrent relays, directional relays and reclosers depends on the detection of abnormal currents. Hence, protections based on these devices can suffer malfunctioning because of the reduced grid contribution.

iv. Islanding

Islanding is the condition where a part of the network is disconnected from the main grid and operates as an independent system supplied with one or more generators. Islanding results in abnormal variations of frequency and voltage in the isolated network. Opening of an auto recloser during a fault may lead to the formation of two independent systems that operate at two different frequencies. Reclosing of the auto recloser while the two systems are out of phase could bring disastrous results. Further, islanding operation may create an ungrounded system depending on the transformer connection. An unidentified island would be dangerous for the maintenance staff. Islanding is considered as an unsafe situation and thus, immediate disconnection of the DGs from the main grid is recommended in the event of formation of an island.

4.0 Possible solutions to address renewable integration challenges

Several possible solutions are being proposed in the literature for addressing the challenges associated with the variability and uncertainty of RE power generation. The main consideration in selecting a particular method is the cost-effectiveness of the technology and the characteristics of the network. Grid infrastructure, operational practices, generation type, and regulatory aspects all impact the types of solutions that are most economic and viable. Generally, systems need additional flexibility to be able to accommodate the additional variability of renewables. Flexibility can be achieved through better forecasting, operational practices, energy storage, demand-side flexibility, flexible generators, and other mechanisms 0.

i. Forecasting of wind and solar resources: Forecasting of solar and wind can help reduce the uncertainties associated with these generations. It can help grid operators more efficiently commit or de-commit units to accommodate changes in wind and PV generation, besides helping to reduce the amount of operating reserves. There are different forecast methods such as short-term and long-term forecasts. The short-term forecast, usually in hours, is relatively less complex as compared to long-term forecast. Forecast errors typically range from 3 to 6% of rated capacity one hour ahead and 6 to 8% a day ahead.

ii. Operational practices: Fast dispatch and larger balancing authority areas: Fast dispatch helps manage the variability of RE power as it reduces the need for regulating resources, improves efficiency, and provides access to a broader set of resources to balance the system. With faster dispatch, load and generation levels can be more closely matched, reducing the need for more expensive regulating reserves.

iii. Reserves management: Modified reserve management practices can be used to help address the variability of wind and solar power. This include (a) putting limits on wind and PV power ramps to reduce the need for reserves and (b) by enabling variable renewables to provide reserves or other ancillary services such as regulation, inertia etc.

iv. Interconnecting more distributed resources: The impacts of intermittence of RE power can be minimised by interconnecting large number of small distributed resources spread over a larger geographical area instead of large unit concentrating in one area. Fluctuations in the total output will be minimum as the local variations affect only small units, not the total output power.

v. Energy storage: With increased levels of renewable penetration, energy storage is a standard solution to minimise generation curtailment. An alternative to expensive storage systems is large overbuilding (200-300%) and curtailment.

vi. Wind-PV hybrid systems: Since wind and solar PV outputs are complementary types, hybrid arrangement of these two resources will improve the overall power fluctuations to some extent.

vii. Demand response: Flexibility at demand-side is a good option to reduce the impacts of fast ramps.

Demand response can be used to supply reserves and ancillary services as well as peak reduction. The use of demand response to balance the system during infrequent events in which there is substantial under- or oversupply of renewable generation can lead to cost savings compared to continually maintaining additional reserves.

3.0 Conclusion

Increased environmental awareness and energy security concerns have pushed renewable energy systems towards the top of the power generation programme. Among various renewable energy resources, wind and solar PV systems show exponential growth rate during the past many years and are capable for grid integration. Due to the low energy density of wind and sunlight as compared to fossil fuels, power generation from these resources usually takes place in a distributed manner. Integration of RE based distributed generation into the power system can be done at either the transmission level or the distribution level, depending on the scale of generation. However, due to the proximity to distribution system in remote areas where majority of the RE based generators are installed, they are normally connected to the grid at the distribution level. Due to the variable and intermittent nature of the renewable resource, the generation technology used in these units is different from the conventional units. The frequency of the power generated by these units will not be normally at the standard system frequency and hence, a large group of DG technologies use power electronics converters for grid connectivity. The decoupling of machine dynamics from the system dynamics by the power electronics devices introduces several technical issues. This paper reviewed some of the technical challenges that need to be addressed for the effective grid integration of renewable energy based distributed generators. The major concerns in interconnection of renewable energy generation at the distribution level are related to voltage control, power quality and protection.

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