Revision Week 1-5

Introduction to DG

Distributed Generation

- Distributed Generation (DG) is the generation from a power station that is embedded in a Distribution Network. This means that any generation that is connected to the downstream of distribution substation can be categorized as DG.
- Nowadays, DGs are mostly renewable power generations
- Question: Which ones of the followings are Distributed Generation?
  - 1. Centralized power plant using coal
  - 2. 40- MW PV arrays with direct connection to a transmission line
  - 3. Off-shore windfarm
  - 4. Wind turbines connecting to 35 kV bus in a substation supplying a small town
  - 5. Roof-top PV system

  - Answer: 4 and 5

Other Terms for Distributed Generation

The concept of "Distributed Generation" has been developed for a few decades. In the history of electrical power engineering, it has been referred to as some other "names". Some of them are still being used:

- Embedded Generation (traditionally often refers to those small-scale diesel synchronous generator)
- Decentralized Generation
- Dispersed generation (to distinguish it from central generation)
- Distributed Generation (DG: more popular nowadays)

Driving towards DG - 1

- The environmental concerns is global –Diversification of energy sources: different types of energy sources can be the backup for each other so failure of one type does not extend to the complete outage in short term or energy depletion in long term.
- Technological Development
- New Government Policy

The use of DG can also bring about flexibilities, such as

- Availability of modular generating plant:
- Ease of finding sites for smaller generators:
- Short construction time and lower capital costs per plant:
- Generation closer to the load which may reduce resistive losses during power delivery, which means that both the utilities and the owner can benefit from DG in terms of operational cost.

Common Attributes of DG

- Not centrally planned:
- Usually operated by Independent Power Producers (IPPs) or consumers:
- Not centrally dispatched
- Connected to the distribution system (medium or low voltage system): e.g . in UK, DG is supposed to be connected to 35 kV level and below.
- Normally smaller than 50 MW

Hosting Capacity against Feeders overloading

Hosting Capacity Approach

The determination of HC may follow a generic approach as follows:

- Pick up a location for DG installment.
- Choose a phenomenon and one or more performance index that is likely to be deteriorate to examine (example: voltage, loading, etc.)
- Determine a suitable limit or limits of the index
- Calculate the performance index as a function of the amount of generation
- Obtain the corresponding HC value when the index has reached a pre-defined limit
- Repeat the previous process with other index and make decision accordingly.

Please read < Chapter 3.3, Math Bollen And Fainan Hassan - Integration of Distributed Generation in the Power System>

Overloading in Radial Distribution Network: the 1st Hosting Capacity

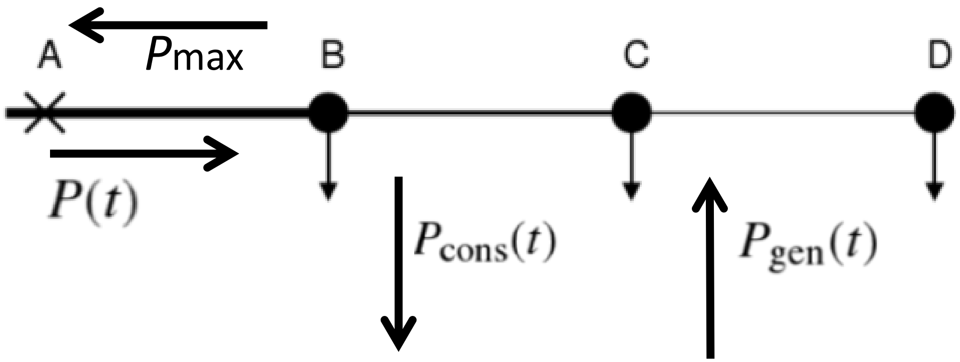


Image : by < Chapter 4.2.1, Math Bollen And Fainan Hassan - **Integration of Distributed Generation in the Power System**>

Considering a radial network on the left. Before DGs are installed, the power flows from A to D at P(t).
The total load fed from A is P_{cons}(t).
After installing DGs, the total generation power is P_{gen}(t).

Therefore, there is $P(t) = P_{cons}(t) - P_{gen}(t)$

Since $P(t)$ will not exceed $P_{cons}(t)$ as long as $P_{gen}(t)$ is smaller than $P_{cons}(t)$, the loading of the feeder will not be lighter in such scenario; and the only possibility of overload is when the generation exceed the load.

If the feeder capacity is considered to be designed for the maximum load level, the maximum reverse power P_{max} should follow: $P_{max} < P_{cons,max}$

- The maximum reverse power flow occurs when the maximum generation and minimum consumptions are reached and it can be described as

$$P_{max} = P_{gen,max} - P_{cons,min}$$

The corresponding HC is $P_{gen,max} = P_{cos,max} + P_{cos,min}$
, which is also referred to as the "First Hosting Capacity" (1st HC).

The 1st HC for B,C and D can be calculated in a similar way.

Overloading in Radial Distribution Network: the 2nd Hosting Capacity

- If the limit for the reverse power is set to be the thermal limit of the feeder $P_{max,limit}$, there is

$$P_{gen,max} - P_{cos,min} < P_{max,limit}$$

The corresponding HC becomes

$$P_{gen,max} = P_{max,limit} + P_{cos,min}$$

, which is called the "Second Hosting Capacity" (2nd HC).

- The difference between the 1st and 2nd HC is the set limit of the reverse power.
- Considering the designed maximum load is always lower than the feeder thermal limit, the 1st capacity is a rather conservative estimation of HC.
- The 2nd HC is the actually HC that may cause a network trip, since the nominal value of a feeder protection is more likely to be the actual thermal limit, which will degrade the system power distribution reliability.

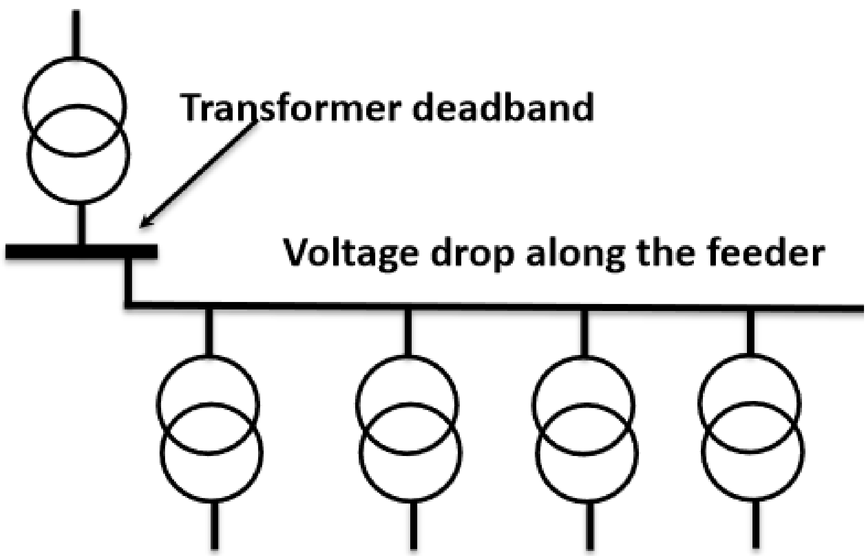
Increasing the Hosting Capacity - 1

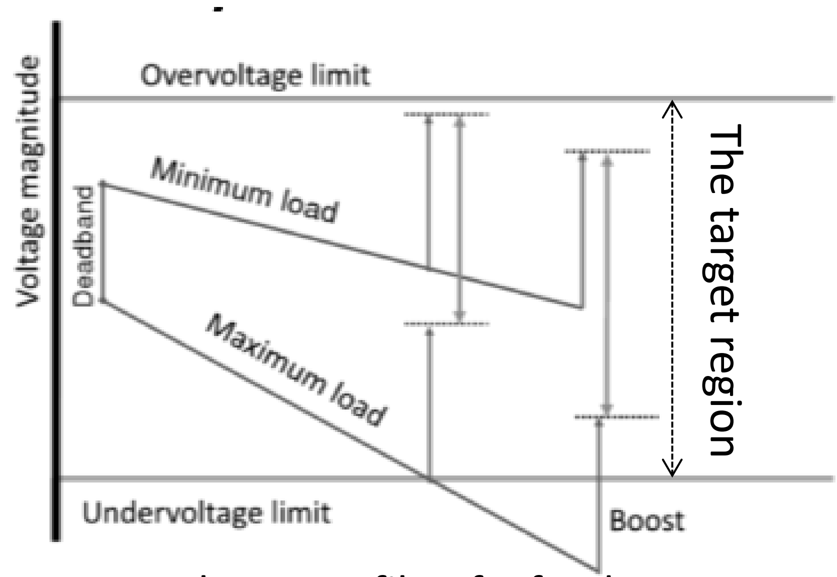
As is fore cited, the DG generation can significantly improve system efficiency, provided it does not exceed the local loads. Since the DG in most areas are still limited, the main issue for most of the distribution networks is how to increase the hosting capacities against feeder overloading?

- The first thought is always to increase the size of feeders.
- Building new connection to provide extra path for the DG can be another option.
- Use of Intertrip schemes
- Energy Management System (EMS) with advance protection system
- The latest attempt is to use DC technology in distribution network employing power electronics technology.
- Prioritizing Renewable Energy
- Dynamic loadability

Hosting Capacity against Voltage Variations

Voltage Control in Contentional Distribution Systems



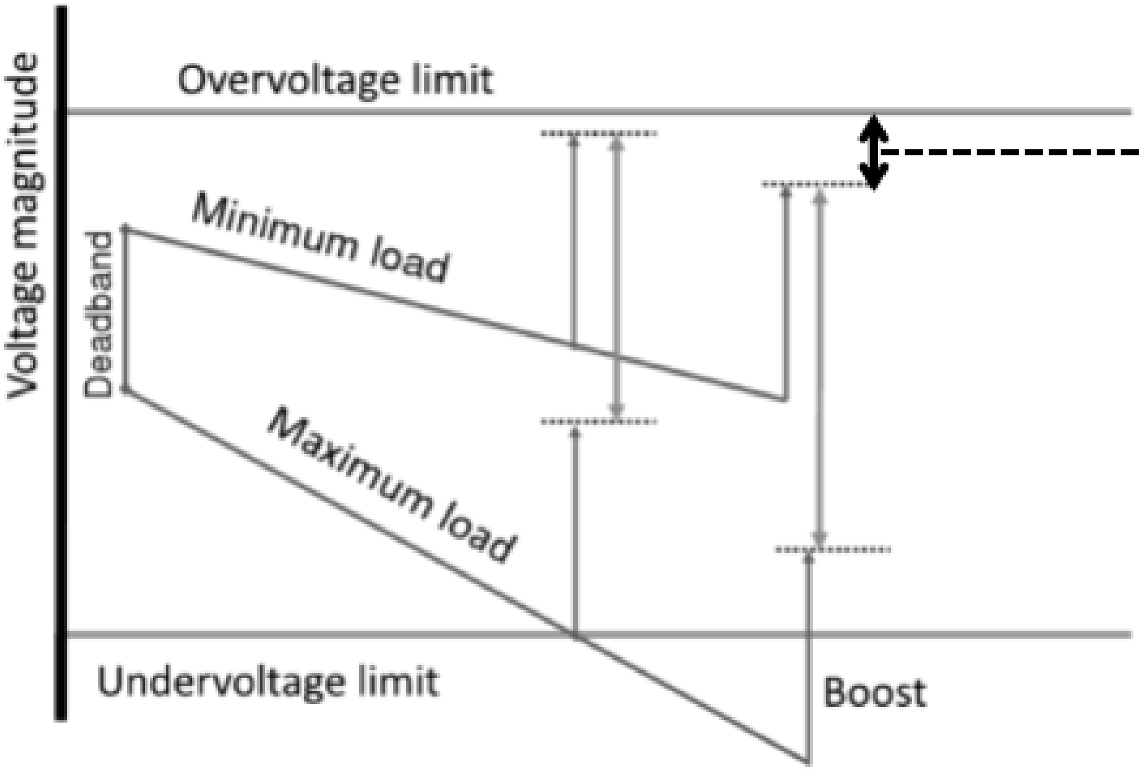


Voltage profile of a feeder

Image by Chapter 5, Bollen, Math H. J., <Integration of distributed generation in the power system>,2011

- The further away the grid point is from the upstream substation, the lower the voltage on the MV feeder will be.
- To compensate for this, MV/LV transformer with different turns ratio are used (off-load tap changer).
- The voltage in the distribution network can be boosted by up to 5%

Overvoltage Margin



Overvoltage margin:
The difference between the highest voltage magnitude, for a given customer and the overvoltage limit.

Image by Bollen, Math H. J., <Integration of distributed generation in the power system, Chapter 5>

- To install a DG, it must be ensured that the overvoltage is not reached at all time.
- Obviously, a sufficient overvoltage margin, which is defined above, is needed to allow new DG installment.

Host Capacity Against Overvoltage

- Hosting Capacity (HC): The maximum amount of generation that can be connected without unacceptable quality or reliability for other customers.
- In this case: the HC against the voltage variation should be amount of generation that gives a voltage rise equal to the overvoltage limit.
- By manipulating the voltage equation we have below, there is

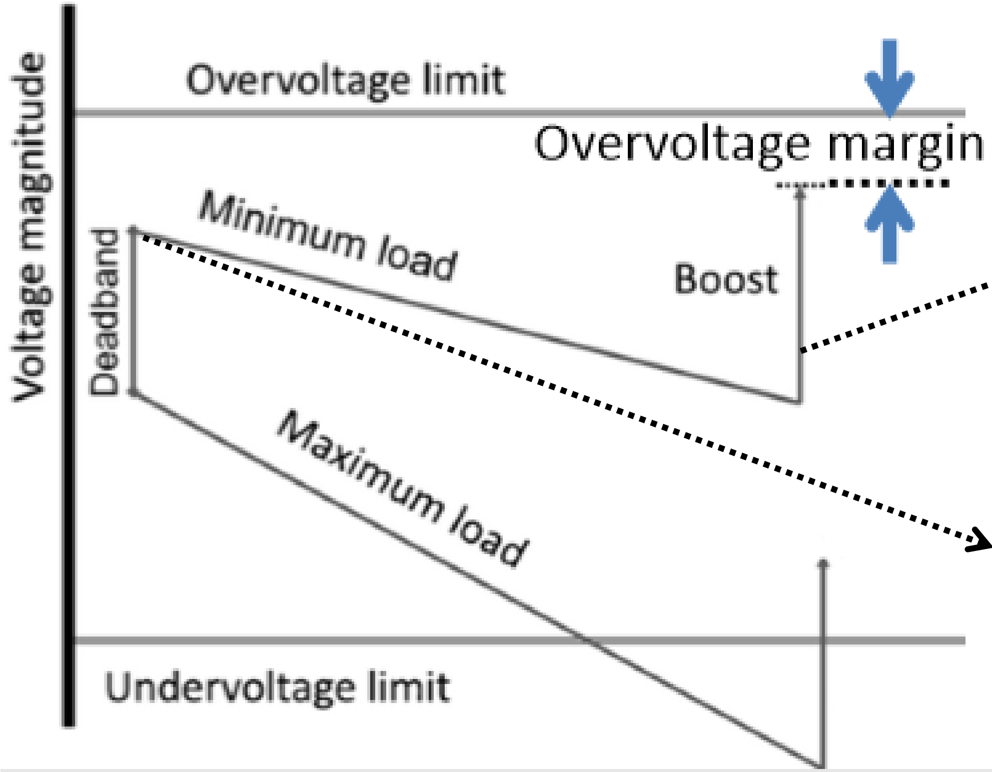
$$\frac{\Delta U}{U} = \frac{R \times P_{\mathrm{gen}}}{U^2} \quad \Rightarrow \quad P_{\mathrm{max}} = \frac{U^2}{R} \times \delta_{\mathrm{max}}$$

where δ_{max} is the voltage margin allowed in percentage.

From the above equation, it can be seen that the HC is proportional to the square of the voltage level U^2 and the voltage margin δ_{max} .

Estimating the Hosting Capacity against Overvoltage -Steps breakdown - 1

The step breakdown of how to calculate the HC against over voltage is shown as follows:



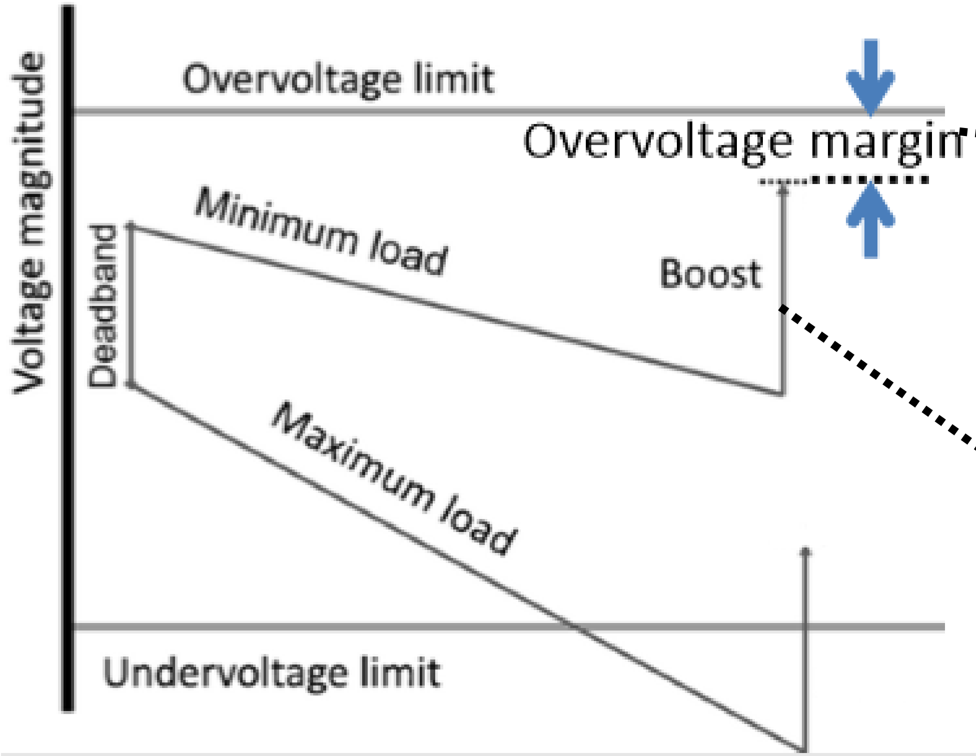
3. The voltage drop along the medium-voltage feeder during lowest load is estimated to find the highest voltage.

1. The upper limit of the deadband is used as the highest voltage at the main medium-voltage bus.

2. The voltage drop over the distribution transformer during low load is estimated.

Image by Bollen, Math H. J., <Integration of distributed generation in the power system, Chapter 5>

Estimating the Hosting Capacity against Overvoltage -Steps breakdown - 2



5. The overvoltage margin is the difference between this voltage and the overvoltage limit.

4. The boost due to the distribution transformers (up to 5%) is added to give the highest voltage on secondary side of the distribution transformers.

Image by Bollen, Math H. J., <Integration of distributed generation in the power system, Chapter 5>

6. The HC is proportional to the margin in terms of overvoltage.

Host Capacity Considering Voltage Limit and Overload

- The hosting capacity depends strongly on the feeder size and length.
  - For short feeders, large generation can be connected with a voltage rise of less than 1%. The thermal capacity will probably be the main concern.
  - For cables longer than several kilometers, the voltage rise is more likely to be the limiting factor, especially for long, small cross-sectional cables.

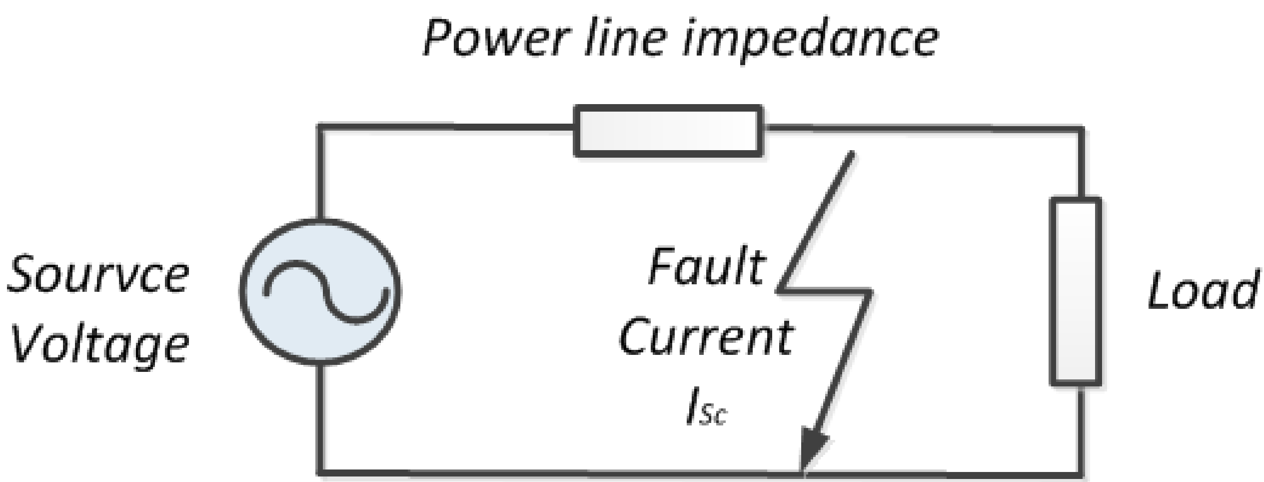
Increasing the Host Capacity (against overvoltage)

- New or stronger feeders:
- Allowing higher voltage
- Increasing the minimum load.
- Overvoltage Protection
- Overvoltage Curtailment
- Distributed Generation with voltage control

DG and Faults, Protections and Stability

Fault Analysis - Symmetrical (three-phase) fault

- Using Thevinin Equivalent, the 3-phase fault modeling can be simplified as illustrated below:
- The fault current is supposed to be produced by the source voltage. In a conventional power network, this voltage is produced the power grid, which is the aggregation of all the generators in connection.
- The impedance of network between the source and the fault determines the fault current and the rating of the Circuit Breaker (CB) that should be used.



Fault level

- At any given point of the network "the fault level" is the maximum current that would flow in the case of a short circuit (fault). It can be either measure
  - In real unit (MVA), or
  - In per unit
- Assuming that the voltage was equal to its nominal value prior to the fault:
- The fault level is defined as

$$FL = \sqrt{3} V_{nominal} I_f$$

,where I_f is fault current and $V_{nominal}$ is the nominal voltage of the fault location.
In a per unit system, there is

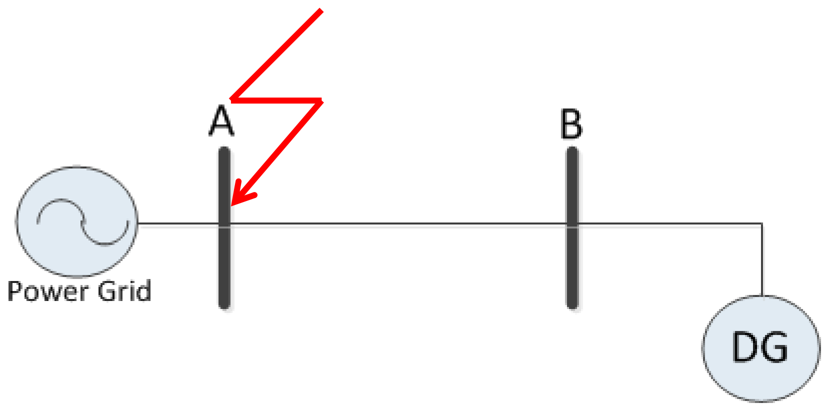
$$FL^{pu} = I^{pu} = \frac{1}{|Z^{pu}|} \qquad FL^{pu} = I^{pu}$$

,where *Z* is the fault impedance between the fault location and the source of the fault current.

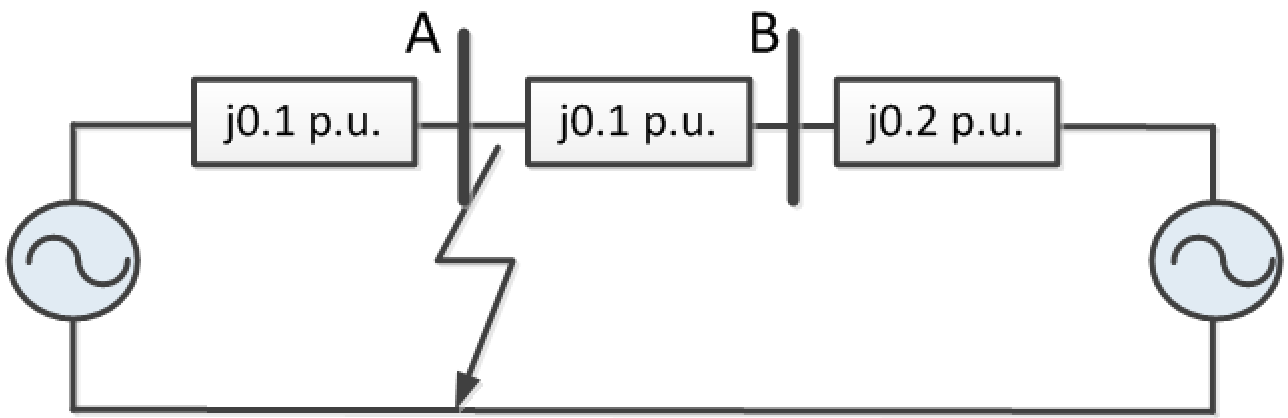
Example – Fault Calculation - 1

The diagram below shows an embedded synchronous generator connected to a large power system through a distribution network. The fault level at the near end of this network is 500 MVA at zero power factor (i.e. X/R = inf). The impedances of the grid side, between A and B, DG are is j0.1 p.u., j0.1 p.u. and j0.2 p.u., respectively.

If the network is operating at nominal voltage and the load current is negligible, what is magnitude of the current that would flow if faults were to occur at the end of the feeders?



Example – Fault Calculation -2



The equivalent circuit for fault calculation is shown above. The large power system has been replaced by its Thevinin equivalent with the impedance. Since the network operates at nominal voltage and the load current is assumed negligible, both voltage source has been set at 1.0 p.u.. The magnitude of the fault current at Bus A is given by

$$I_{f,A} = \frac{1}{X_A} = \frac{1}{0.075} = 13.3\text{p.u.}$$

where X_A is the parallel combination of the impedances of both sides, which are j0.1 p.u. and j0.3 p.u.

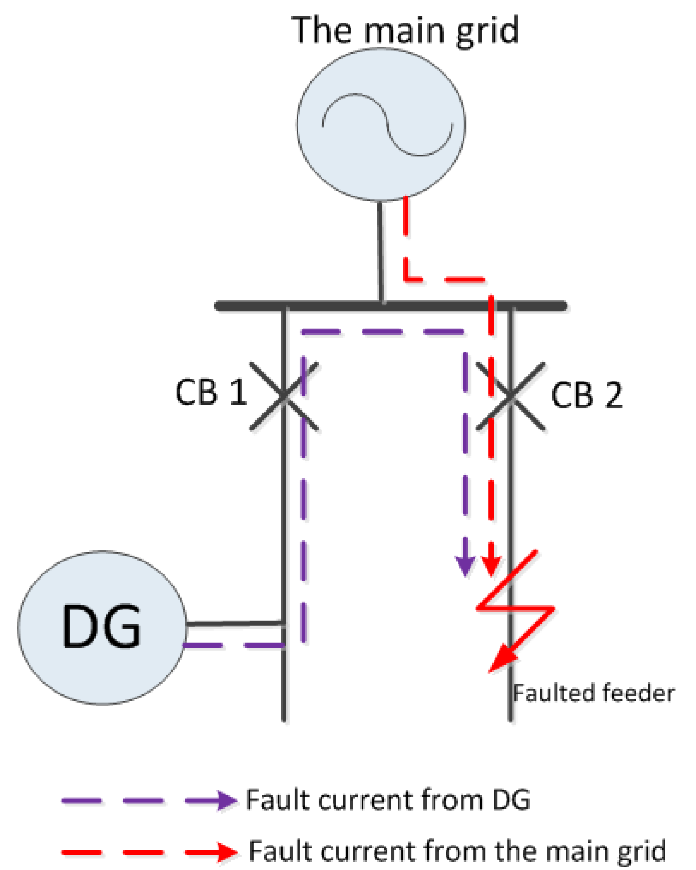
and $X_A = \left\| \frac{1}{\frac{1}{j0.1}+\frac{1}{j0.3}} \right\|$=0.075 p.u.

Example : Interference of DG upon Overcurrent Protection - 1

As shown in the right, the upstream network is from the main grid. Two feeder Circuit Breakers, CB 1 and CB 2 are located at one end of each feeder.

A new Synchronous Machine(SM) based DG is installed in an established distribution network.

Suppose the fault occurs at the feeder of CB 2, as shown.



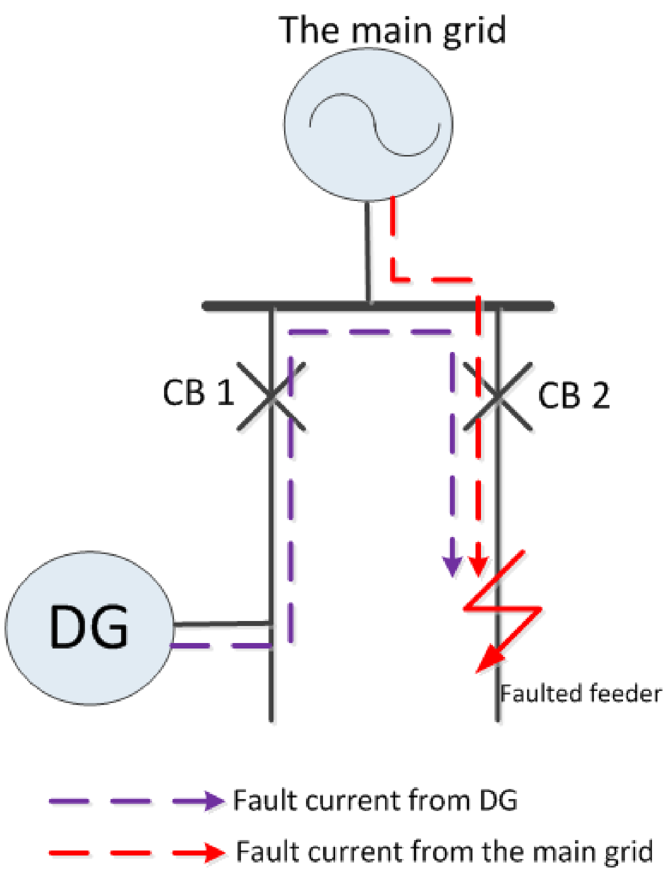
The interference with the protection selectivity:

- For a correct operation of the protection, CB 2 should open and CB 1 will not.
- The contribution of the synchronous machine to the fault may be mistaken as a downstream fault of CB 1
- Using conventional O/C protection, the result would be a mal-trip of breaker CB 1 and the downstream of CB 1 is mistakenly tripped from the upstream network. If there is other power sources, an unnecessary outage will happen at the downstream of CB 1.

Example: Interference of DG upon Overcurrent Protection - 2

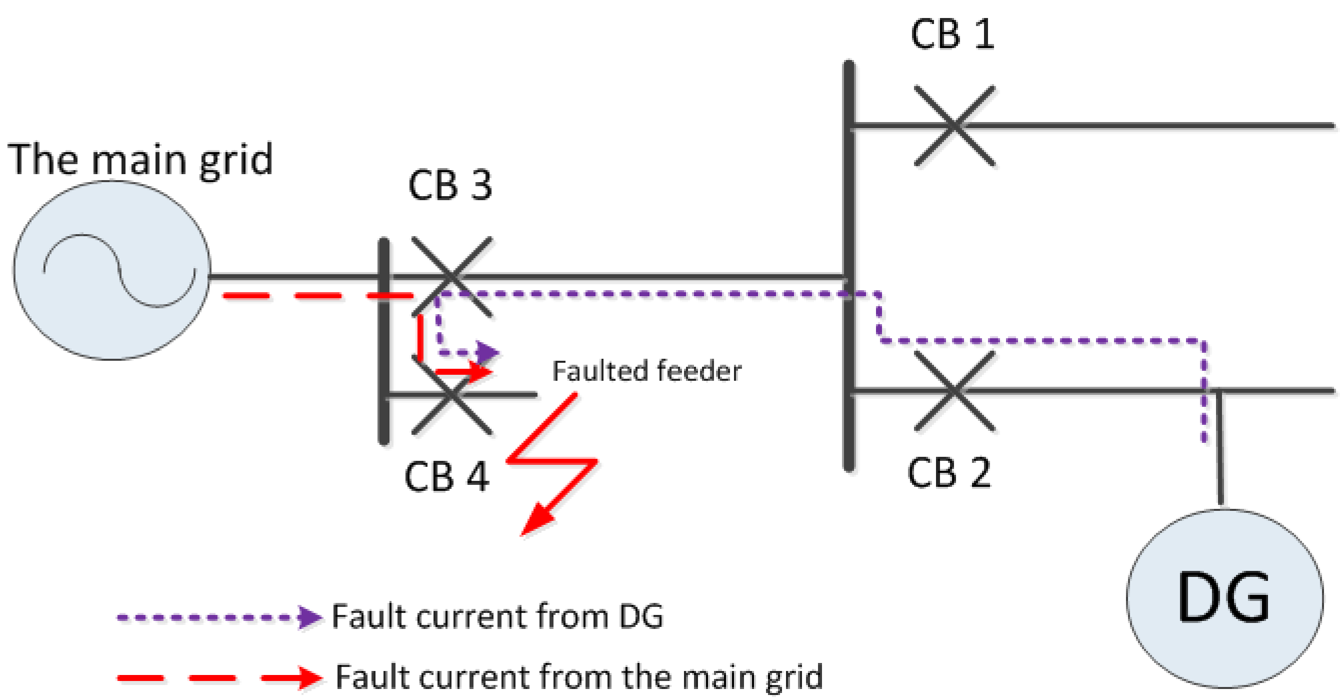
The interference with the ratings of the protective device:

- The total fault current through breaker CB 2 will be the sum of the fault currents provided by the main grid and the DG.
- The prospected current will be higher than without the DG.
- The prospected fault current may exceed the rating of the switchgear CB 2.
- To effectively protect the feeder, CB 2 has to be replaced with larger rating if the prospected fault current from the DG is significant.



Example: Interference of DG upon Overcurrent Protection - Upstream

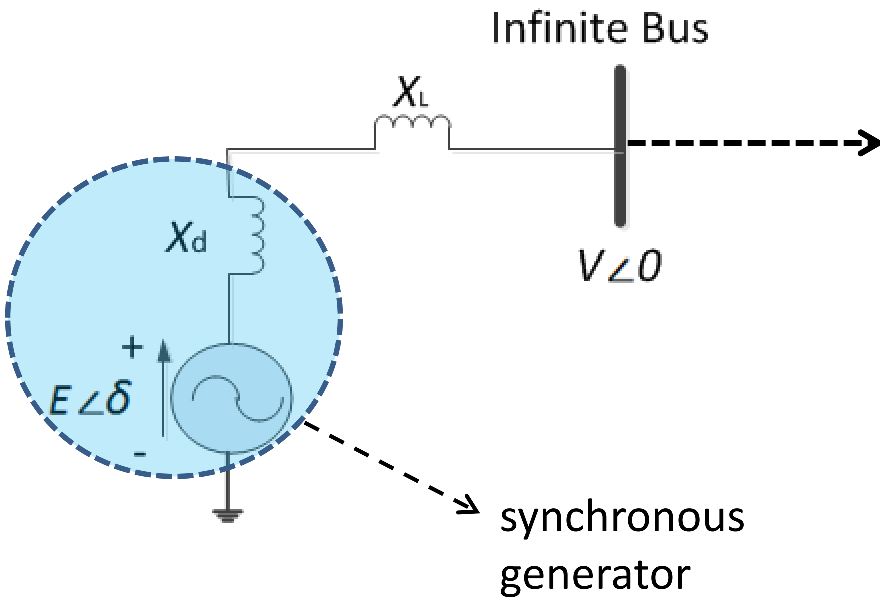
- The problem may also occur for faults at a higher voltage level.
- As is shown below, when a fault happens at the feeder of CB 4, DG will contribute fault current to the fault location as well as the grid.
- As a result, CB2 and CB3 may operate mistakenly causing outage for the entire down stream area.



Modeling Power Transfer between Two Buses

One of the concern about DG stability is that if a fault happens, will the DG still be able keep stability after the fault cleared, which is illustrated below.

- The simplified stability analysis can be considered with a single-infinite bus scenario as illustrated where is the power grid is modeled as an infinite bus in connection with an impedance X_L. The grid angle can be defined as 0 for simplicity.



Infinite Bus:
voltage unchanged no matter what the current is; usually used to model a connection point to a large power grid.

- A Synchronous Generator (SG) based DG is connected to an infinite bus through a transformer and a transmission line with a total reactance of X_L .

So the total reactance between the bus and the SG emf is

$$X = X_d + X_L$$

Modeling Power Transfer between Two Buses

- The voltage at the infinite bus (*V*) is constant and considered to be the voltage reference.
- the real (active) power transmitted to the infinite bus (*P*e) is:

$$P_e = \frac{EV}{X}\sin\delta = P_{e,\max}\sin\delta$$

where δ is the power angle.

Since once a system is established, the change of emf *E*, grid voltage and the total reactance is very limited, the power exchange between the generator and grid is therefore determined by δ, the angular difference between the emf and grid voltage ; hence the terminology of “power angle”.

Stability Analysis in a 2-bus System - 3

Considering the new impedance after the fault is

$$X_1 = X_S + \frac{1}{2} X_L$$

, which is less than what was in the pre-fault condition, therefore

$$P_{max}' = \frac{EV}{X_1} < P_{max}$$

As is shown above, the post-fault P-δ curve will be lower than the pre-fault curve as the reactance value on the denominator of the power expression has increased due to the disconnection of one power line.

As the DG capacity may grow large or the power lines grows longer, the post-fault P'_{max} can become less than the input mechanical power as

$$P_{max}' < P_m{}^0$$

, which means the strength of the connecting grid is very weak that the mechanical torque can never be balanced by the electrical. The generator will loose synchronism and the system will be unstable after a severe fault.

Please try Tut 3-9

DG and Power Quality

Major Concerns of Protection - DG

Before installing DG into distribution network, from the network protection point of view, the following aspects should be considered:

- Protection of the DG equipment from internal faults
- Protection of the faulted distribution network from fault current supplied by the DG
- Anti-islanding or loss-of-mains protection
- Impact of DG on existing distribution system protection

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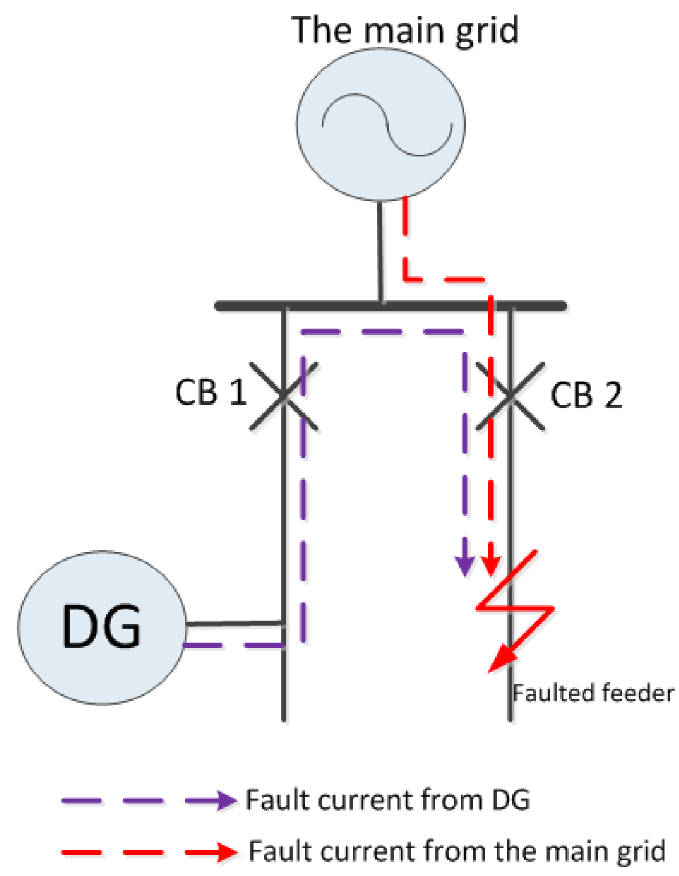

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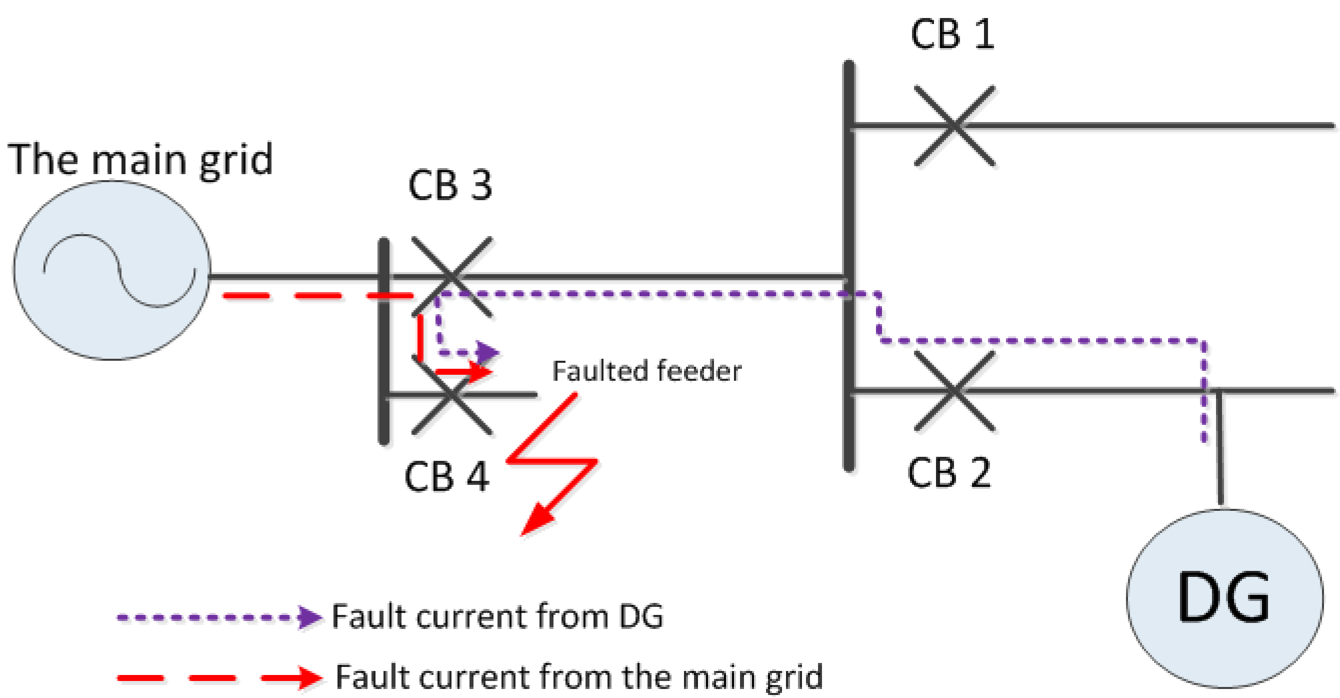

Power Quality – Voltage

- Voltage profile is mainly determined by the grid and by events in the grid.
- Significant end user activity can also affect the voltage profile
- The impact of voltage disturbance

  (watch what voltage disturbances may look like<video>)

  - The disturbances include voltage dips, overvoltages, harmonics, unbalance and voltage fluctuations, etc.
  - Voltage disturbances may apply extra voltage to the nominal to power equipment hence a reduction of equipment lifetime
  - The transient voltage and its consequent currents may reach the threshold of some protections causing erroneous protective operation
  - For the most severe case, a voltage disturbance and consequent current can damage to equipment straightway when the magnitude is excessive

Islanding

When a power network is energized without the connection to the main grid, an island is created. This is particularly possible when DGs are in place but unlikely happen to a passive distribution network.

- An island has to be either detected immediately or be well-planned before it occurs
- Islanding is also known as Loss-of-main
  - An unintentional islanding may lead to electrical hazards for maintenance personnel
  - The island frequency will quickly deviate from the main network causing phase shift; in case of a reconnection, it can cause excessive current spike.
  - The fault level within the island will be reduced and if a fault were to develop, the resulting current might be insufficient to operate the protective devices.
- An anti-islanding relay is essential to detect unplanned islanding and trip the source

Case Study - Series Resonance Risk Caused by Interaction between Shunt Capacitor Bank and Transformer - 2

The series resonance frequency is

$$f_{res} = f_0 \times \sqrt{\frac{S_{tr}}{X_{tr} Q}}$$

where
Q is the size of the capacitor bank (in Var);
f_0 is the fundamental frequency
X_{tr} the reactance of the distribution network transformer;
S_{tr} is the power rating of the network transformer.

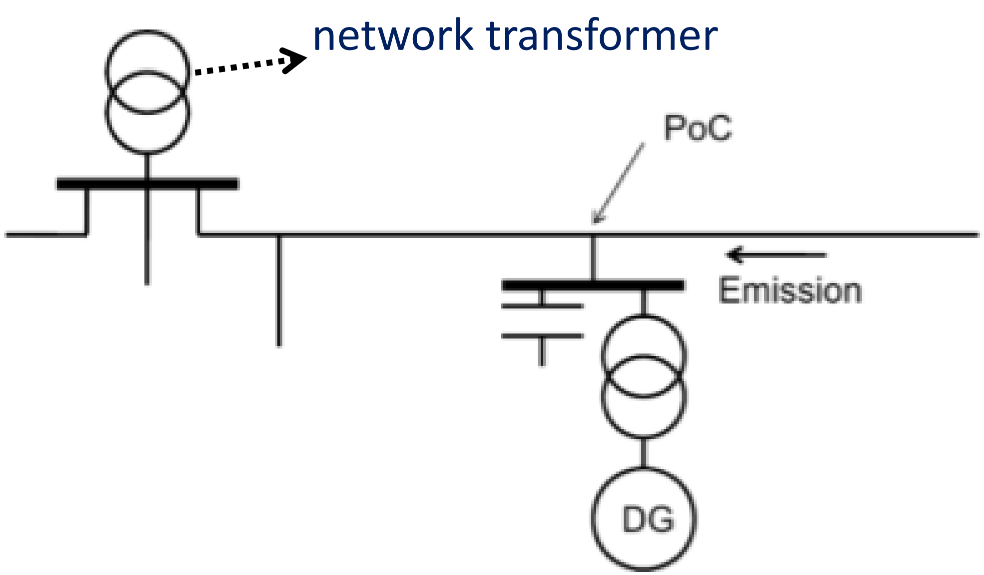

Image by Bollen, Math H. J., etl . <Integration of distributed generation in the power system Chapter 6.4>

Hosting Capacities for Induction Generators

Reactive power consumption for IG

In order to reduce the losses caused by reactive power, the components of the reactive power consumed by an IG has to be studied:

- The 1st component is proportional to the magnetizing current, which is almost fixed.
  - The magnetizing reactance is considered to be unchanged at steady state
  - This means it can be compensated with a fix reactive power compensation: e.g. a shunt capacitor bank.
- The second term is proportional to the active power, when the max power to generate is P_{max}, the corresponding leakage reactive power consumption will be:

$$Q_{max} = \alpha \times P_{max}$$

where is α a factor determined by induction impedances and slip corresponding to the maximum power.

Thus, the voltage rise of a feeder at maximum production is:

$$\Delta U_{gen,max} = RP_{max} - XQ_{max}$$

where X an R are the feeder impedance

Therefore

$$\Delta U_{gen,max} = R \times (1 - \alpha \frac{X}{R}) P_{max}$$

Host Capacity for Induction Generator - 1

- From the general constraint of voltage margin, the host capacity of DG with predefined relative voltage margin δ_{max} at unit power is

$$P_{max} = \frac{U^2}{R} \times \delta_{max} \qquad (\delta_{max} = \frac{\Delta U}{U})$$

- Considering the new voltage rise with reactive power is

$$\Delta U_{gen,max} = R \times (1 - \alpha \frac{X}{R}) P_{max}$$

- The Hosting Capacity for an induction generator against voltage variation (with reactive power consumption) is

$$P_{max} = \frac{1}{(1 - \alpha \frac{X}{R})} \frac{U^2}{R} \times \delta_{max}$$

Host Capacity for Induction Generator - 3

$$0.95 \geq 1 - \alpha \frac{X}{R} \geq 0.55$$

$$P_{max} = \frac{1}{(1 - \alpha \frac{X}{R})} \frac{U^2}{R} \times \delta_{max}$$

- From the above, it can inferred that he HC of an induction generator can be higher than the unit power factor condition as the reactive consumption can neutralize the voltage rise cause by active power injection. The HC can be increased with
  - larger X/R ratio (longer distribution line)
  - Larger α : larger leakage reactance values of induction machine and transformer
- For large α values, the hosting capacity may become twice the value for generators without any reactive power compensation.

Host Capacity for Induction Generator - 4

- For a small-scale IG connecting to an infinite bus via a distribution feeder, Considering

$$\Delta U_{gen,max} = R \times (1 - \alpha \frac{X}{R}) P_{max}$$

To make the voltage unchanged, there is

$$\Delta U_{gen,max} = 0$$

hence

$$1 - \alpha \frac{X}{R} = 0$$

Therefore, when the IG can match the feeder characteristics and let the following condition happens:

$$\boldsymbol{\alpha} = \boldsymbol{R} / \boldsymbol{X}$$

The steady state voltage variation of the IG terminal against the infinite bus is 0.

Sharing of HCs

The Sharing of Hosting Capacity - 1

- It is common that more than one DG is connected at a certain location.
- To make sure the performance index are met, DGs at the same location have to share the HC properly.
- The maximum production should not exceed the hosting capacity at that location
- The hosting capacity should be distributed roughly inversely proportional to the generator location:

$$\sum_i \lambda_{gen,i} P_i \leq P_{HC}$$

where PHC is the hosting capacity at the end of the feeder;
$\lambda_{gen,i}$ is the ratio of the distance from the start of the feeder to ith DG against the length of the entire feeder;
P_i is the HC for the *i*th DG.

Hosting Capacity Sharing - 2

- For *N* generators connecting to the same feeder bus:
  - Considering each DG is outputting full power at the same time for the most severe case
  - the allocation of each generator is:

$$P_i \leq \frac{1}{\lambda_i}\frac{P_{HC}}{N}$$

This equation means that the closer one DG is located to the main bus (λ=0) the larger HC it can be allocated.

Future Distribution Power System

Concepts of Future Distribution Power System

Although it is agreed that distributed generation must be integrated more effectively into the power system, which is one the drive towards smart grid, there remains considerable ambiguity as to what this means in practice. A few illustrative concepts are as follows:

- Active network management
  – which allows more distributed generation to be connected to distribution networks and operated effectively
- Virtual power plants
  – which provides a means of aggregating a large number of small generators and facilitating access to markets
- Microgrids
  – which allow the formation of small cells of microgeneration and controllable loads (and storages) as one distributed entity
- The use of power electronics technology
  – which upgrades the system performance with great flexibility and potential

Please read: Jenkins, N , etl. <Distributed generation> Chapter 7