# Energy Sector Capacity Building Activity
# Medium and Low Voltage Networks – Grid Impact Study
# Training No. 1
# December 4 – 6, 2016

Day - 1

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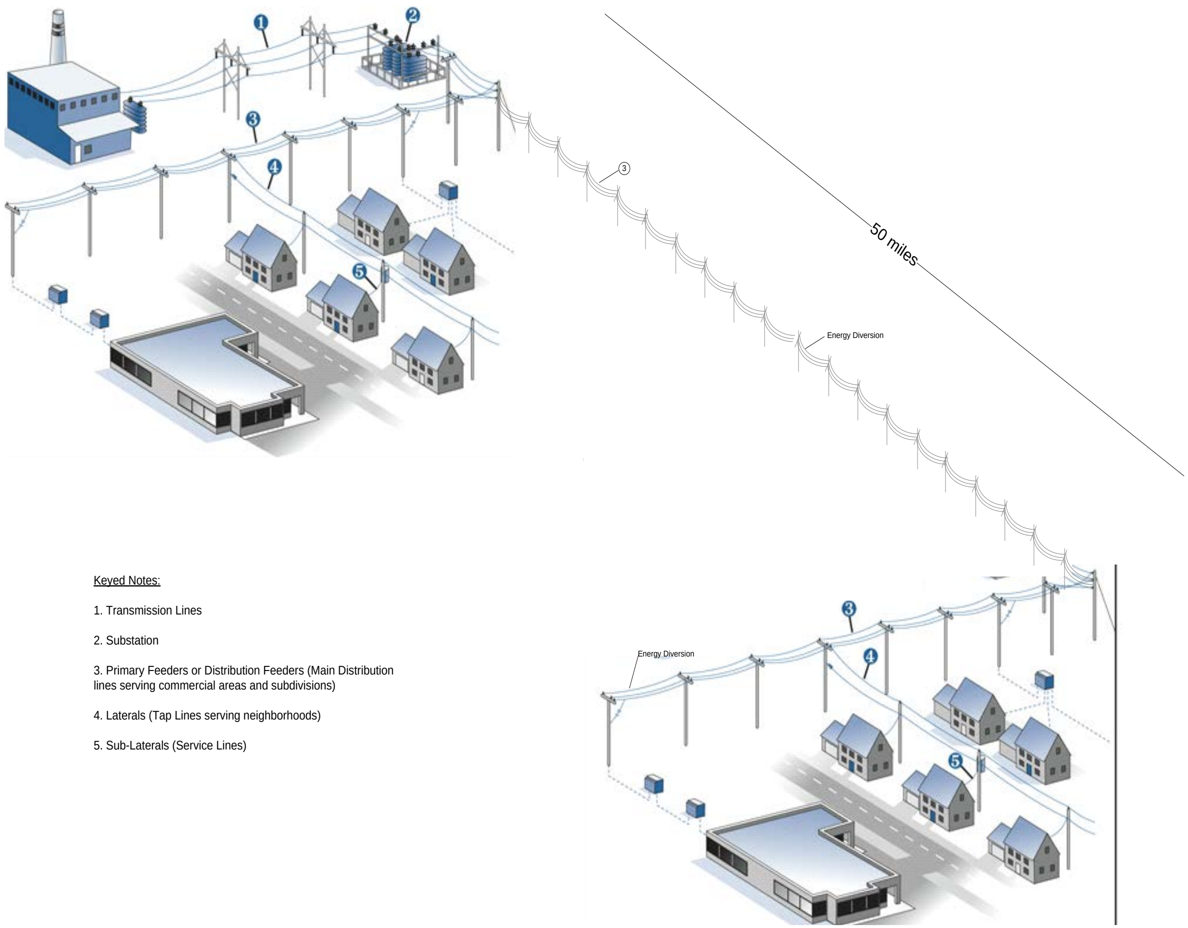
## Agenda for December 4, 2016

- Introduction to Grid Impact Studies
- PV Technology
- Wind Technology
- Review of Distribution Code for IRR
- Software Algorithms
- Performing and Reviewing Load Flow Studies

# Introduction to Grid Impact Studies

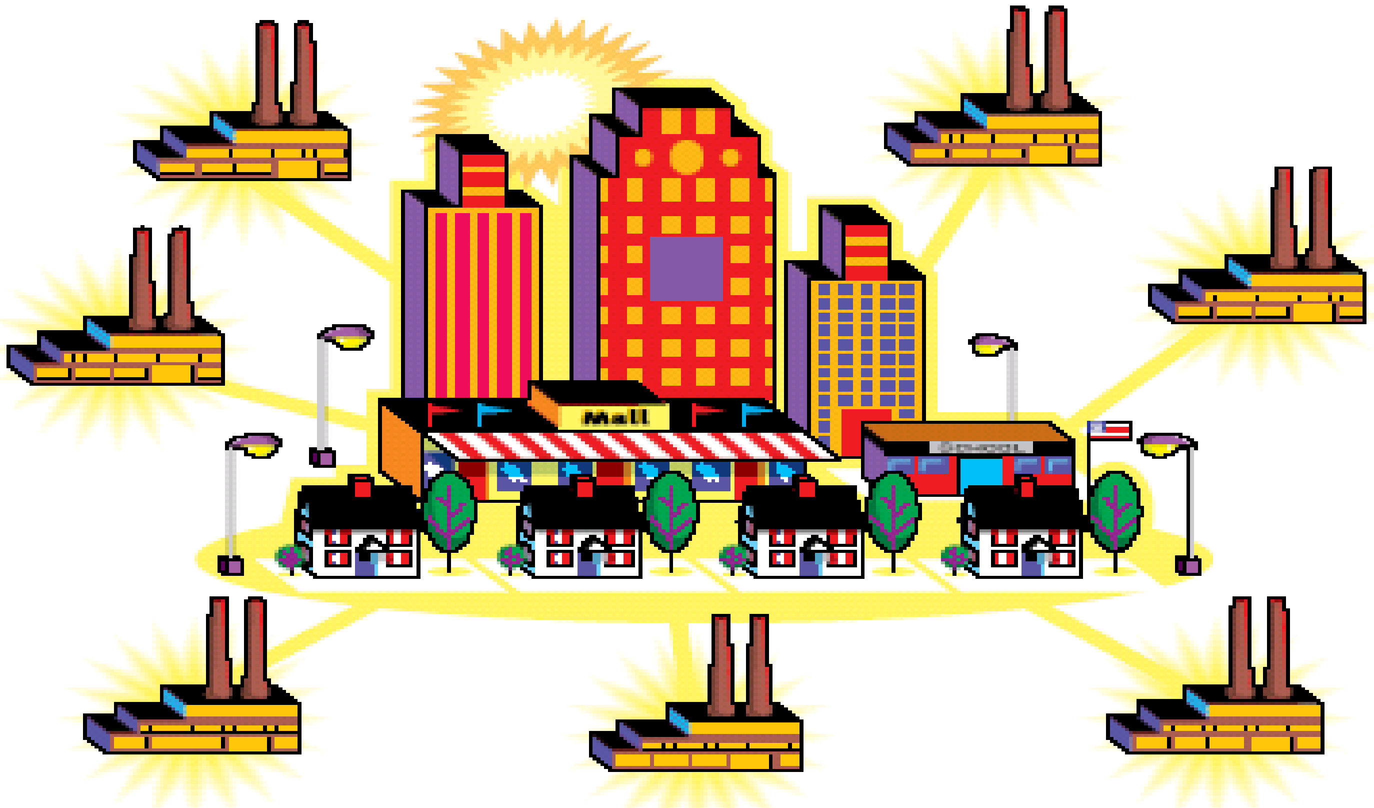
# Traditional Transmission & Distribution System




Keyed Notes:

1. Transmission Lines
2. Substation
3. Primary Feeders or Distribution Feeders (Main Distribution lines serving commercial areas and subdivisions)
4. Laterals (Tap Lines serving neighborhoods)
5. Sub-Laterals (Service Lines)

# What is a Grid?



## What is Grid Impact Study?

- Evaluation of the bulk power grid performance with addition or retiring of any facility that is part of the High Voltage Grid.
- Examples of Facilities: Generators, transmission Lines and large loads.

# What are the Grid Performances?

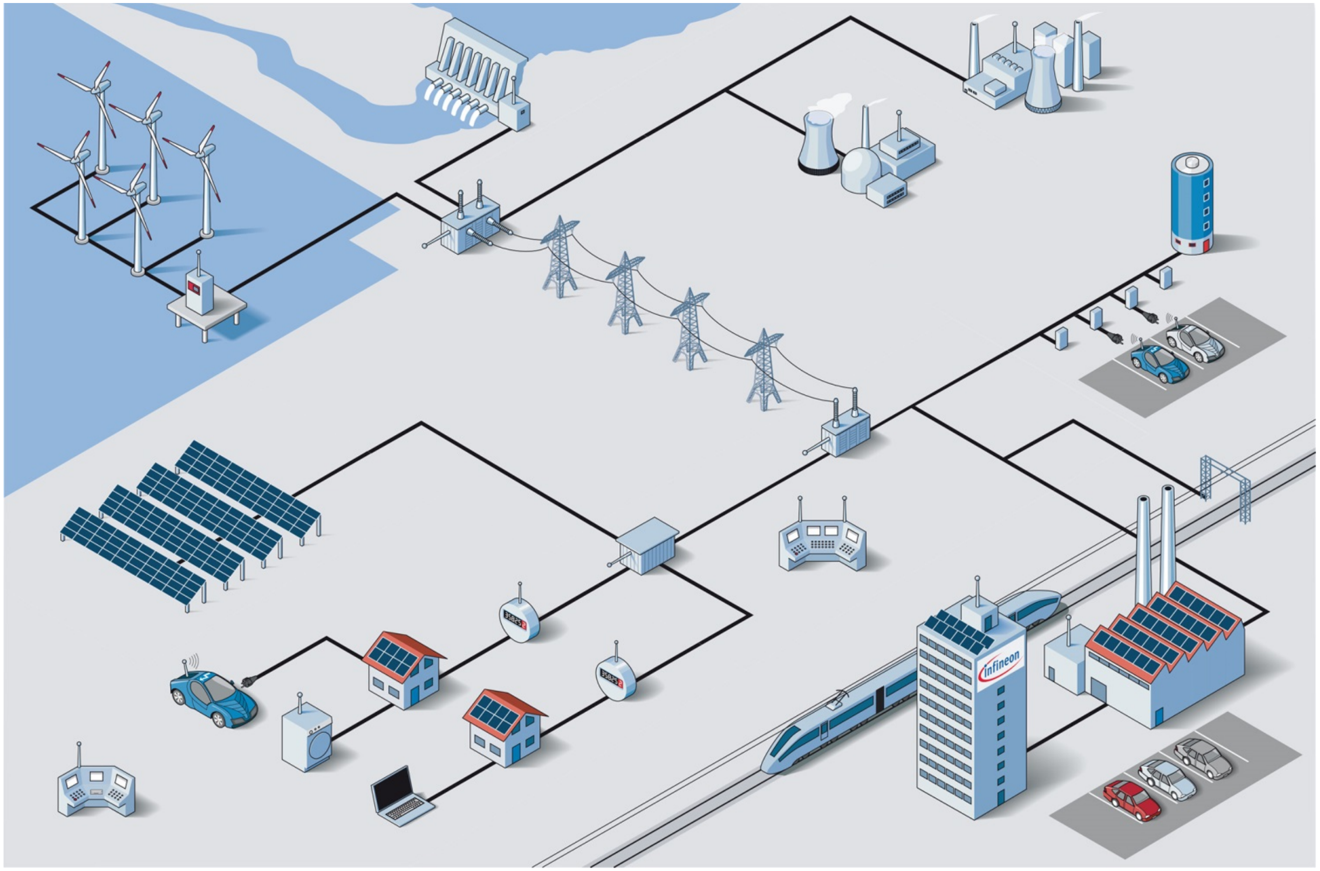
- System Reliability
  - To ensure power system is reliable under all operating conditions

- System Security
  - To ensure power system is secured and stable following a large disturbance

## Why do we need Grid Impact Studies for Distribution Systems?

- Grid Impact Studies are normally performed for high voltage bulk power systems, typically for systems above 100 kV
- Distribution systems have traditionally been designed to serve load
- The facilities that were connected at distribution level did not affect the bulk power grid reliability or impact the local customers, except under special circumstances such as arc furnaces
- Now the nature of distribution systems is changing

# Modern Power Grid



# What is New with Distribution Systems?

- Uni directional power flow no longer exists
- Distributed Generators have altered the functioning of existing devices such as regulators and capacitors
- Forecasting of net feeder load has become a challenge
- Generation intermittency causes power quality issues
- Feeder isolation needs to consider Distributed Generations

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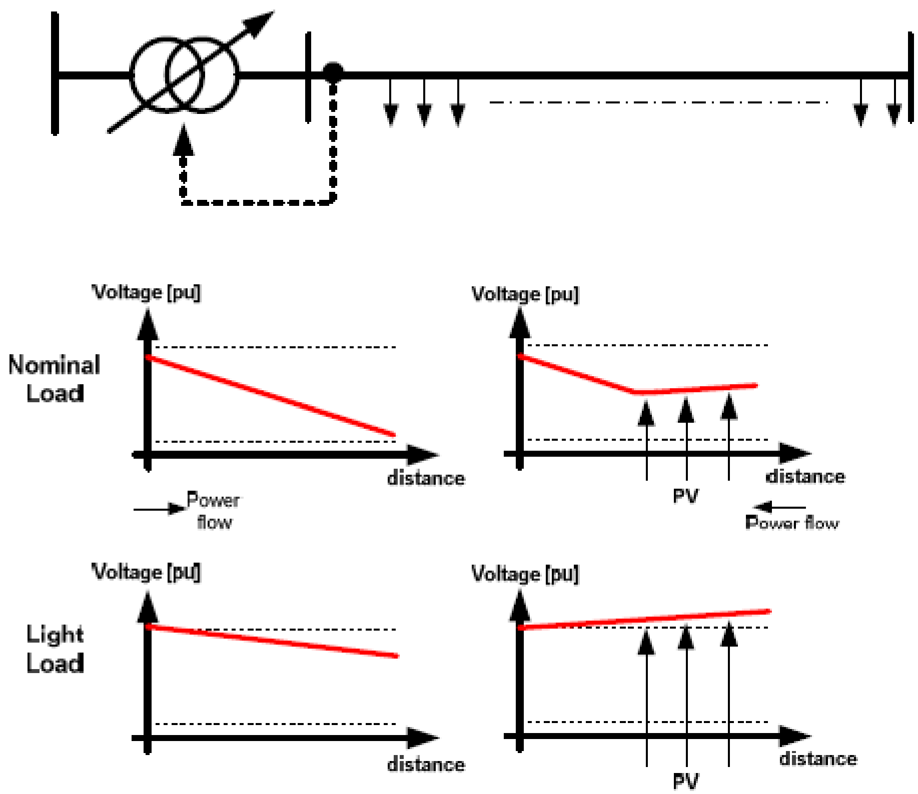
# Typical Voltage Profile



# Grid Impact Study Overview

- Studies are performed to evaluate the generators connected to MV and LV network whether they meet Distribution Code for Intermittent Renewable Resources (IRR)
- Evaluate reliability such as thermal and voltage performance
- Evaluate the ability to stay connected during grid disturbances

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## Who Conducts the Grid Impact Studies

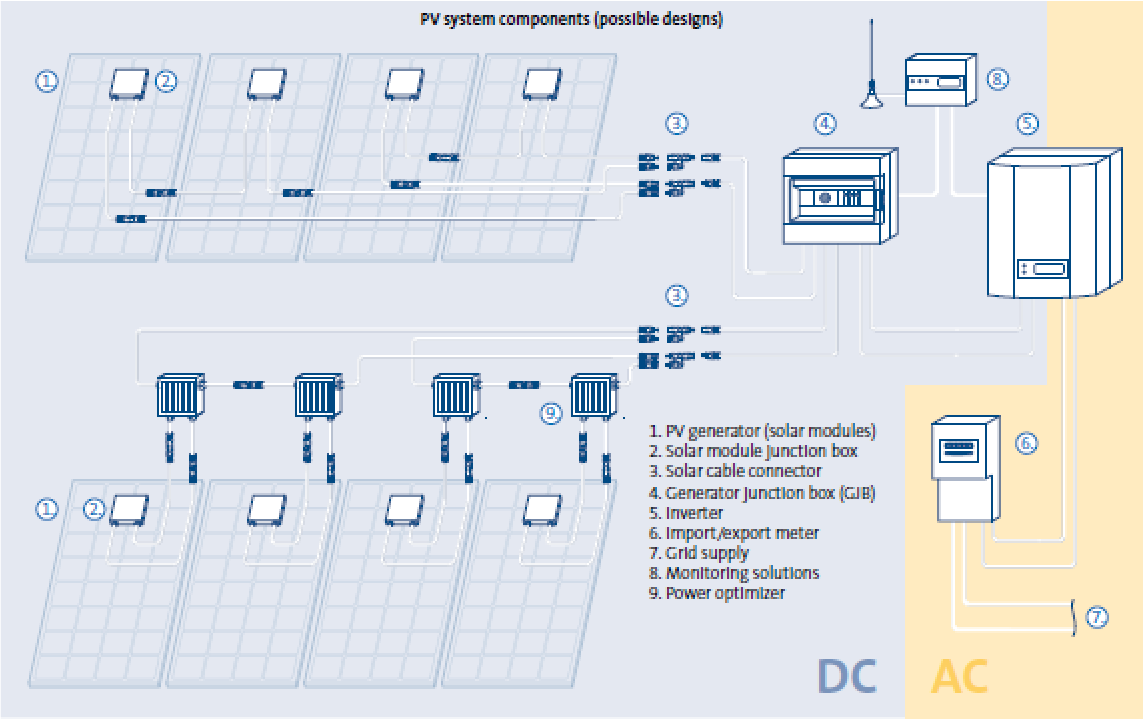
- Distribution Companies
- Third Party Consultants on behalf of Project Developers

## What Information Do we Need?

- Project size and Interconnection Location
- Project’s Electrical One line Diagram
- Manufacturer’s data sheets
- Collector system impedances
- For PV, estimated generation profile
- Feeder load profile
- PV inverter / Wind turbine dynamics models

# Photovoltaic (PV) Technology

# PV System Components



## Solar Panel (Module)

- Solar panel is a packaged, connected assembly of solar cells
- Solar panel can be used a component of larger PV system to generate electricity
- Each panel is rated by its dc output power under test conditions and typically ranges from 100 to 300 watts
- The efficiency of a panel determines the area of a panel, given the same output power

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## Solar Panels

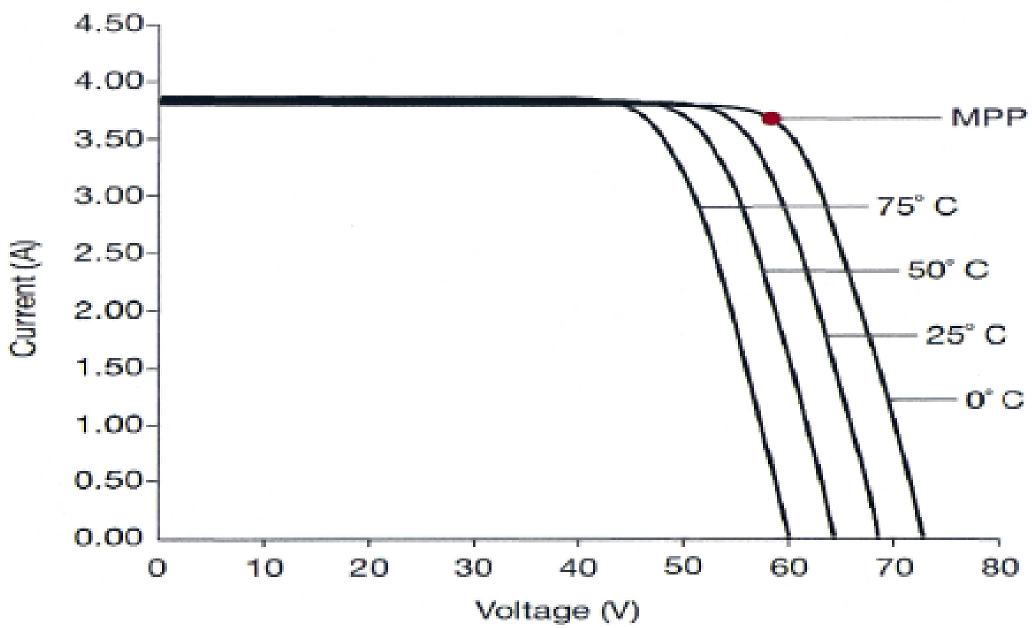
- Solar cells use light energy (photons) from the sun to generate electricity
- Solar modules mostly use wafer based crystalline silicon cells or thin film celss based on cadmium telluride or silicon
- The structural load carrying member of the cell can either be top or back layer
- The cells are protected from mechanical damage and moisture

# Module Efficiency

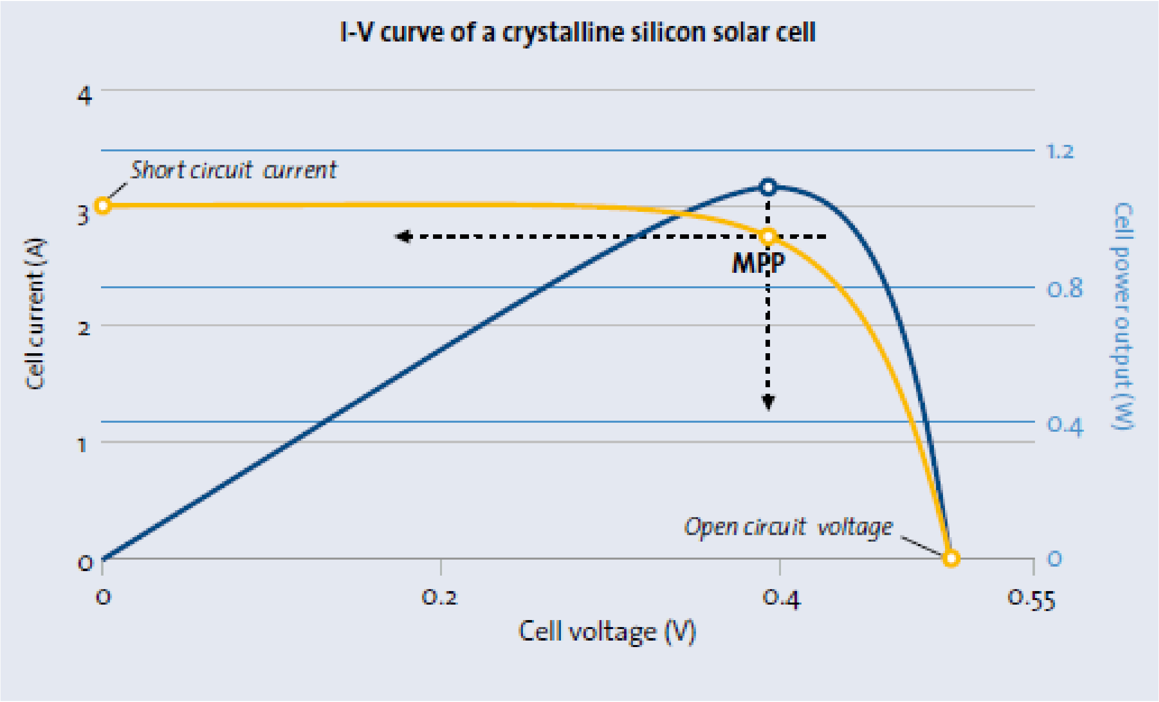
- Solar panels cannot cover entire solar frequency range, especially ultraviolet, infrared and/or low diffused light
- Much of the incident sunlight is wasted
- Typical space requirement: 5-7 acres / MW

| Cell material | Module efficiency | Surface area need for 1 kWp |
|---|---|---|
| Monocrystalline silicon | 13–19% | 5–8 m² |
| Polycrystalline silicon | 11–15% | 7–9 m² |
| Micromorphous tandem cell (a-Si/µc-Si) | 8–10% | 10–12 m² |
| Thin film copper-indium/gallium-sulfur/ diselenide (CI/GS/Se) | 10–12% | 8–10 m² |
| Thin-film cadmium telluride (CdTe) | 9–11% | 9–11 m² |
| Amorphous silicon (a-Si) | 5–8% | 13–20 m² |

# I – V Characteristics of Solar Cells

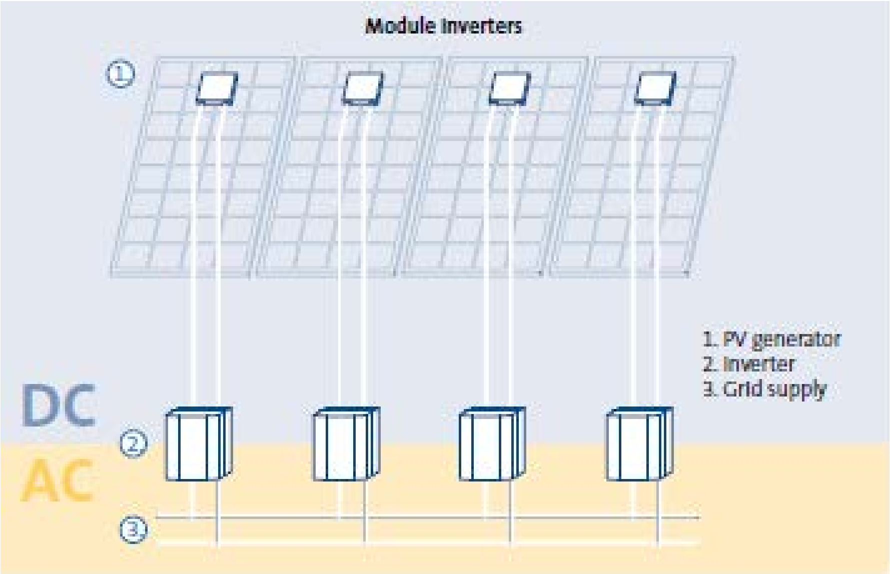


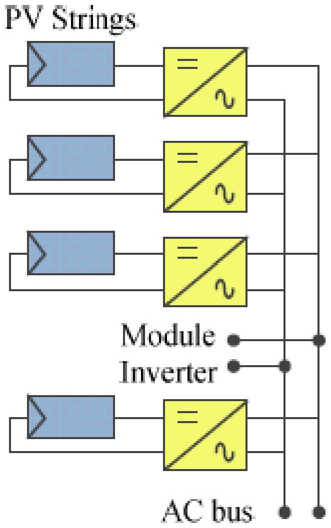
# Maximum Power Point (MPP)



## Module Integrated Inverters

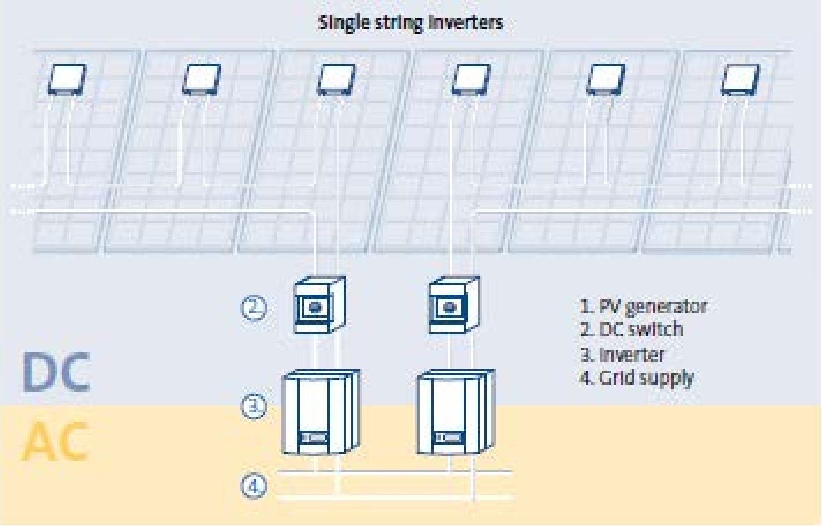
- Typically for very small PV plants (single panel), in the range of 50 – 400 W.

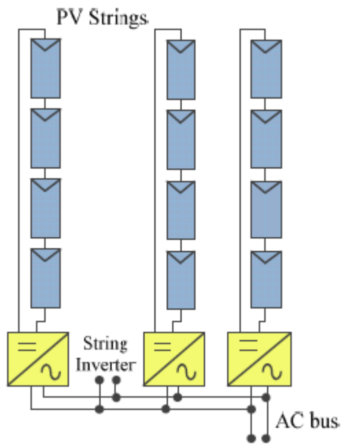


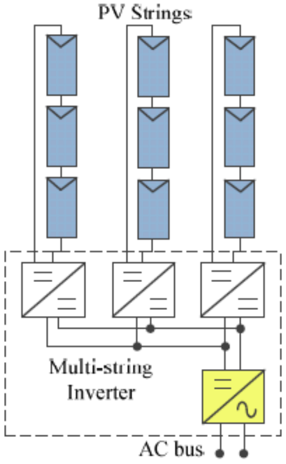



## String Inverters

- String Inverters – Typically for small roof-top plants with panels connected in one string, in the range of 400 W – 2 kW.
- Multi-string Inverters – For medium to large roof-top plants with panels connected in two or more strings, in the range of 1.5 – 6 kW.

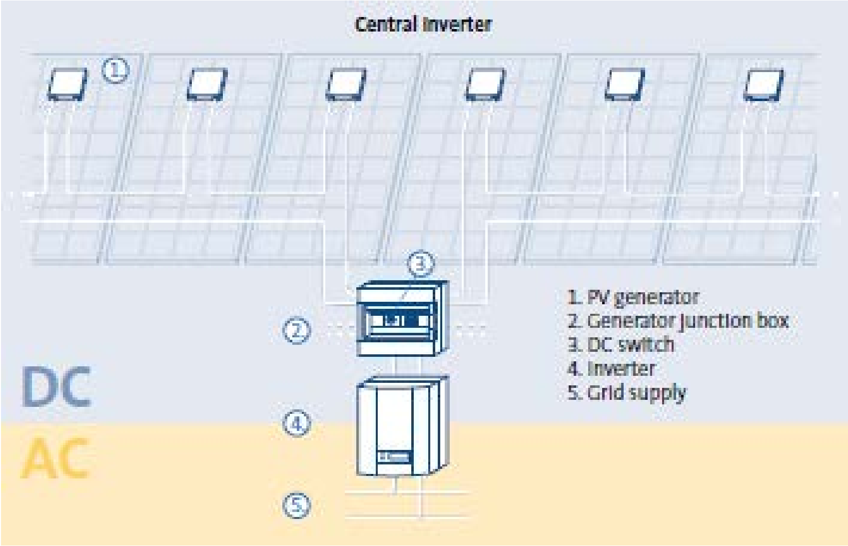


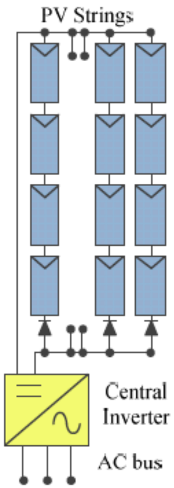



## Central Inverters

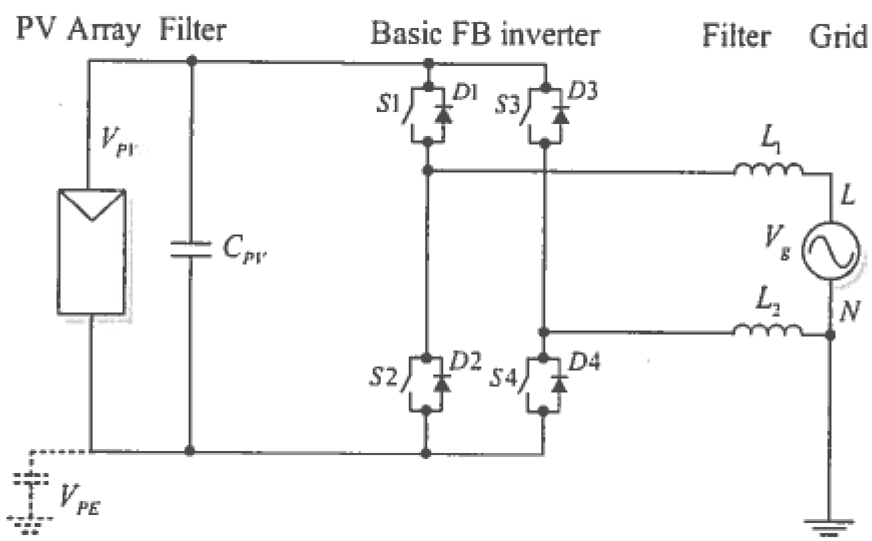
- Mini Central Inverters – consists of three phase topology and modular design for larger roof-top applications, in the range of 6 kW – 100 kW.
- Central Inverters – three phase topology for ground mounted application, in the range of 100 kW – 1500 kW.



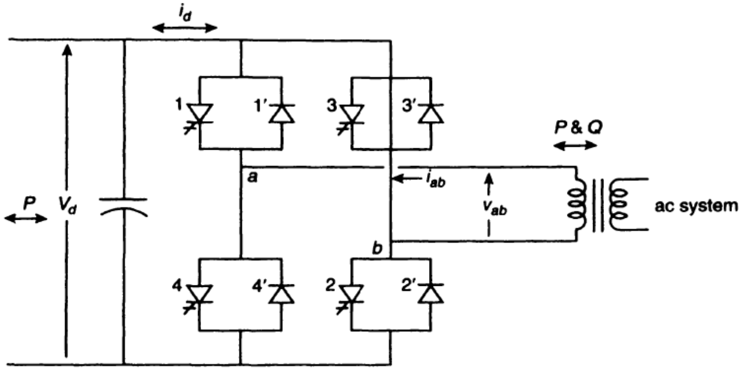



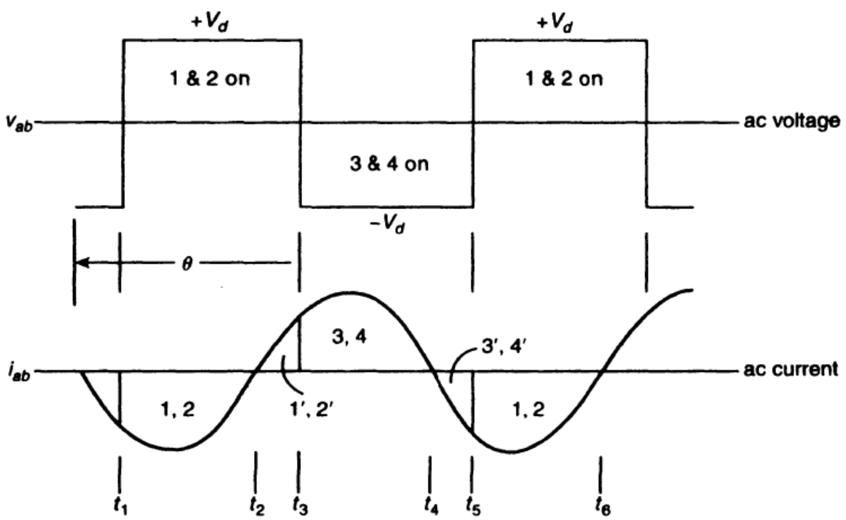
## Basic Full Bridge Structure

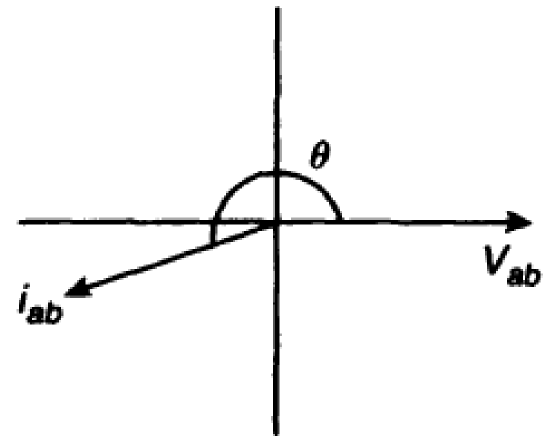
- The switches S1 – S4 are Insulated Gate Bipolar Transistors (IGBT). Earlier inverters used Gate Turn-Off Thyristors (GTO).



# Basic Full Bridge Inverter Operation

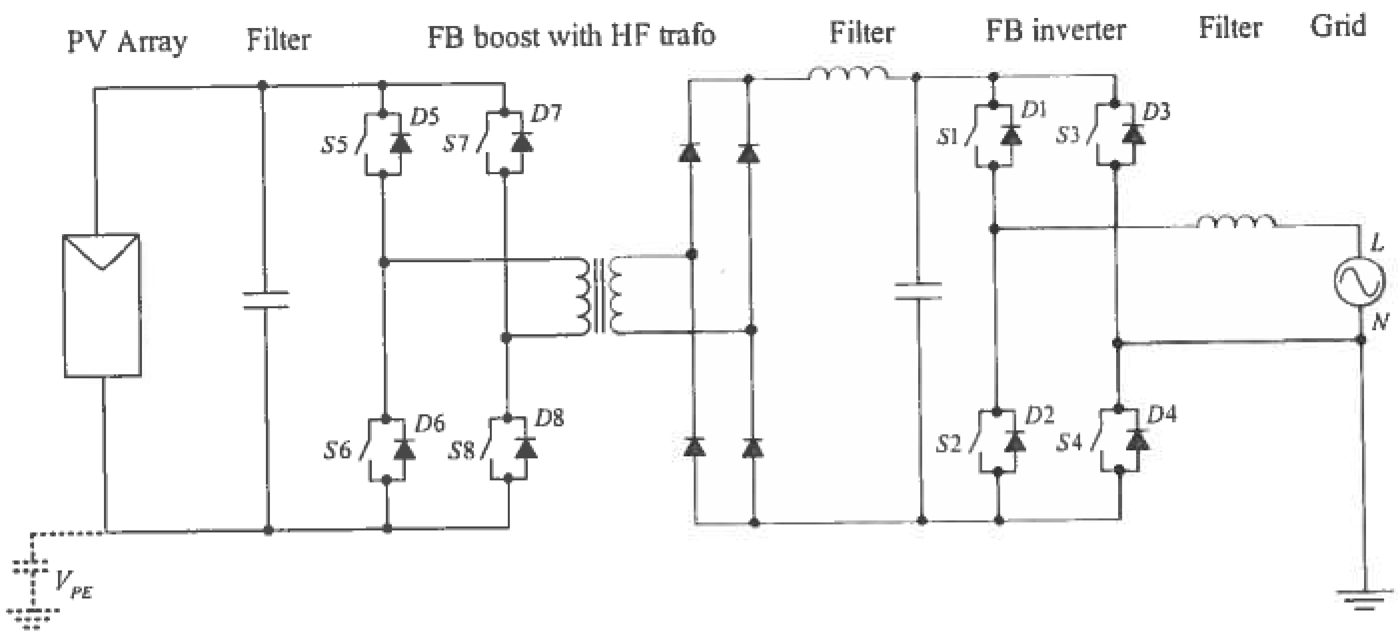


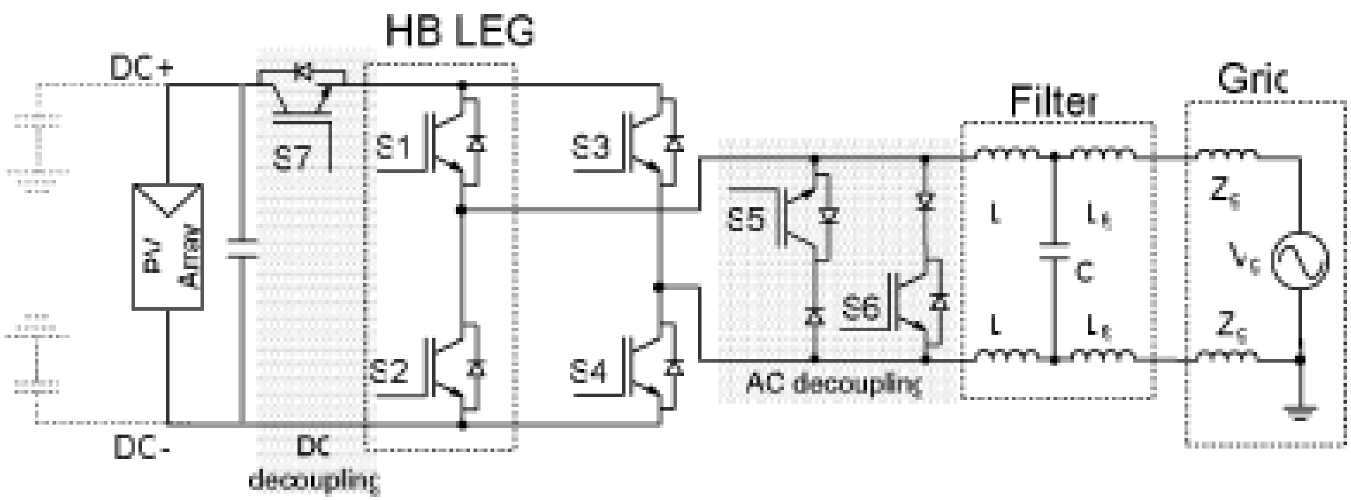
## Booster With High Frequency Transformer

- Due to the dc voltage restriction, a booster stage is typically required.

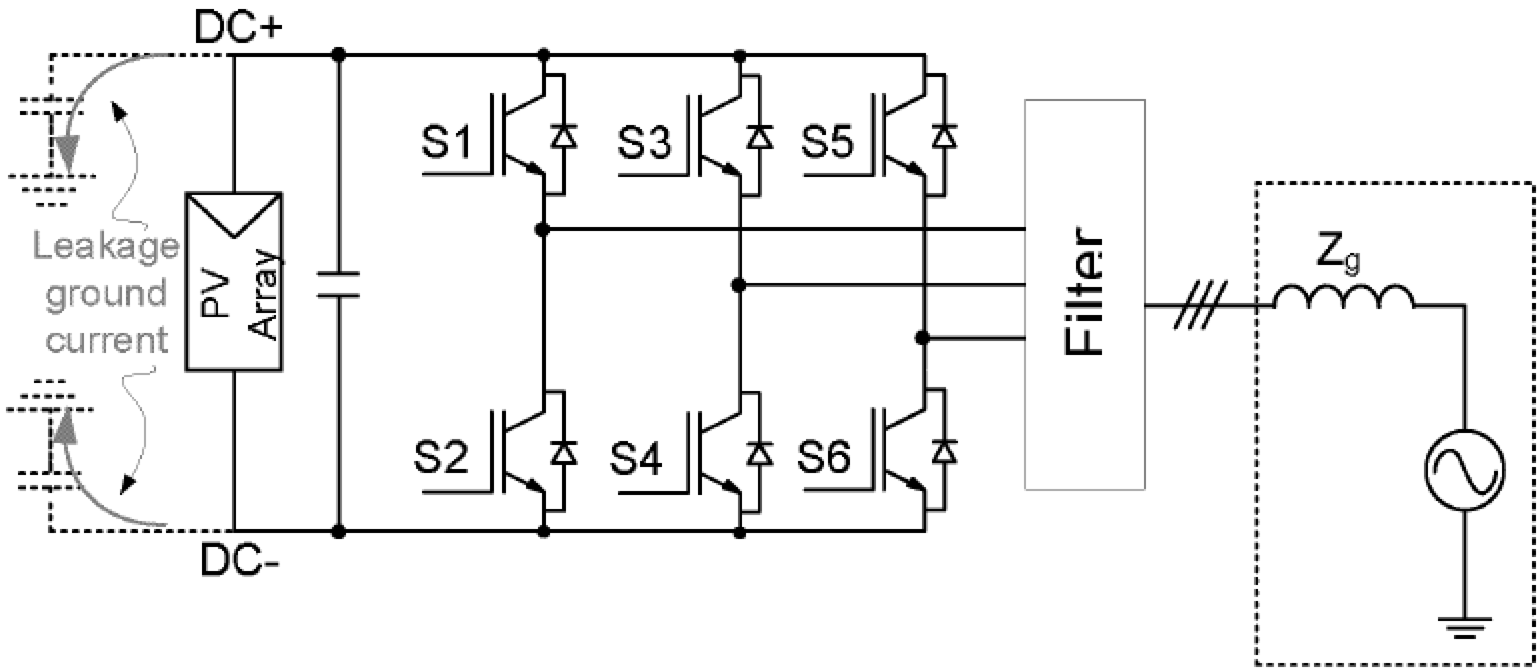


## Transformerless Inverters

- In order to make inverters compact and reduce costs, transformerless inverters are also used.

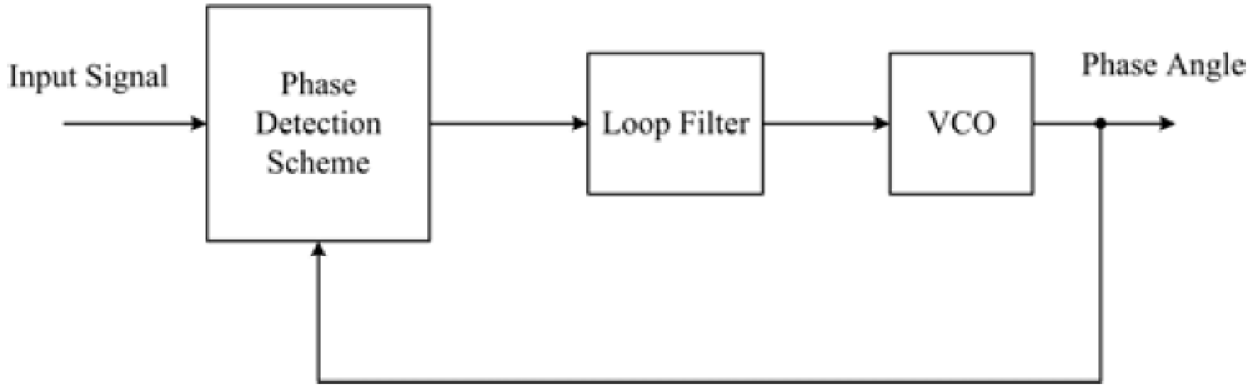


# Three Phase Topology



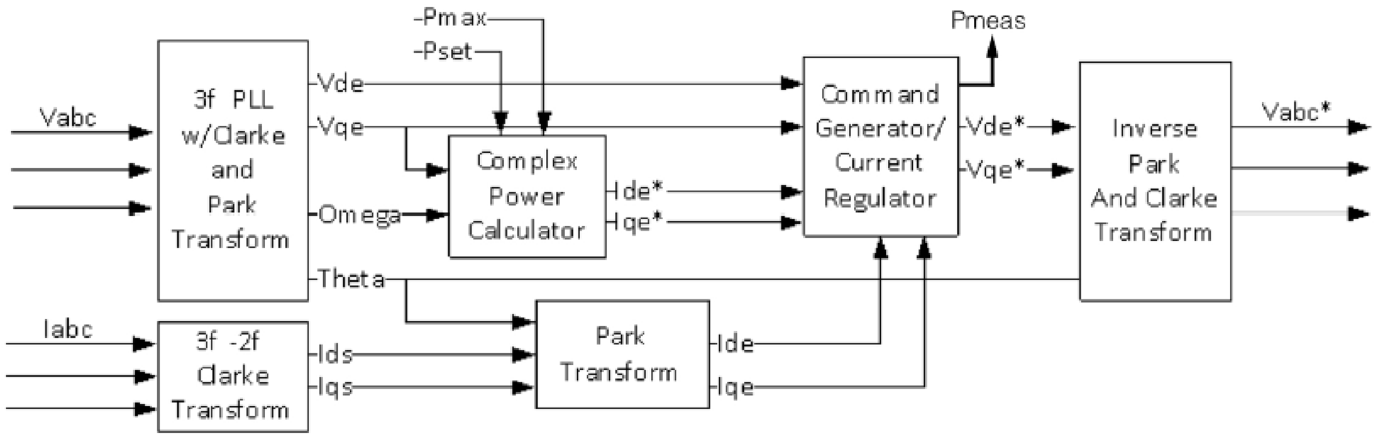
## Grid Synchronization

- Inverter controllers use internally generated fundamental signals as references.
- The internal reference signals need constant adjustment (synchronization) with the ever changing grid voltage / frequency.
- Phase Locked Loop (PLL) schemes are adopted for grid synchronization.

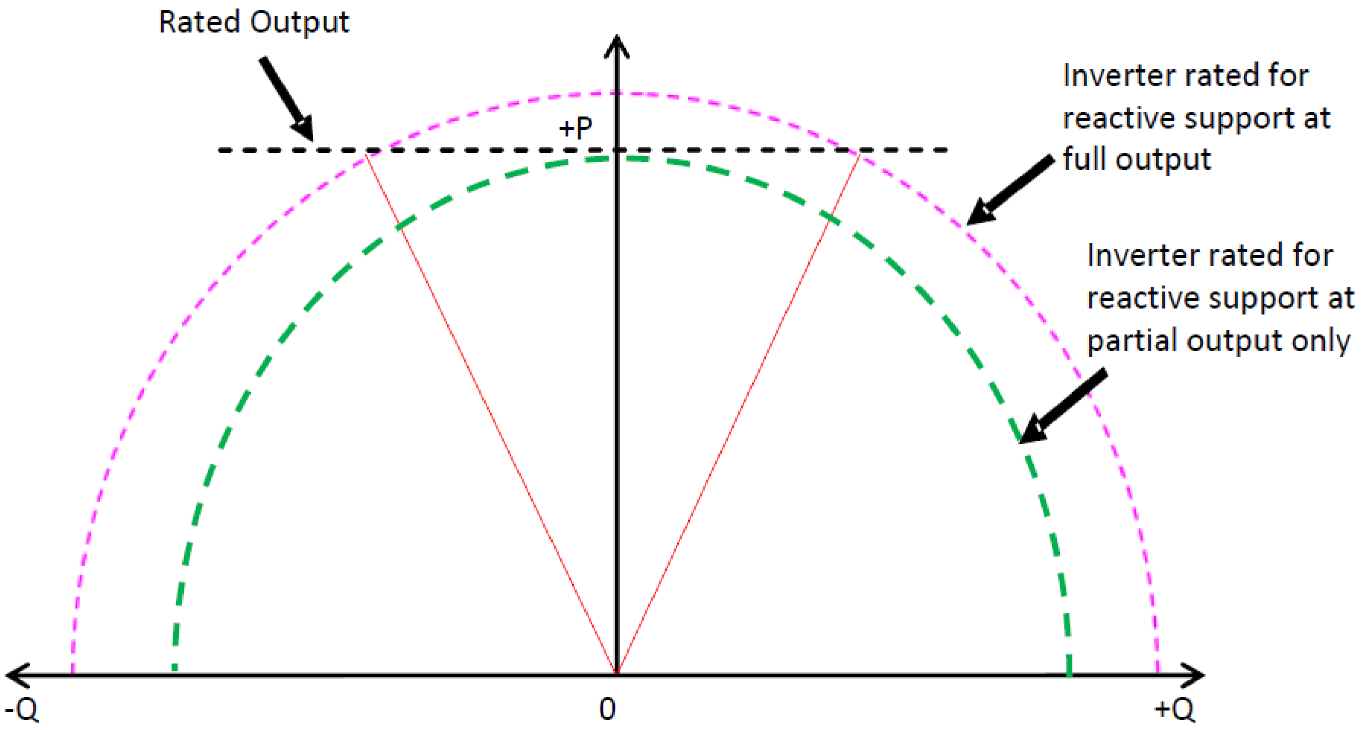


## Inverter Controls – Current Control

- Keeping (controlling) the current to the same value that is calculated by the MPP tracking.
- Maintaining the current to be in same phase as that of the grid voltage and thereby keeping unity power factor or at a specified power factor.
- Functionally, the inverters are like current sources seen from the ac side.

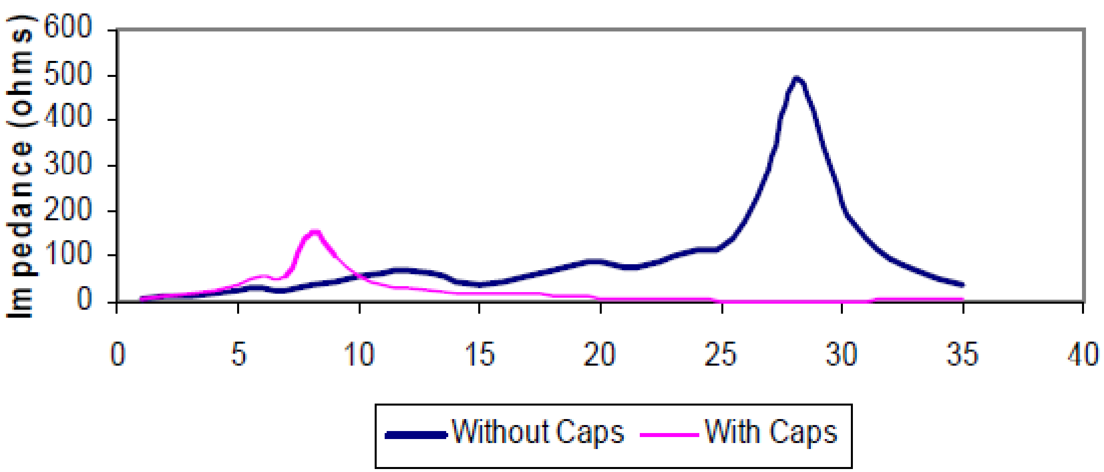


# Inverter Reactive Power Capability

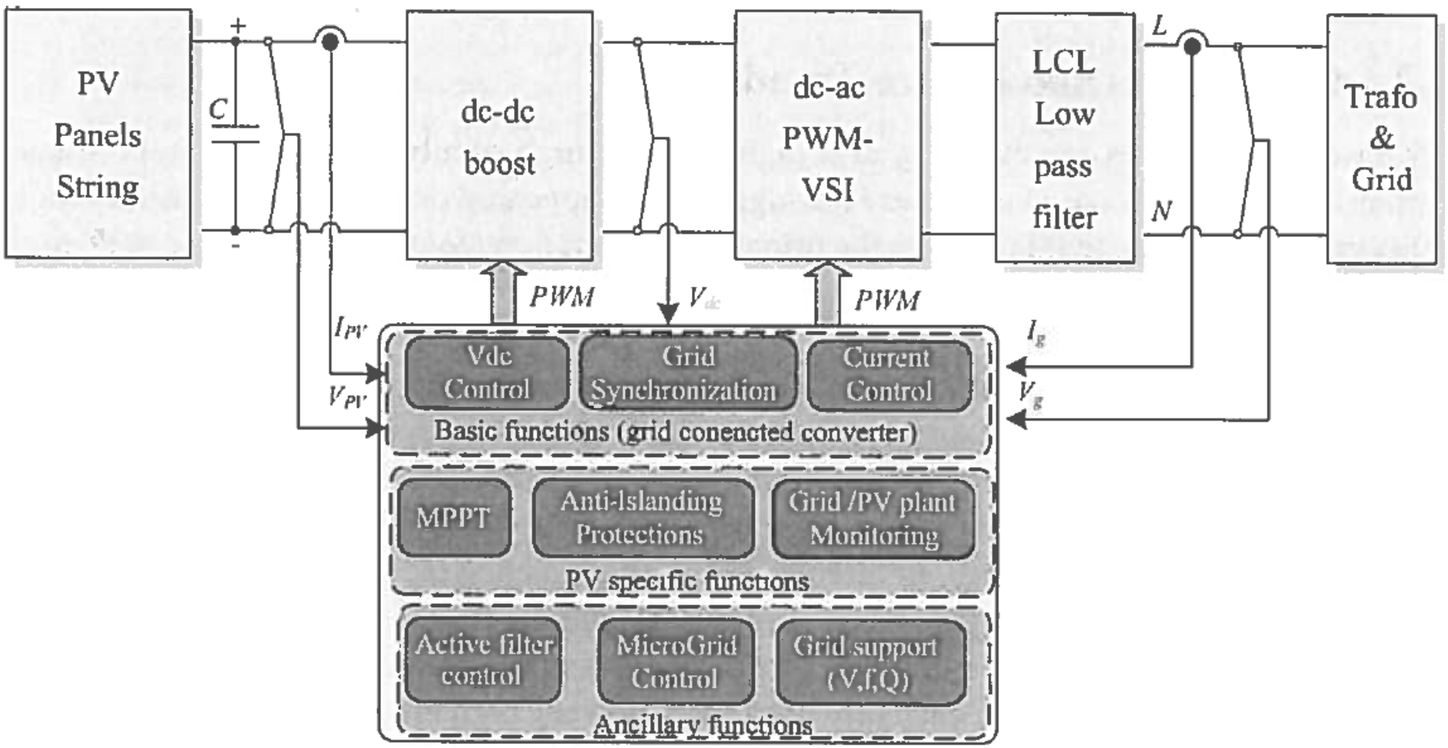


# Harmonic Frequency Resonance

- If shunt capacitors are added, frequency resonance points need to be away from the dominant harmonic frequencies.
- Addition of shunt capacitors shift the resonant frequency to lower order.

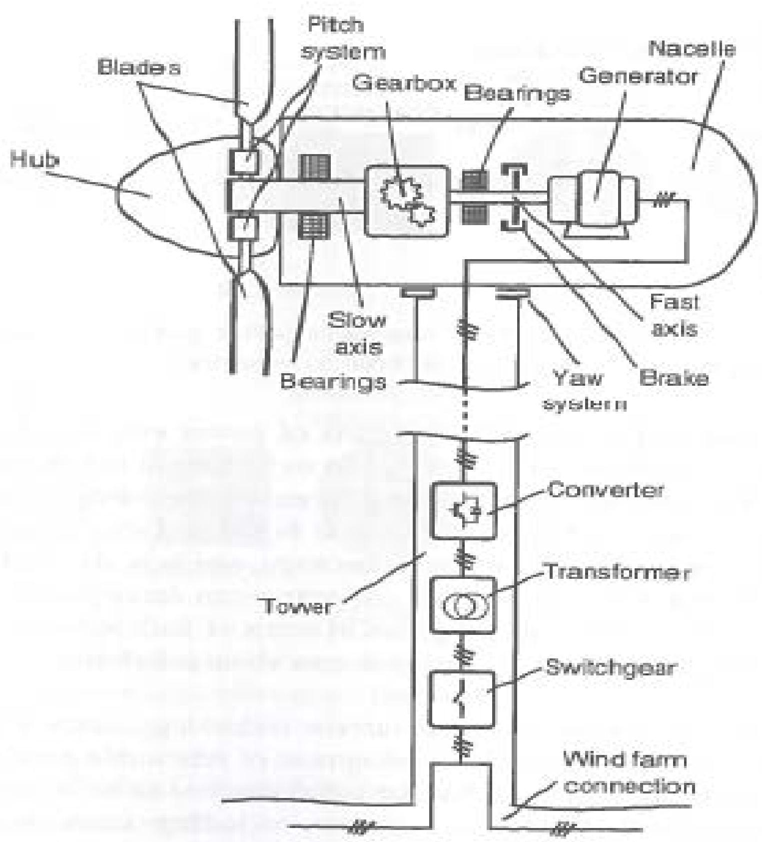


# Overall PV Control Structure



# Wind Turbine Technology

# Conceptual Arrangement of a Wind Turbine

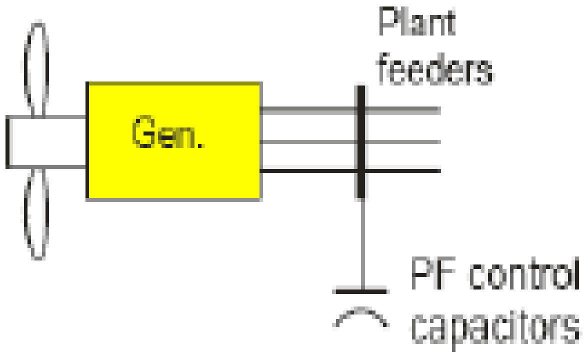



Pitch System adjusts the blade angles to limit power output

Generator could an induction or a synchronous generator

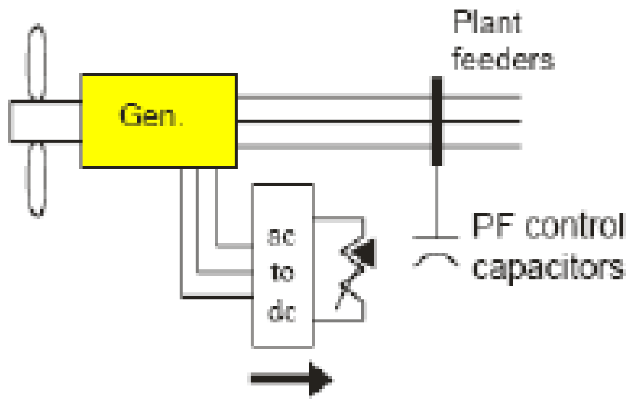
## Type 1 Wind Turbine

- It is a fixed speed wind turbine
- Uses a squirrel cage induction generator
- It has simpler controls
- Consumes a lot of reactive power



# Type 2 Wind Turbine

- It is a limited variable speed turbine
- Uses wound rotor induction generator
- Uses variable resistor in the rotor circuit for speed control
- Consumes reactive power



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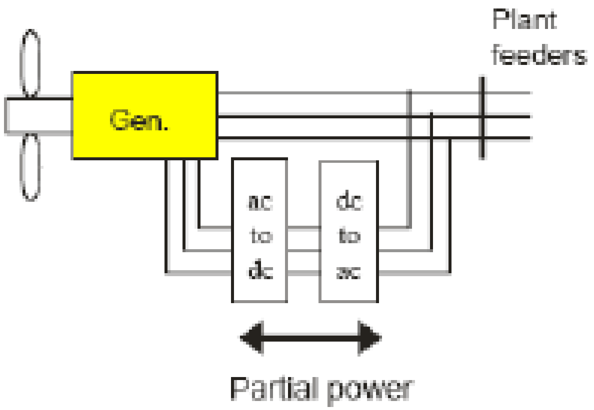
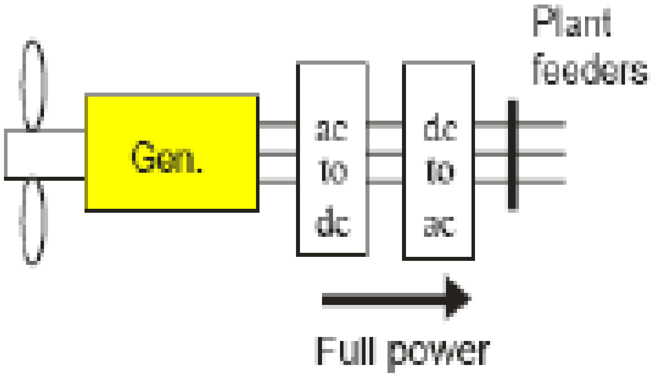
## Type 3 Wind Turbine

- It is also known as "Doubly Fed Induction Generator"
- Uses wound rotor induction generator
- Stator windings are directly connected to the grid and the rotor windings connected through power converters
- Power converters are usually rated about 30% of generator rating and provides limited amount of reactive power.



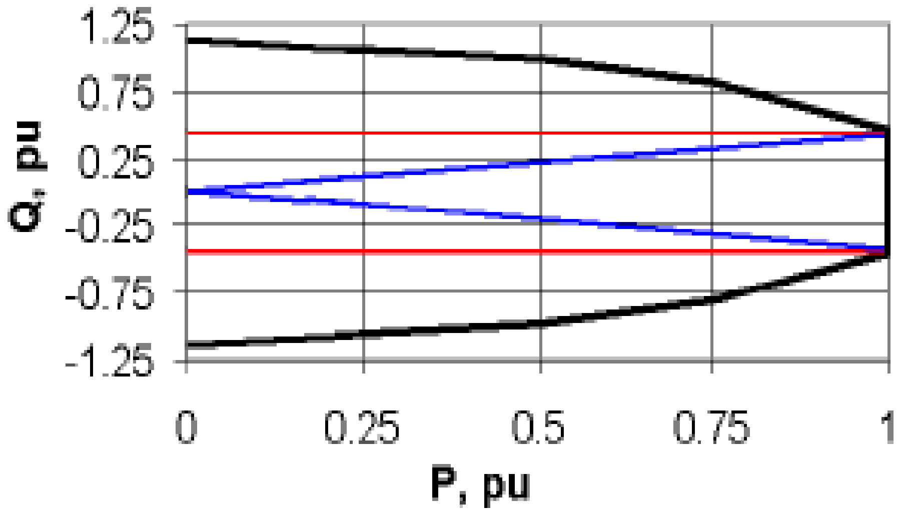
# Type 4 Wind Turbine

- Known as variable speed full converter turbine
- Uses either a squirrel cage induction or wound rotor induction or a permanent magnet synchronous generator
- Full scale converter provides reactive power and frequency support



## Reactive Power Capability of Wind Turbines

- Type 3 and Type 4 turbines are offered with either triangular or rectangular or D shape reactive power capability



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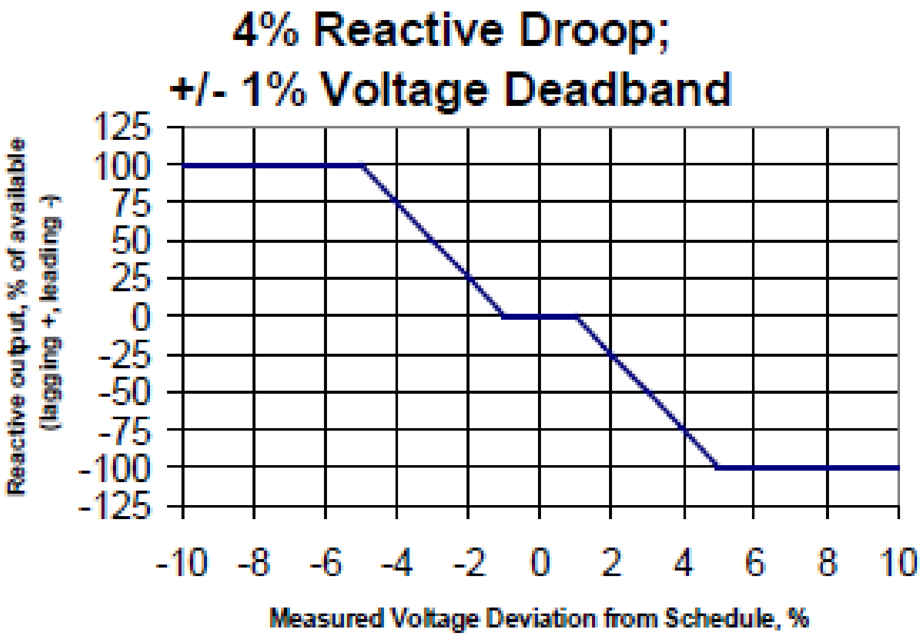
## Voltage Ride Through Capability

- Most wind turbines have low voltage and zero voltage ride through capabilities
- If voltage ride through capability is not available, external dynamic reactive power compensation devices will be necessary.

# Dynamic Reactive Power Capability

- Wind (and PV) generators can operate with reactive power droop setting



# Review of Distribution Code (IRR-DCC-MV)

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## Objective of the Distribution Code

- To ensure that the new Intermittent Renewable Resource (IRR) does not degrade the reliability of the distribution system
- To ensure that the new IRR does not adversely impact the transmission (NEPCO) system

# Applicable Generators

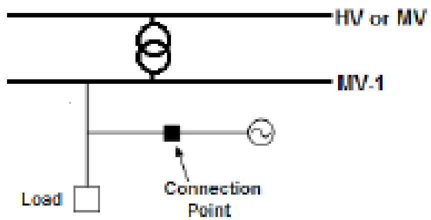
<table>
<tr><th>Type</th><th>Schematic</th><th>Project Size</th></tr>
<tr><td><u>Type A-1:</u><br>Connected to the MV distribution on an existing feeder with load.<br><br>**MV-1: 6.6 kV**</td><td>

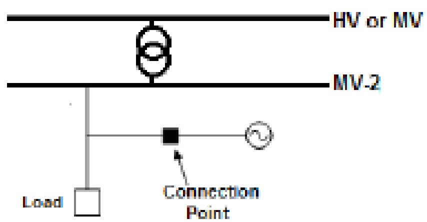
Figure 2-1 –IRR Type A-1</td><td>Up to 2 MW</td></tr>
<tr><td><u>Type A-2:</u><br>Connected to the MV distribution on an existing feeder with load.<br><br>**MV-2: 11 kV**</td><td>

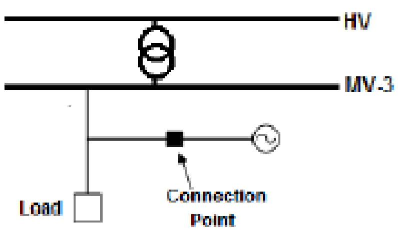
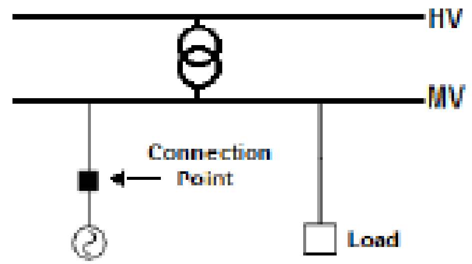
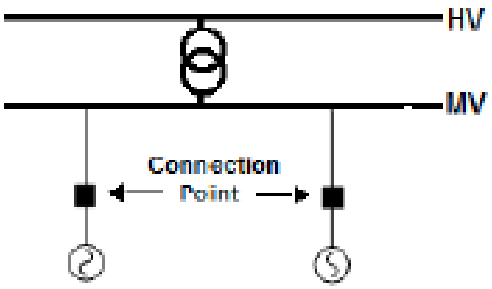
Figure 2-2 –IRR Type A-2</td><td>Up to 3 MW</td></tr>
<tr><td><u>Type A-3:</u><br>Connected to the MV distribution on an existing feeder with load.<br><br>**MV-3: 33 kV**</td><td>

Figure 2-3 –IRR Type A-3</td><td>Up to 10 MW</td></tr>
</table>

# Applicable Generators

| | | |
|---|---|---|
| **Type B:**<br>Connected to the MV distribution via a DISCO owned or operated dedicated feeder that serves only the IRR.<br><br>Other loads are connected to the MV source however through other feeders.<br><br>**MV: 33 kV** | <br>Figure 2-4 –IRR Type B | Up to 15 MW |
| **Type C:**<br>Connected at MV to a dedicated NEPCO renewable generation collection substation directly or through a privately owned line.<br><br>There are no loads connected at the MV substation level. | <br>Figure 2-5 –IRR Type C | NEPCO requirements |

## Frequency Requirement

Table 4-1 - Frequency Protection Setting Requirements

| Frequency Range | Delay to Trip |
|---|---|
| 52.0 Hz ≤ Freq | .5s |
| 51.5 Hz < Freq < 52.0 Hz | 90s |
| **47.5 Hz ≤ Freq ≤ 51.5 Hz** | **Continuous Operation** |
| 47.0 Hz < Freq < 47.5 Hz | 20s |
| Freq ≤ 47.0 Hz | .5s |

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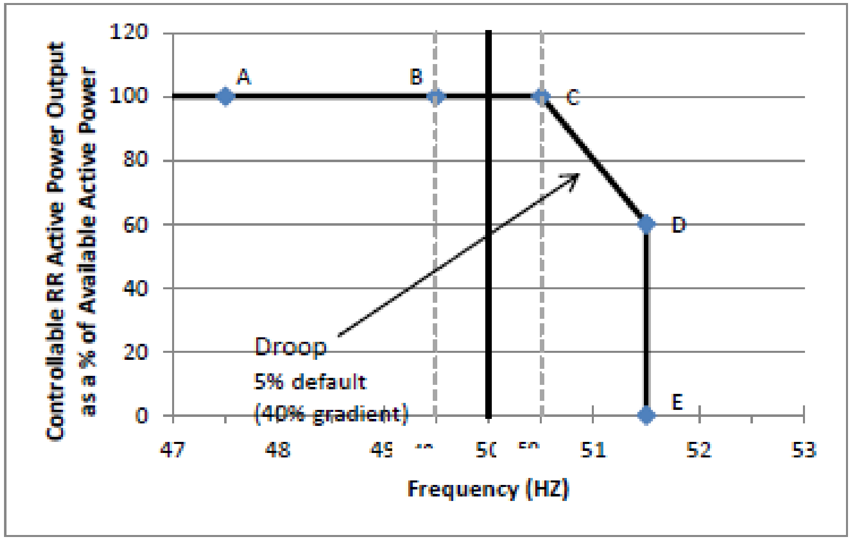
## Active Power Requirement

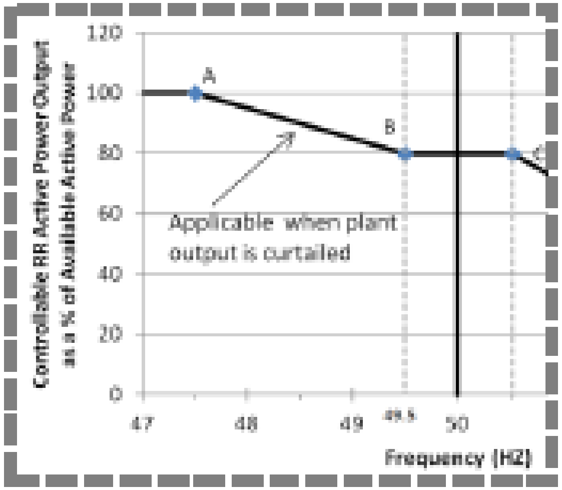
- IRR should have the capability to reduce its active power when required by  DISCOs
- The reduction in power shall be at 10% step up to the required value
- DISCO is responsible only for providing the signal to IRR

## Primary Frequency Response (PFR)

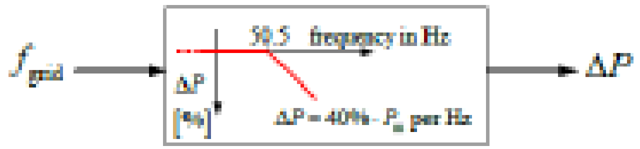
- This function will be activated when required in coordination with NEPCO
- IRRs that have capacity available to either decrease or increase in real time must provide this frequency response
- PFR is similar to governor droop characteristic in a conventional generator
- The droop shall be set by DISCOs in the range of 2% to 10%, with a default value of 5%

# Power Frequency Response Curve



# Droop Characteristic




$$\Delta P = 20 P_m \frac{50.5\ \text{Hz} - f_{\text{grid}}}{50\ \text{Hz}} \quad \text{at } 50.5\ \text{Hz} < f_{\text{grid}} < 51.5\ \text{Hz}$$

$P_m$ instantaneously available power

$\Delta P$ power reduction

$f_{\text{grid}}$ grid frequency

For $47.5\ \text{Hz} < f_{\text{grid}} \le 50.5\ \text{Hz}$ continues operation

At $f_{\text{grid}} \le 47.5\ \text{Hz}$ and $f_{\text{grid}} \ge 51.5\ \text{Hz}$ disconnection from grid

# Voltage Tolerance at Point of Common Coupling (PCC)

Table 5-1 –IRR Plant Voltage Protection Setting Requirements at the PCC

| Voltage Range (% $V_{nominal}$) | Delay to Trip |
|---|---|
| V= 119% | 0.5s |
| V= 114% | 1s |
| $90 \leq V \leq 110$ | Continuous Operation |
| V = 87% | 2.5s |
| V = 81% | 0.5s |

## Voltage Flicker

- The voltage step limit at PCC for sudden loss of IRR shall not be more than 3% of nominal voltage
- The flicker severity (Pst and Plt) at the PCC shall not be above the maximum values stated in IEC 61000-3-7 for more than 3% of the measured period.

## Voltage Ride Through Requirement

- The Low Voltage Ride Through (LVRT) requirement specifies the capability range for IRRs to remain connected during grid faults
- IRR must survive a zero voltage dip of at least 250 ms

# Low Voltage Ride Through Requirement

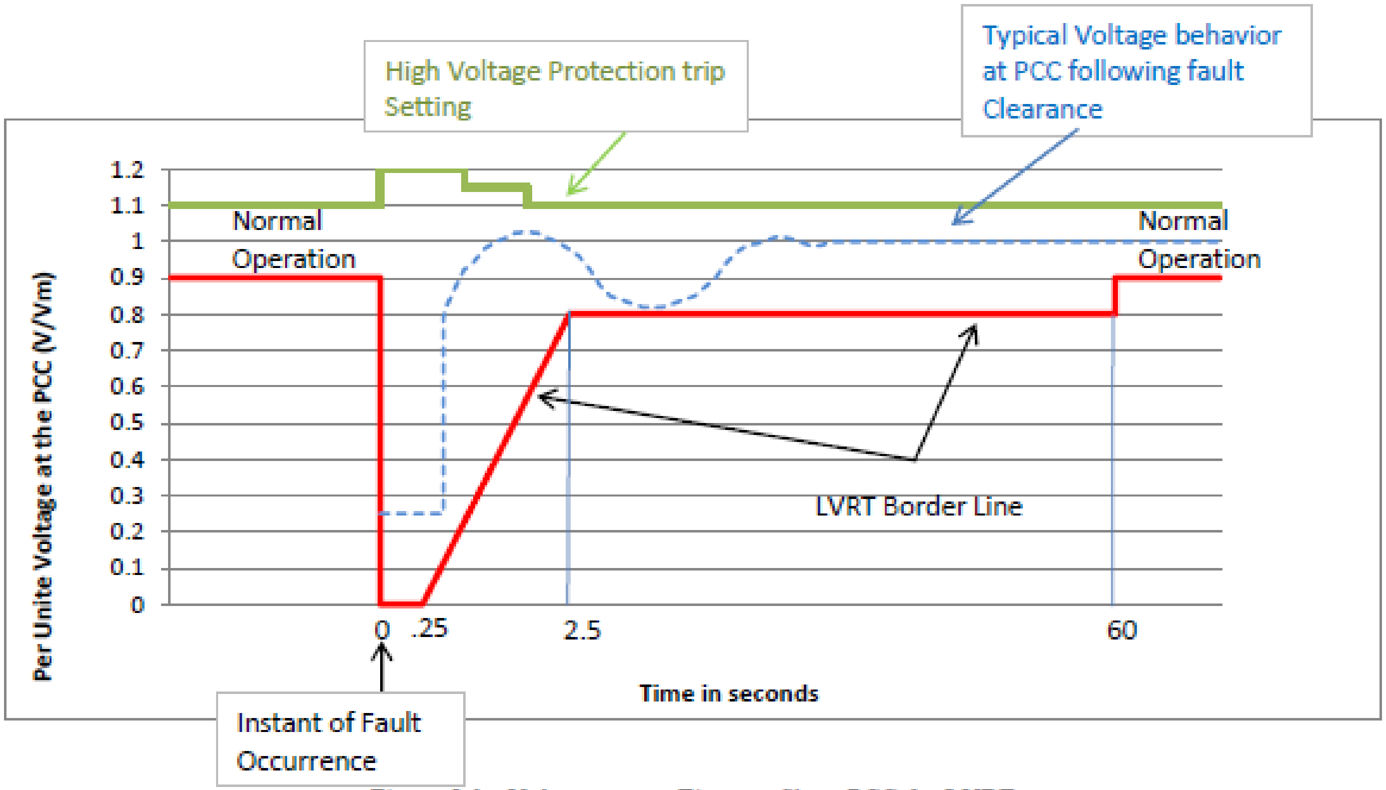



Figure 5-1 - Voltage versus Time profile at PCC for LVRT

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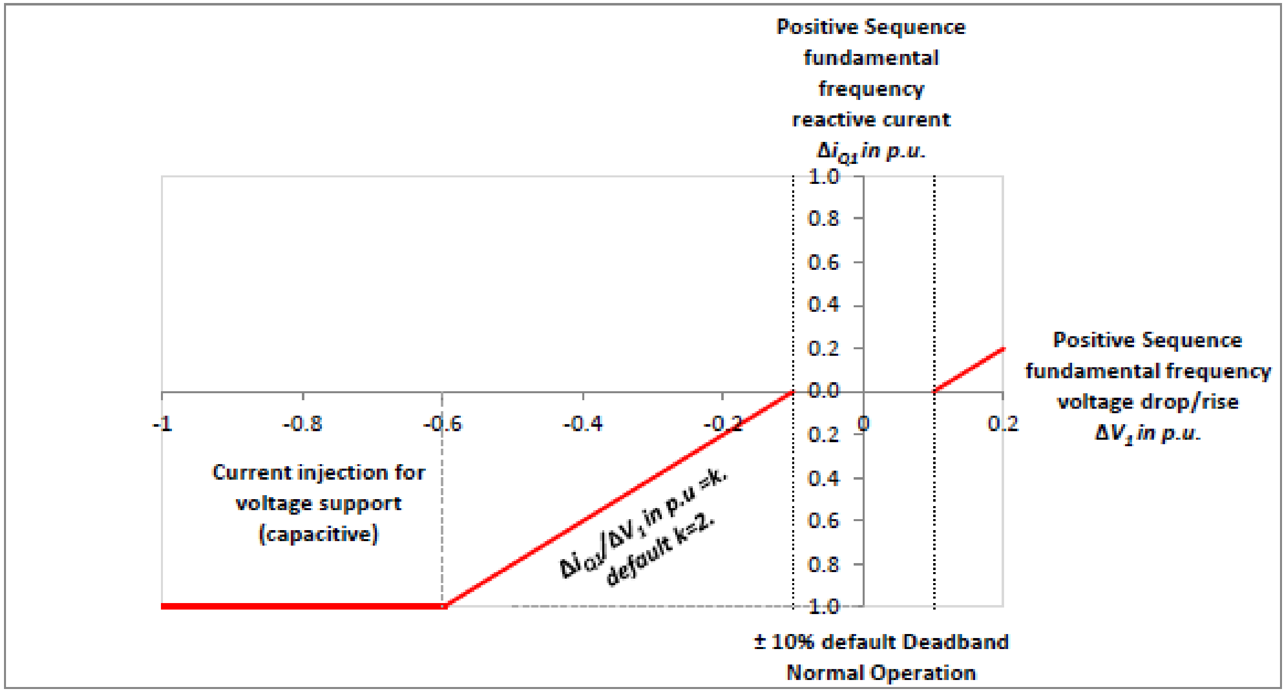
## Reactive Current Injection

- The IRR shall support the voltage during grid faults by injecting or absorbing reactive current
- 100% reactive power must be possible over 0.5 seconds
- Active current shall be maintained during voltage drops, but a reduction in the active current is permitted only to maintain IRR within its design limits

# Reactive Current Injection Characteristic



## Reactive Power Requirement

- IRR must be able to operate in reactive power control mode and follow operating point within 0.88 lag power factor to 0.88 lead power factor at the PCC
- Full 0.88 lagging reactive capability shall be available at 100% to 95% of nominal voltage
- Full leading reactive capability of 0.95 power factor shall be made available at 100% to 105% of nominal voltage
- The reactive power support must be dynamic up to the plant's rated capacity

# Required PQ Capability

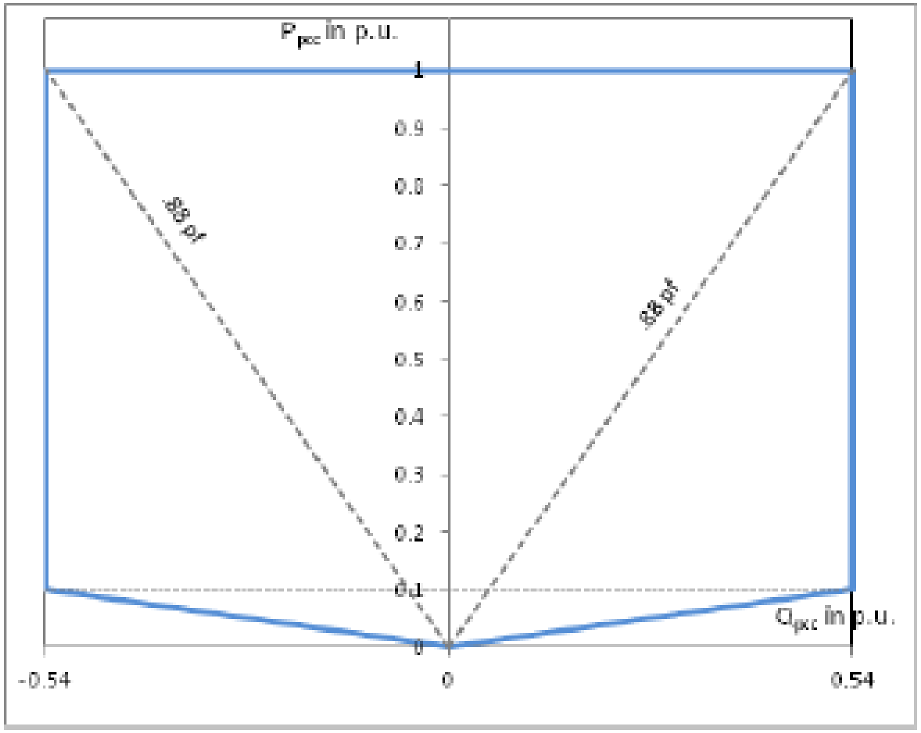



Figure 5-3 - Minimum PQ Diagram to be Fulfilled by IRR plant

## Harmonics

- Total harmonic voltage distortions at the PCC shall not exceed 6.5%
- No individual harmonic voltage distortion shall be higher than 5%

Table 7-1 – Harmonic Voltage Distortions Planning Level for MV

| Indicative planning levels for harmonic voltages (in percent of the fundamental voltage) in 33 kV power systems | | | | | |
|---|---|---|---|---|---|
| Odd harmonics non-multiple of 3 | | Odd harmonics multiple of 3 | | Even harmonics | |
| Harmonic order h | Harmonic voltage % | Harmonic order h | Harmonic voltage % | Harmonic order h | Harmonic voltage % |
| 5 | 5 | 3 | 4 | 2 | 1.8 |
| 7 | 4 | 9 | 1.2 | 4 | 1 |
| 11 | 3 | 15 | 0.3 | 6 | 0.5 |
| 13 | 2.5 | 21 | 0.2 | 8 | 0.5 |
| $17 \leq h \leq 49$ | $1.9 \times 17/h - 0.2$ | $21 \leq h \leq 45$ | 0.2 | $10 \leq h \leq 50$ | $0.25 \times 10/h + 0.22$ |

The indicative planning level for the total harmonic distortion is THDMV = 6.5%

## Ramp Rate

- Active power ramp rate average over 1 minute shall have a setting of 20% per minute of name plate rating
- Another ramp rate setting shall apply over 10 minutes
- The ramp rate setting shall be applicable for start up, normal operation and shut down

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## Anti-Islanding Requirements

- The IRR must be capable of tripping off line upon loss of main power (LoM) from the grid
- If no facilities exist for subsequent re-synchronization, IRR should ensure that the plant is disconnected
- The preferred method of tripping of the IRR is by means of Transfer Trip Schemes

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# Study Requirements

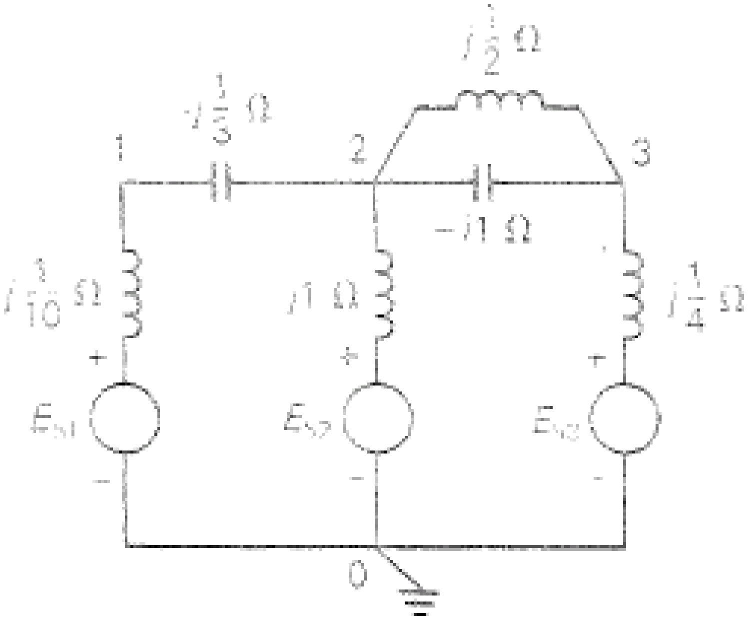
Table 11-1– Study Requirements

| Study | Type A | Type B | Type C |
|---|---|---|---|
| | | | |
| To be completed by NEPCO | Affected System | Affected System | ALL |
| | | | |
| Steady State Power Flow Study & Losses | ALL | ALL | |
| Short Circuit and Protection Study | ALL | ALL | |
| Voltage Flicker | ALL | ALL | |
| Harmonics | ALL | ALL | |
| Voltage Transient Stability Study | >5 MW | > 5 MW | |
| System Dynamic Response Study | >10 MW | >10 MW | |

# Software Algorithms

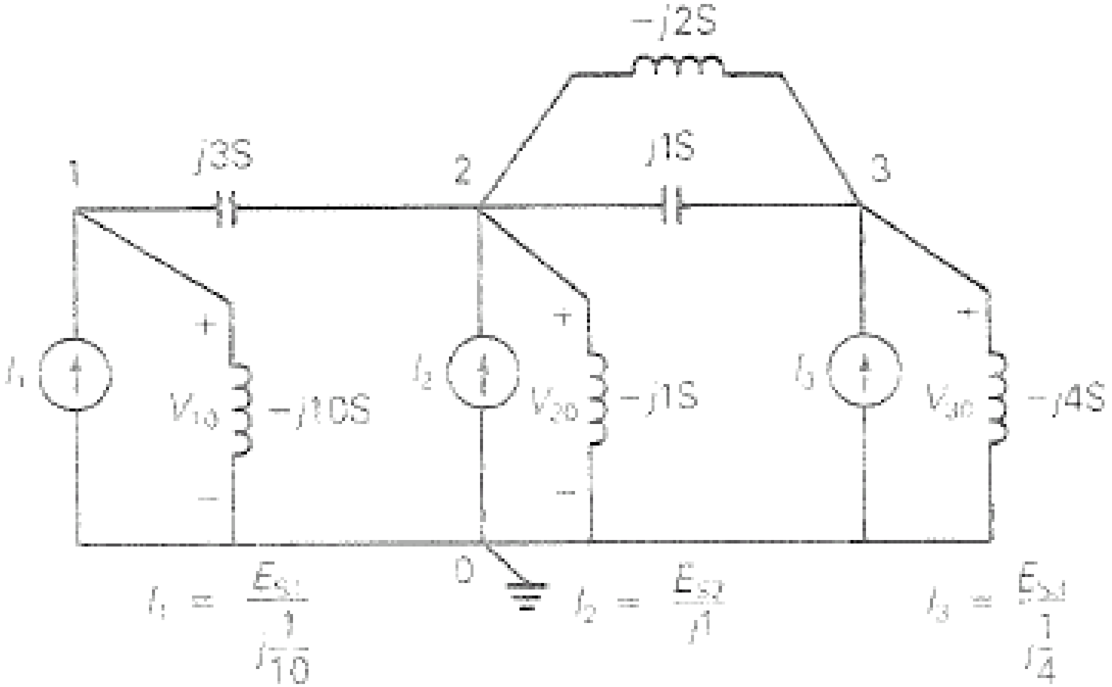
# Network Equations

Consider the following network:




Bus 0 is selected as the reference bus and the bus voltages $V_{10}$, $V_{20}$,… are Defined with respedt to bus 0.

Transforming each voltage source with current source and admittance, and also Each branch impedance with admittance,



$I_1 = Y_{10} V_{10} + Y_{12} (V_{10} – V_{20})$

$I_2 = Y_{20} V_{20} + Y_{21} (V_{20} – V_{10}) + Y_{23} (V_{20}-V_{30})$

$I_3 = Y_{30} V_{30} + Y_{32} (V_{30} – V_{20})$

Rearranging the above equations,

$I_1 = (Y_{10} + Y_{12}) V_{10} – Y_{12} V_{20}$
$I_2 = -Y_{12} V_{10} + (Y_{20} + Y_{21} + Y_{23}) V_{20} – Y_{23} V_{30}$
$I_3 = -Y_{32} V_{20} + (Y_{30} + Y_{32})V_{30}$

In matrix form,

$$\begin{bmatrix} Y_{10}+Y_{12} & -Y_{12} & 0 \\ -Y_{12} & Y_{20}+Y_{21}+Y_{23} & -Y_{23} \\ 0 & -Y_{23} & Y_{30}+Y_{23} \end{bmatrix} \begin{bmatrix} V_{10} \\ V_{20} \\ V_{30} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

The Y matrix is called “admittance matrix” or “Ybus matrix”.

$$[Y_{bus}][V_{bus}] = [I_{bus}]$$

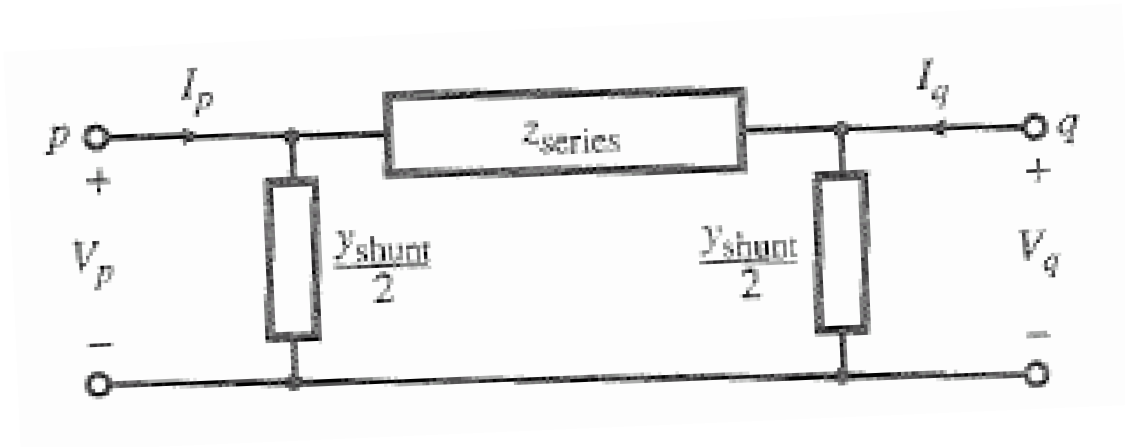
Diagonal elements of Y matrix are called “self-admittance” or the “driving Point admittance” and the off-diagonal elements are called, “mutual admittance” or “transfer admittance” between the two buses.

In Generalized form,

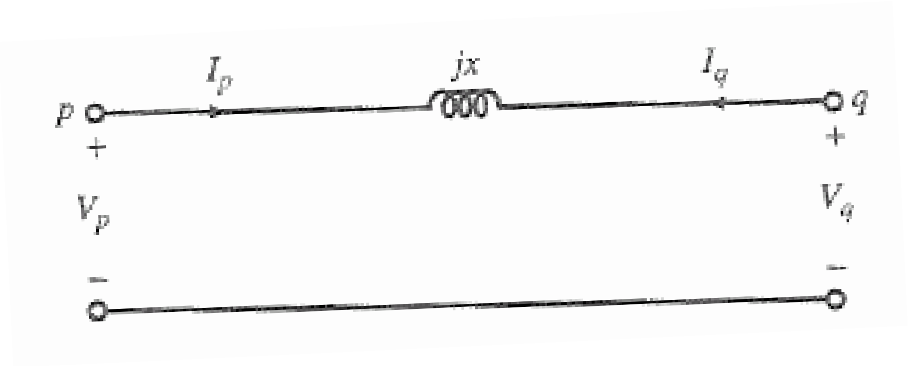
$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & \cdots & Y_{1N} \\ Y_{21} & Y_{22} & Y_{23} & \cdots & Y_{2N} \\ Y_{31} & Y_{32} & Y_{33} & \cdots & Y_{3N} \\ \vdots & \vdots & \vdots & & \vdots \\ Y_{N1} & Y_{N2} & Y_{N3} & \cdots & Y_{NN} \end{bmatrix} \begin{bmatrix} V_{10} \\ V_{20} \\ V_{30} \\ \vdots \\ V_{N0} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_N \end{bmatrix}$$

$$\boldsymbol{YV} = \boldsymbol{I}$$

# Modeling of Transmission Line



# Modeling of Transformers



## Power Flow Equations

$$I = Y_{bus} V$$

Where I is the N vector of source currents injected into each bus and V is the N vector of bus voltages. For bus k, the kth equation is

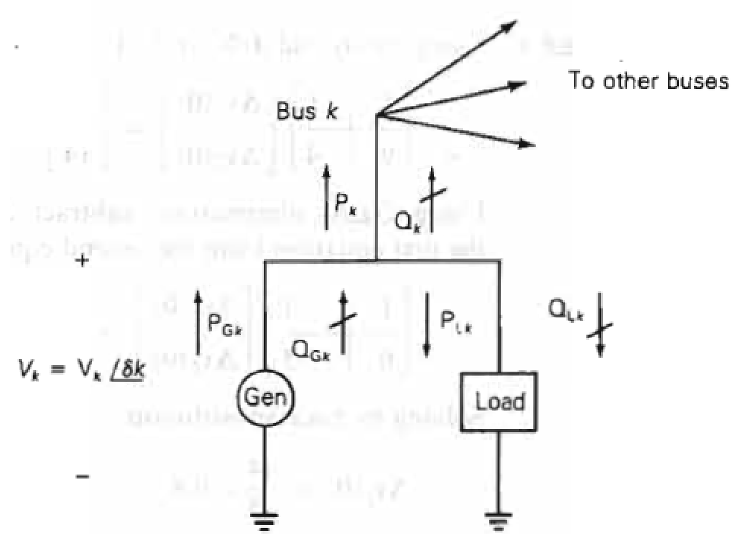
$$I_k = \sum_{n=1}^{N} Y_{kn} V_n$$

The complex power delivered to bus k is

$$S_k = P_k + jQ_k = V_k I_k^*$$

Substituting for $I_k$

$$P_k + jQ_k = V_k \sum_{n=1}^{N} Y_{kn} V_n e^{j(\delta_k - \delta_n - \theta_{kn})}$$



# Title

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Taking the real and imaginary parts,

$$P_k = V_k \sum_{n=1}^{N} Y_{kn} V_n \cos(\delta_k - \delta_n - \theta_{kn})$$

$$Q_k = V_k \sum_{n=1}^{N} Y_{kn} V_n \sin(\delta_k - \delta_n - \theta_{kn})$$

Where k = 1,2,……N

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## Power Flow Problem

Buses that are connected with generators are called ‘Generator Buses’.

Other buses are called ‘Load Buses’.

At generator buses, Pgen and voltage magnitudes are specified. So, they are also called PV buses.

At load buses, both P and Q are specified. So, they are also called ‘PQ buses’.

Normally, one generator bus is designated as ‘reference’ bus. This bus is used to account for the line losses. So, it is also called ‘Slack’ or ‘Swing’ bus. The voltage magnitude is considered to be 1.0 pu and angle bus angle to be 0 deg.

# Example of Iterative Method:

$$\begin{bmatrix} 10 & 5 \\ 2 & 9 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 6 \\ 3 \end{bmatrix}$$

Iterate till the tolerance is

$\varepsilon = 10^{-4}$

Assume initial value of $x_1(0) = 0$ and $x_2(0) = 0$

$$x_1(i+1) = \frac{1}{A_{11}}[y_1 - A_{12}x_2(i)] = \frac{1}{10}[6 - 5x_2(i)]$$

$$x_2(i+1) = \frac{1}{A_{22}}[y_2 - A_{21}x_1(i)] = \frac{1}{9}[3 - 2x_1(i)]$$

For up to 10 iterations:

| $i$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $x_1(i)$ | 0 | 0.60000 | 0.43334 | 0.50000 | 0.48148 | 0.48889 | 0.48683 | 0.48766 | 0.48743 | 0.48752 | 0.48749 |
| $x_2(i)$ | 0 | 0.33333 | 0.20000 | 0.23704 | 0.22222 | 0.22634 | 0.22469 | 0.22515 | 0.22496 | 0.22502 | 0.22500 |

$$\left|\frac{x_1(10) - x_1(9)}{x_1(9)}\right| = \left|\frac{0.48749 - 0.48752}{0.48749}\right| = 6.2 \times 10^{-5} < \varepsilon$$

and

$$\left|\frac{x_2(10) - x_2(9)}{x_2(9)}\right| = \left|\frac{0.22500 - 0.22502}{0.22502}\right| = 8.9 \times 10^{-5} < \varepsilon$$

# Power Flow Solution

The set of simultaneous non-linear equations are solved using either one of the following iterative techniques:

1. Gauss-Seidal iteration
2. Newton – Raphson technique
3. Fast Decoupled technique

Fast decoupled algorithm is the fastest solution technique.

Newton Raphson algorithm is more accurate and stable.

# CYMDIST Algorithm

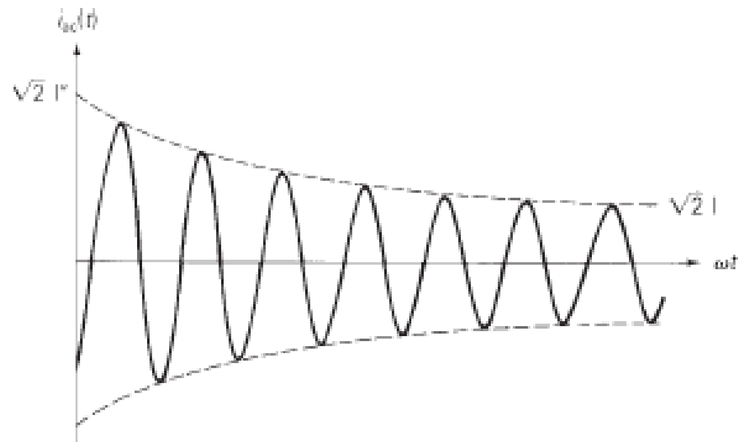
### 1.3.1 Voltage Drop Calculation Technique

The Load Flow analysis of a radial distribution feeder requires an iterative technique that is specifically designed and optimized for radial or weakly meshed systems. The Voltage Drop Analysis method includes a full three phase unbalanced algorithm that computes phase voltages (VA, VB and VC), power flows and currents including the neutral current.

The iterative Voltage Drop calculation technique will compute the voltages and power flows at every section within 10 or less iterations. The calculation returns the results when no calculated voltage on any section of the selected networks changes from one iteration to the next by more than the Calculation tolerance. Example: $|34465.2 - 34464.8|/34464.8 < 0.1\%$.

However, in some cases, the calculation may not converge to a solution which could either be due to bad data such as a very high impedance line or could be due to peculiar network configuration.

# Three Phase Short Circuit Current



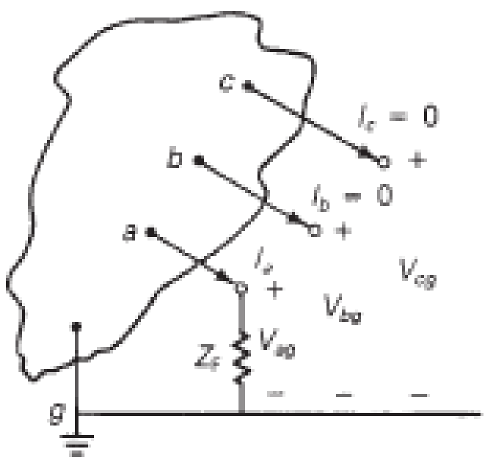

$X_d''$ = direct axis subtransient reactance

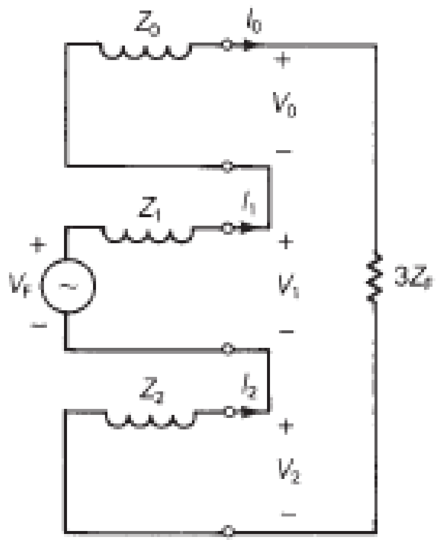
$X_d'$ = direct axis transient reactance

$X_d$ = direct axis synchronous reactance

$$I_{ac}(0) = \frac{E_g}{X_d''} = I''$$

## Line-to-Ground Fault Current




$$I_a = I_0 + I_1 + I_2 = 3I_1 = \frac{3V_F}{Z_0 + Z_1 + Z_2 + (3Z_F)}$$

$Z_1$ = Positive Sequence Impedance
$Z_2$ = Negative Sequence Impedance
$Z_0$ = Zero Sequence Impedance

# Performing and Reviewing Load Flow Studies

# Grid Impact Study Process

**Study Agreement**
- DISCO and the Project Developer signs Study Agreement
- The Developer provides all data required for Impact Study

**Data Review**
- DISCO reviews the submitted data
- DISCO obtains the missing data from the Developer

**Scoping Meeting**
- DISCO meets with the Developer and confirms the project details

**Perform Studies**
- DISCO performs Impact Study

**Issue Report**
- DISCO issues Impact Study Report and meets with the Developer

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## Required Data from Project Developer

- Plant size and interconnection location
- Plant one line diagram
- Manufacturer's data sheets for PV inverter / wind turbine
- Protection settings
- Dynamic models
- Generation profiles

## Steady State Analysis

- Base Case Setup
- Steady state voltage variation
- Reactive power capability and power factor
- Loading of network components
- Network losses
- Short Circuit Currents