# Distribution Systems with Distributed Generation

Operation and Planning of Power Distribution Systems
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# Distributed Generation (DG): Definition*

- The purpose of distributed generation is to provide a source of active electric power.
- The location of distributed generation is defined as the installation and operation of electric power generation units connected directly to the distribution network or connected to the network on the customer site of the meter.
- The term embedded distributed generations seems to be more appropriate to describe that the power output of the distributed generation source is only used locally.

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*Ackermann et al, Electric Power Systems Research, 57 (2001), 195–204

# Distributed Generation (DG): Types based on the source of the energy

- Non-renewable (Gas-turbine)
- Renewable
  - wind
  - solar,
  - hydro,
  - geothermal (earth heat),
  - biomass (waste material)

- The Energy resources of DG units are known as *distributed energy resources (DERs)*.

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# Distributed Generation: Types based on the capacity*

- Micro-distributed generation: 1 Watt to 5kW;
- Small distributed generation: 5 kW to 5 MW;
- Medium distributed generation: 5 MW to 50 MW;
- Large distributed generation: 50 MW to 300 MW

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# DG Integration into Power System

- A DG unit can be defined as stand-alone or grid-connected.
- A *stand-alone* unit provides for the greater part of the demand with or without other generators or storage.
- On the other hand, in *a grid-connected system*, a DG unit supplies power to a large interconnected network that is also supplied power by other generators.
- The connection point of Grid-connected DG is called the *point of common coupling* (*PCC*).

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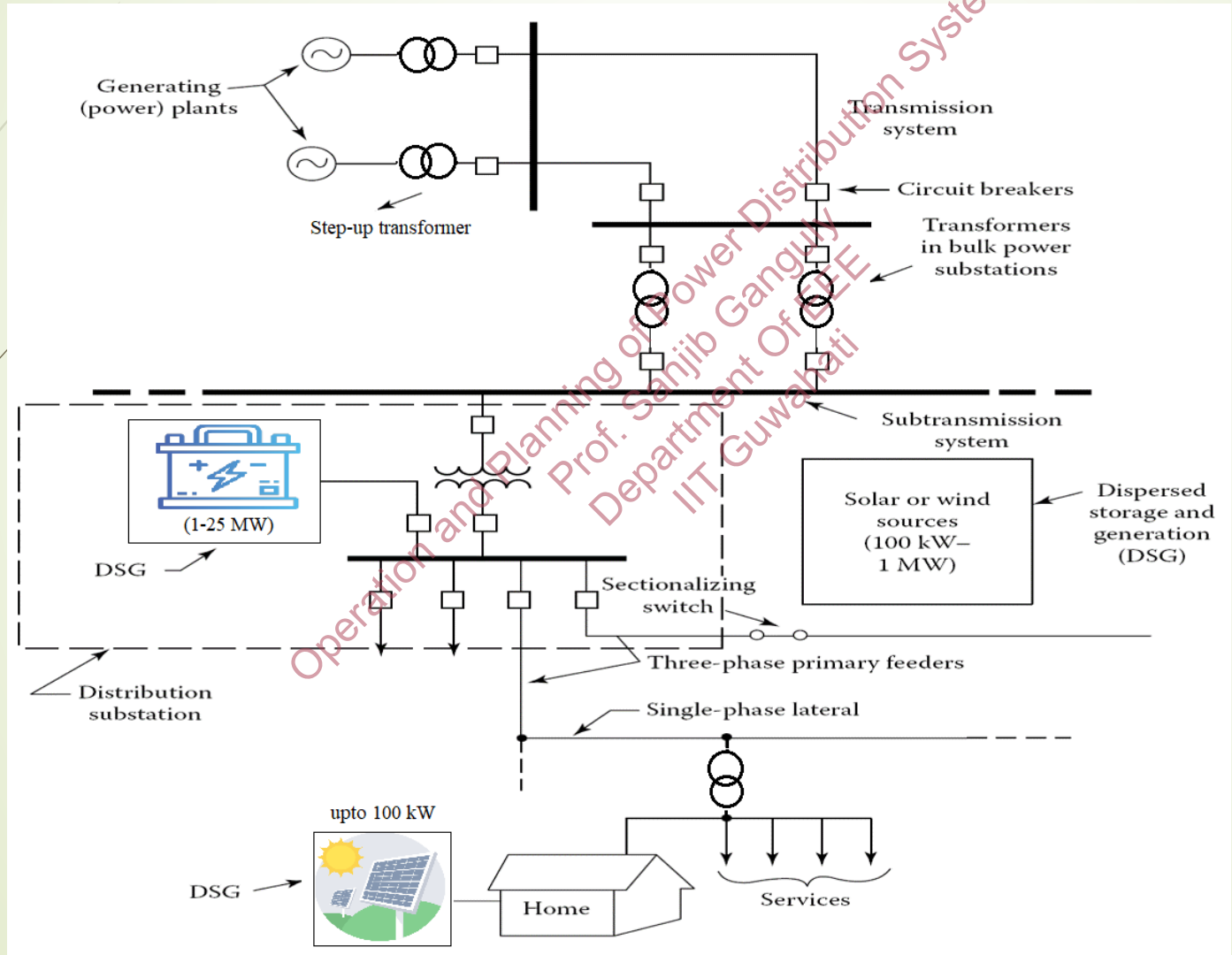
# A typical Power Network with DG Units

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*Ref. T. Gonen. Electric Power Distribution System Engineering*

# The techno-economic and environmental benefits of DG integration

- Reduction of environmental pollution and global warming concerns with the use of the nonconventional/renewable energy resources
- With the fast depletion of the fossil fuel reserves, the use of nonconventional/renewable energy resources is increasingly becoming a requirement.
- DERs are usually modular units of small capacity because of their lower energy density and dependence on geographical conditions of a region.
- The overall power quality and reliability improve due to contributions of the stand-alone and grid-connected operations of DERs.
- The overall plant energy efficiency increases and also associated thermal pollution of the environment decreases because of the use of the renewable DG such as cogeneration.

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# Transition of Passive to Active Distribution Networks: Differences

## Passive distribution networks

- There are no DERs
- The DERs capacity for the integration to the existing networks is limited.

## Active distribution networks

- Distributed management systems for advanced control and planning
- Ancillary services provision
- Possibility of Islanding mode of operation

*Nikos Hatziargiriou, Round table 'The Effect of Distributed Renewable Generation on Power Systems Security, Athens 13 April 2005*

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# Active Distribution Networks: Issues

1. Understanding the value of Technical benefits and economic benefits such as,
   - Enhanced security
   - Reduction in investment cost
   - Reduction in operating costs
2. Identifying the new control techniques
   - Network reconfiguration
   - Coordination of operation of network control facilities

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# Transition of Passive to Active Distribution Networks: Changes required

- Adaptive protection and control
- Wide-area active control
- Advanced sensors and measurements
- Network management apparatus
- Real-time network simulation
- Distributive penetrating communication network
- Knowledge and data extraction by intelligent methods
- New and modern design of transmission and distribution systems

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# Renewable energy penetration

- The proportion of electric energy or power being supplied from wind turbines or from other renewable energy sources is usually referred to as the penetration. It is usually given in percentage. The average penetration is defined by the following equation;

$$\text{Average penetration} = \frac{\text{Annual energy from renewable generators (kWh)}}{\text{Total annual energy delivered to loads (kWh)}}$$

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# Renewable energy *instantaneous* penetration

- However, for other purposes, including system control, the following definition is used:

$$\text{Instantaneous penetration} = \frac{\text{Power from renewable generators (kW)}}{\text{Total power delivered to loads (kW)}}$$

In general, the maximum instantaneous penetration is much greater than the average penetration.

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# Types of DG units

- DG provides both active and reactive power to the system, i.e., DG unit operating at lagging power factor, for example synchronous generator
- DG provides active power, but consumes reactive power from the system, i.e., DG operating at leading power factor, for example induction generator
- DG operating at unit power factor, i.e., supplying only active power
- DG operating at the voltage controlled mode, i.e., with a fixed magnitude

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# DG Integration Capabilities

- Plug and Play
- Supporting active/reactive powers
- Improving power quality
- Fault Ride Through

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# Simulation of DG integration into distribution networks: Steps

- Firstly, identify the location (node), at which a DG unit is to be placed.
- Find out the DG power (both active and reactive)
- If the DG unit is operating at a lagging p.f., subtract the active and reactive power from the active and reactive power demand at this location.
- If the DG unit is operating at a leading p.f., subtract the active power from the active demand and add the reactive power from the reactive power demand at this location.
- If the DG unit is operating at voltage controlled mode, consider it as voltage controlled bus.

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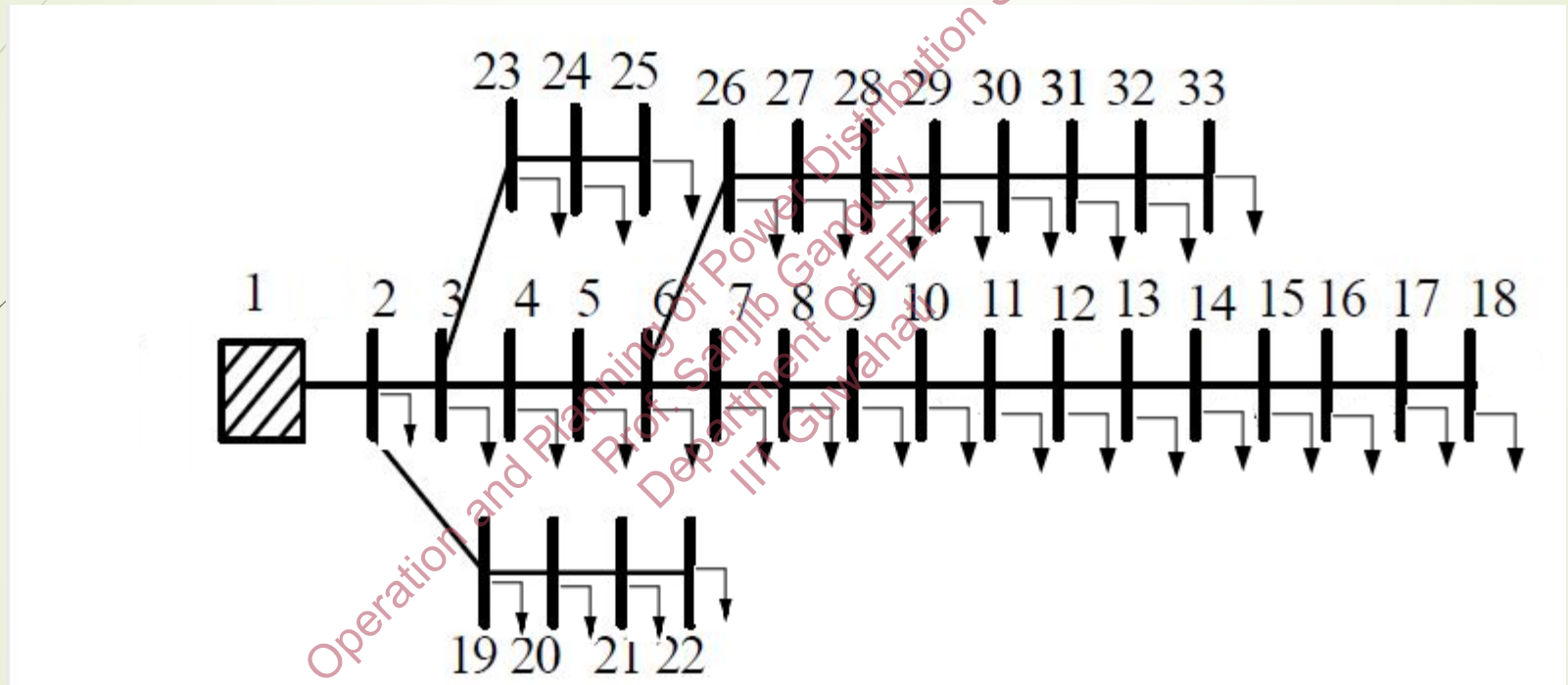
# 33-bus radial distribution network

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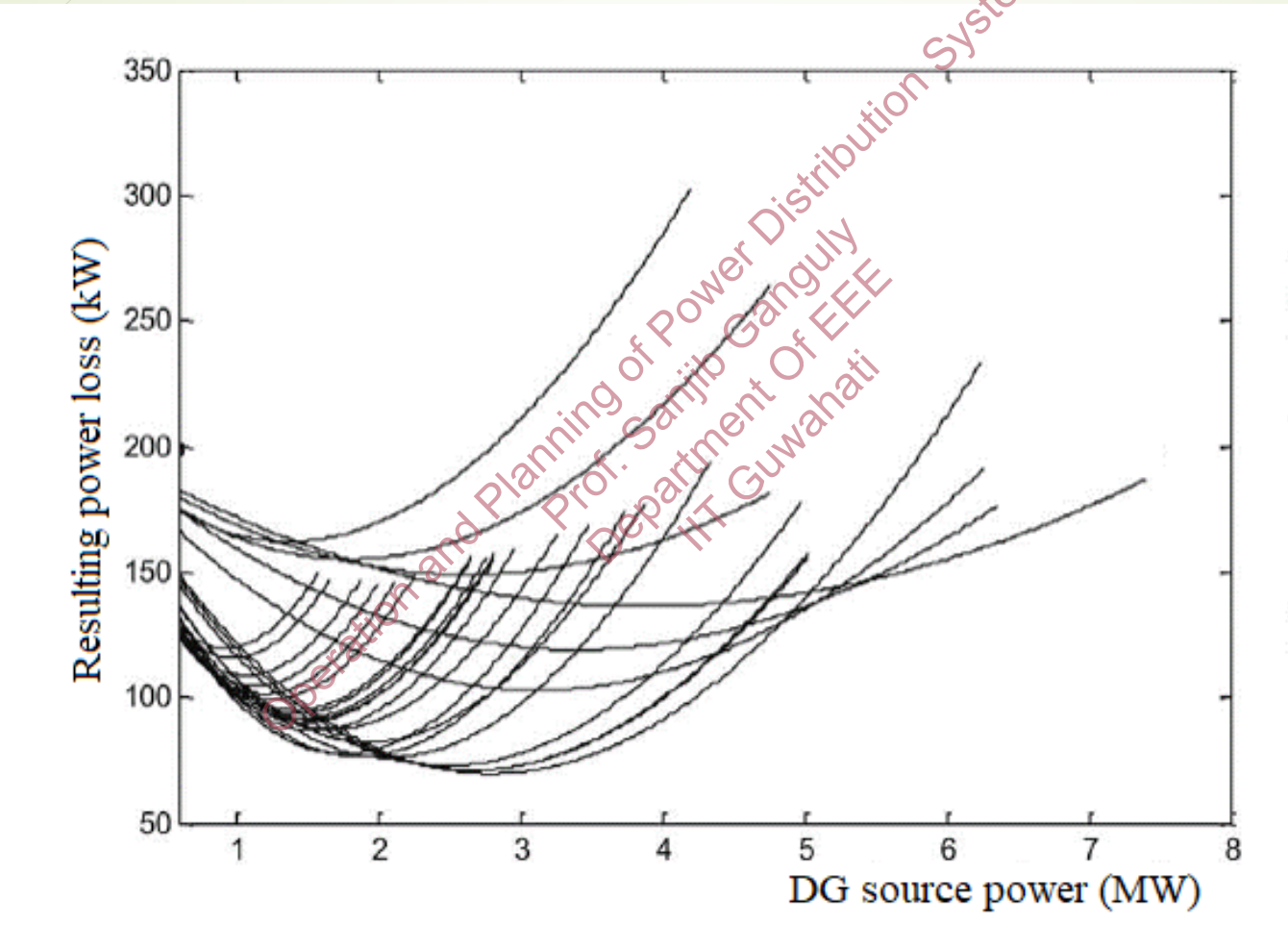
# Effect of DG integration on power loss of distribution networks

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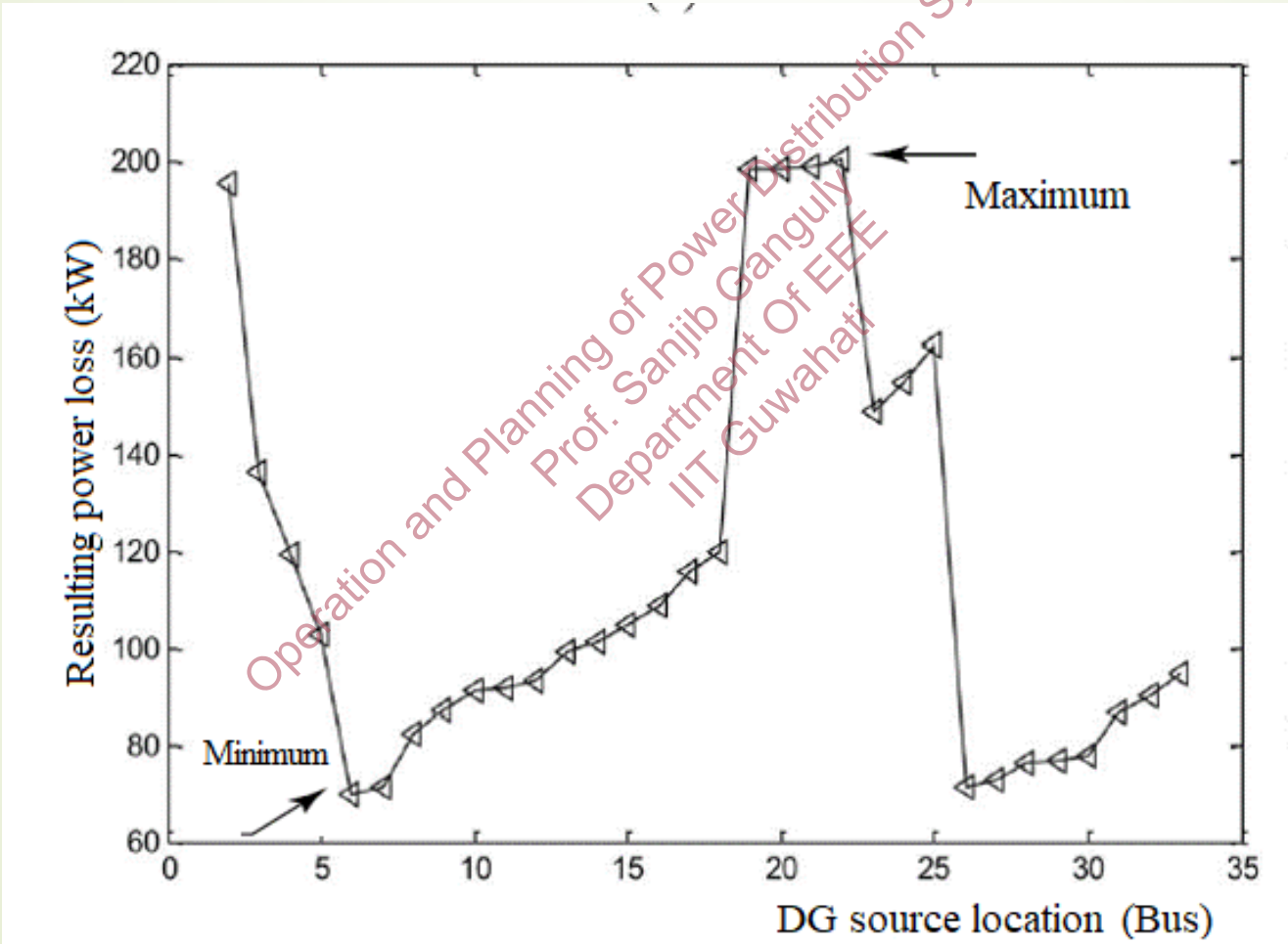
Results of the exhaustive search obtained with the 33-node system:

***S. Ganguly***, *D. Samajpati, "Distributed generation allocation on radial distribution networks under uncertainties of load and generation using genetic algorithm," IEEE Trans. Sustainable Energy, vol. 6, no. 3, pp. 688–697, 2015.*

# Effect of DG integration on power loss of distribution networks

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# Rating of DG integration on power loss of distribution networks

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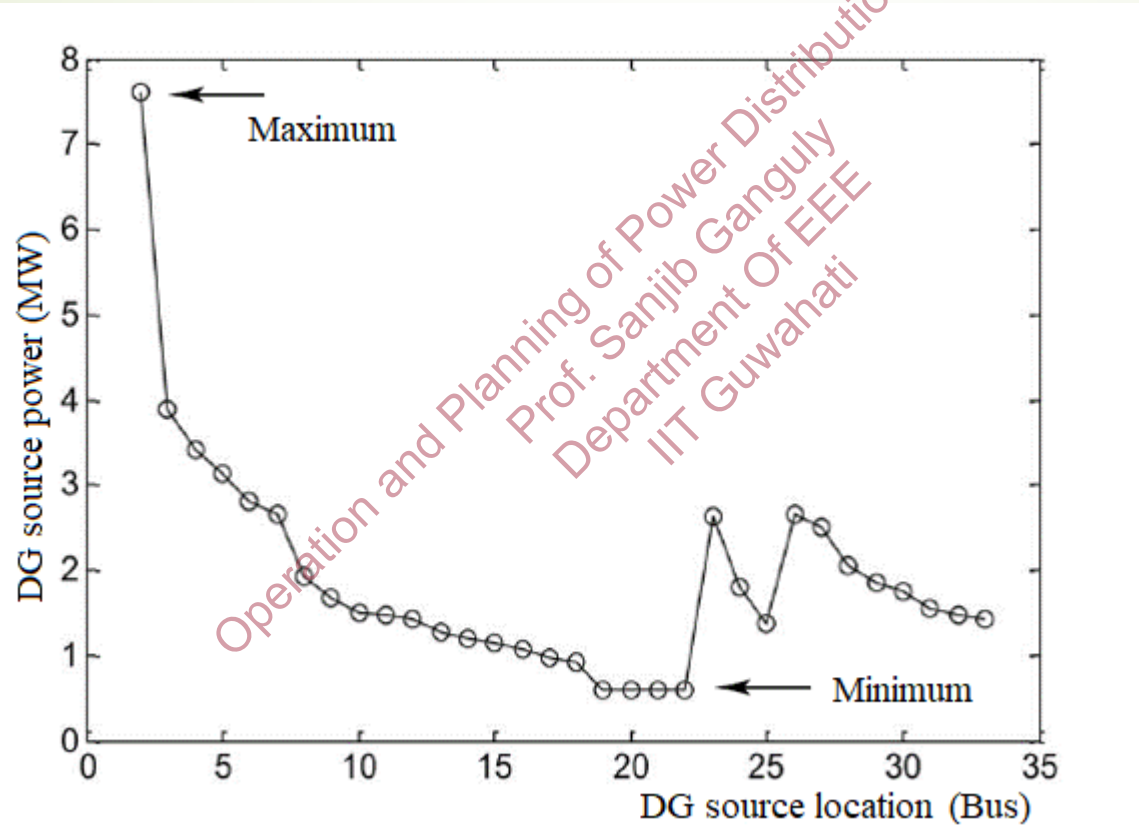


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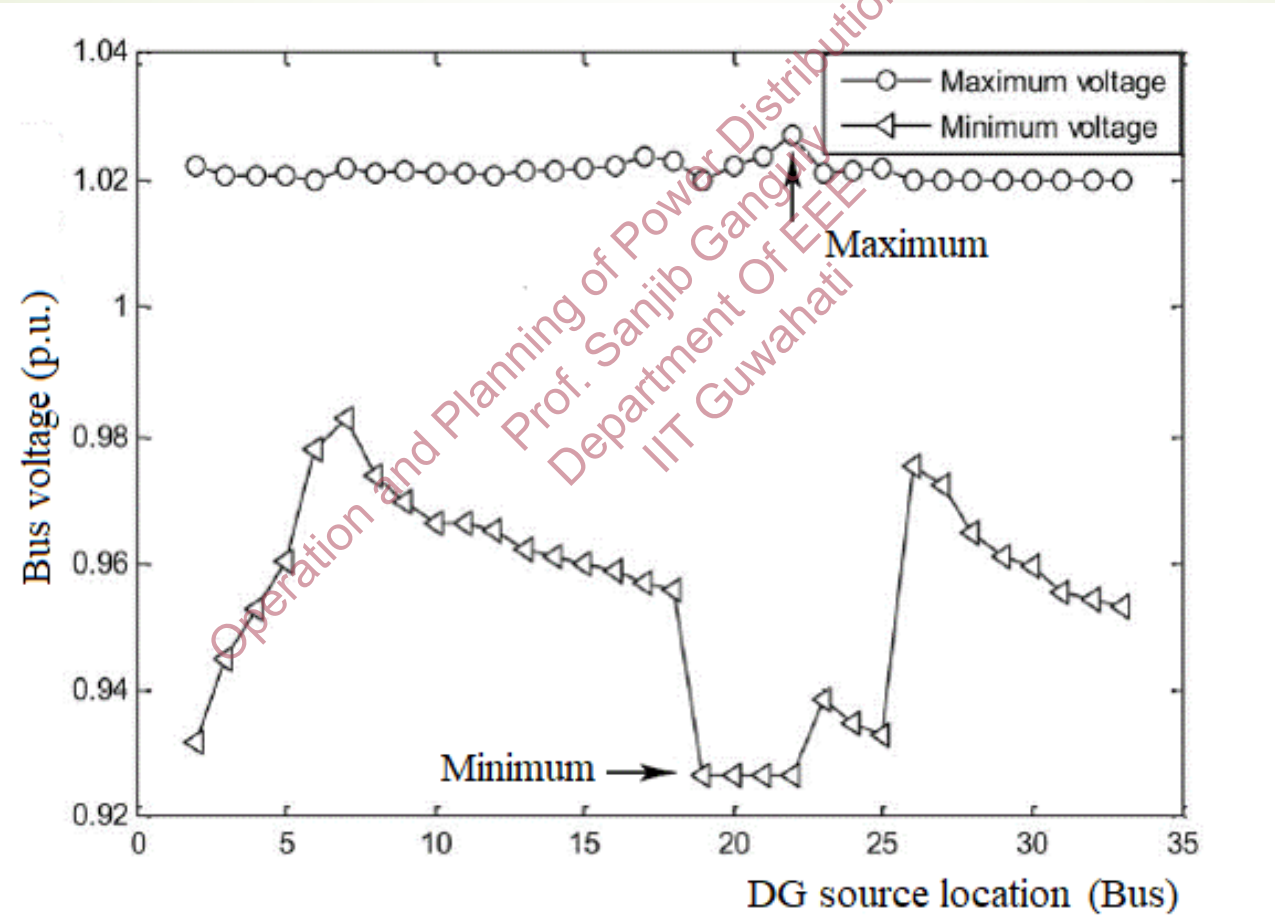
# Effect of DG integration on node voltage of distribution networks

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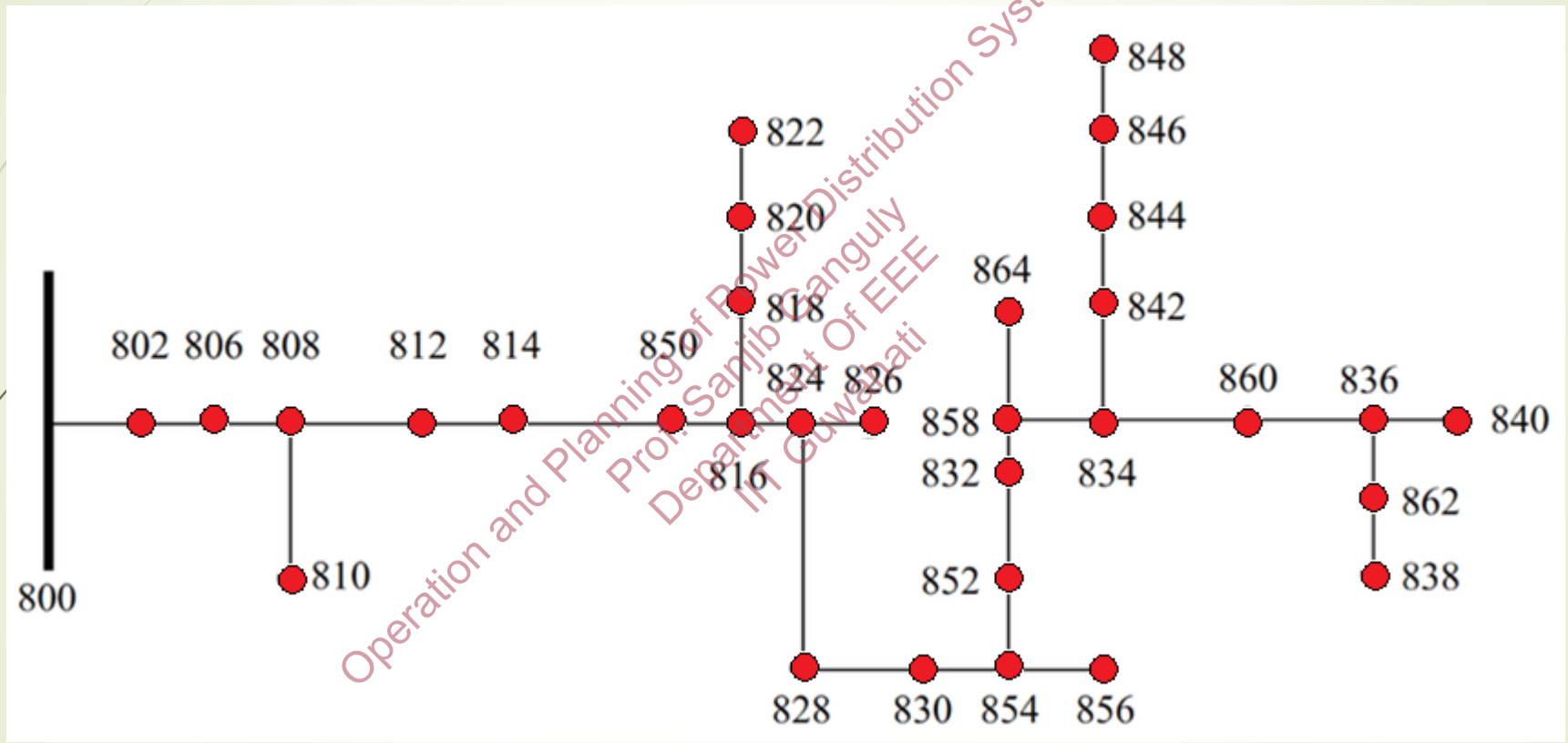
# IEEE 34 bus system

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*Pokharel, P., & Poudel, L. (2019). Impact of Distributed Generation in Distribution Network Losses and Voltage Profile. International Journal of Engineering and Applied Sciences (IJEAS).*

# Power loss with and without DG integration



| Injected power (kW) | Losses | |
|---|---|---|
| | kW | KVAr |
| None | 270 | 550 |
| 10% at bus 890 | 190 | 410 |
| 20% at bus 890 | 140 | 310 |
| 10% at bus 890 | 220 | 460 |
| 20% at bus 890 | 180 | 390 |

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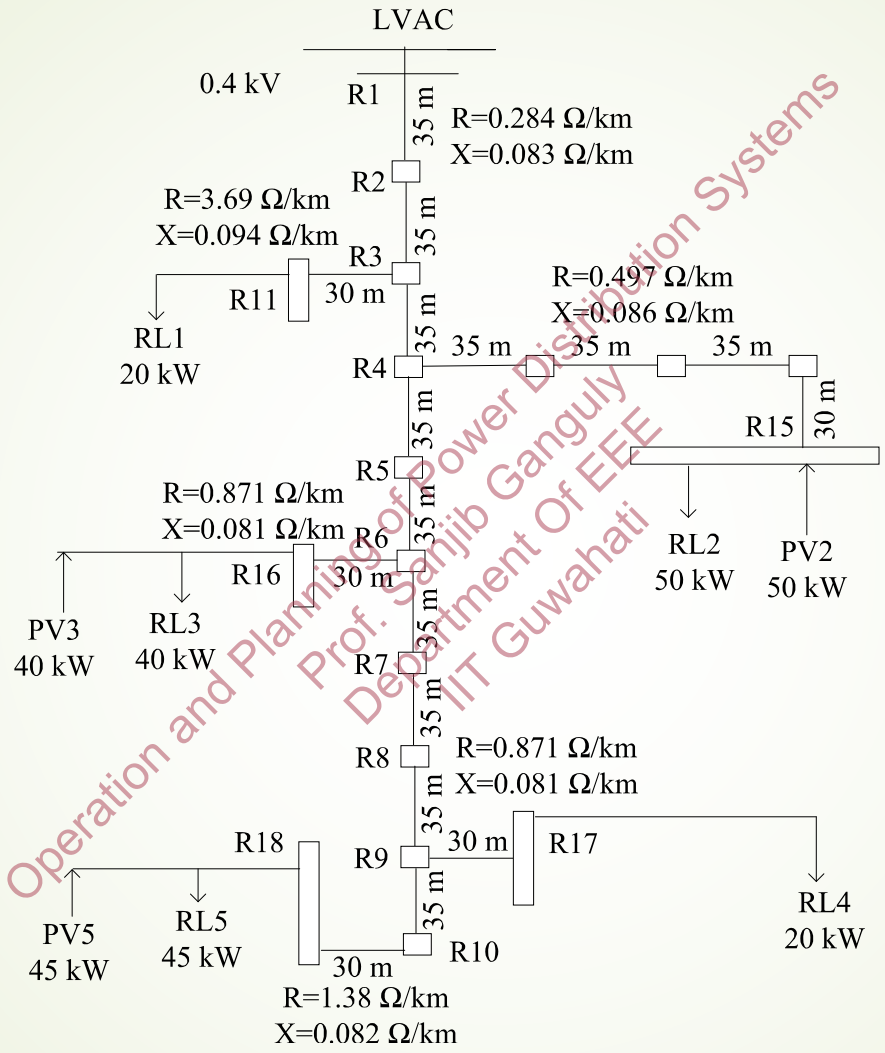
# CIGRE residential network



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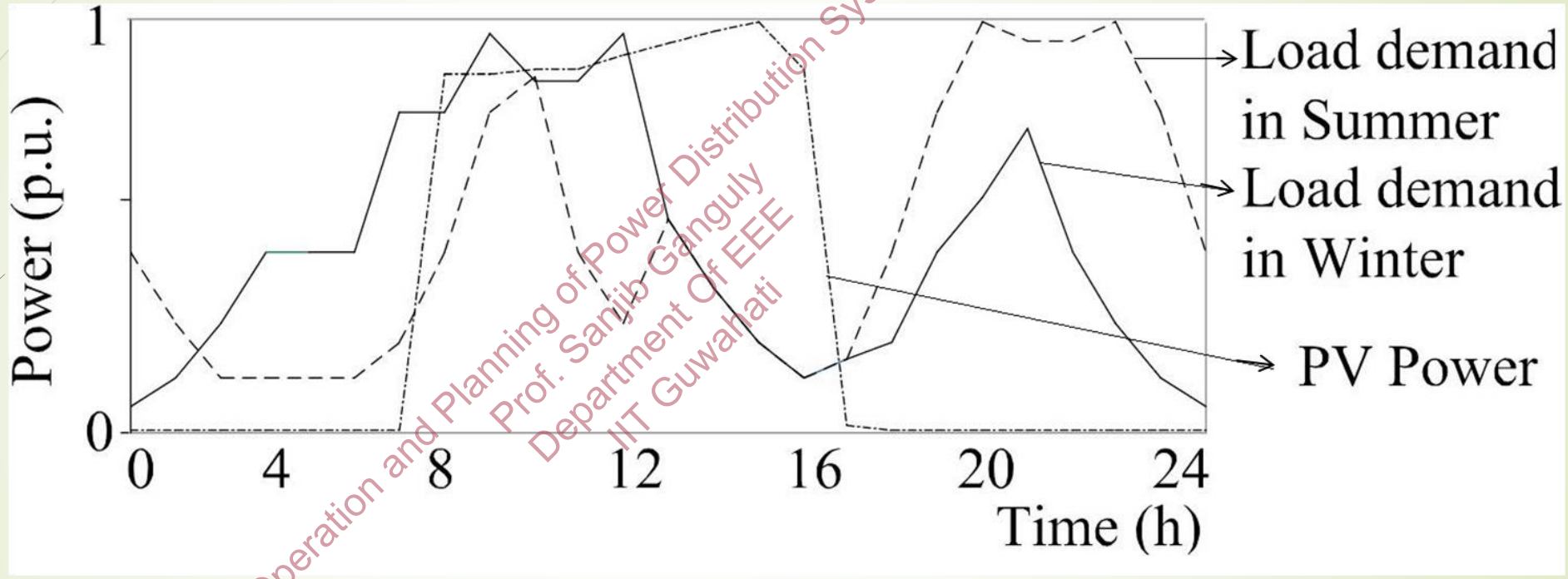
*Manojkumar, Rampelli; Kumar, Chandan; Ganguly, Sanjib; Gooi, Hoay Beng; Mekhilef, Saad: 'Voltage control using smart transformer via dynamic optimal setpoints and limit tolerance in a residential distribution network with PV sources', IET Generation, Transmission & Distribution, 2020, 14, (22), p. 5143-5151*

# Load and PV power profiles

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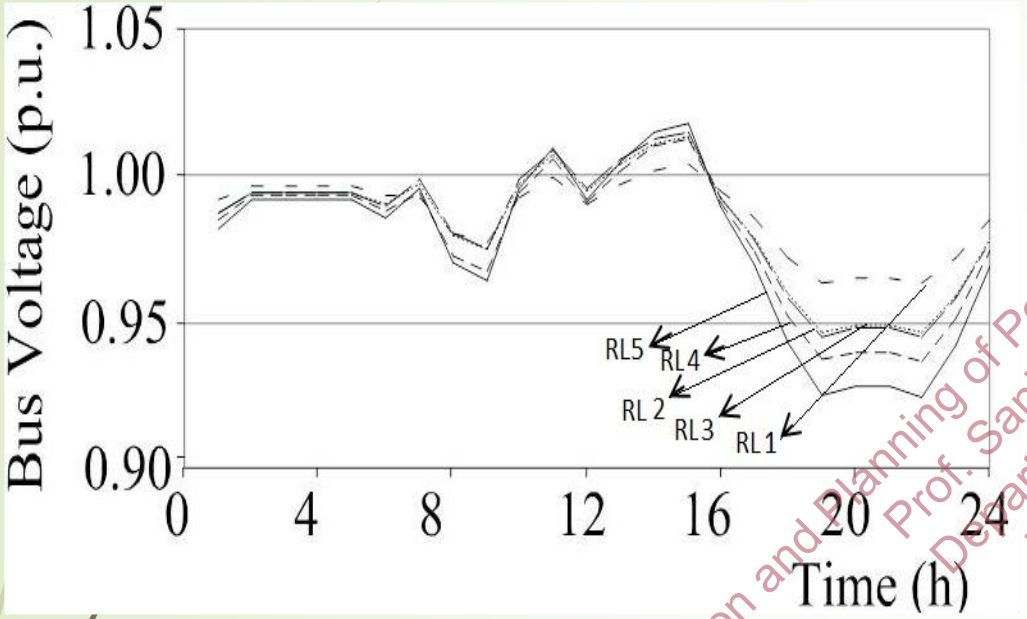
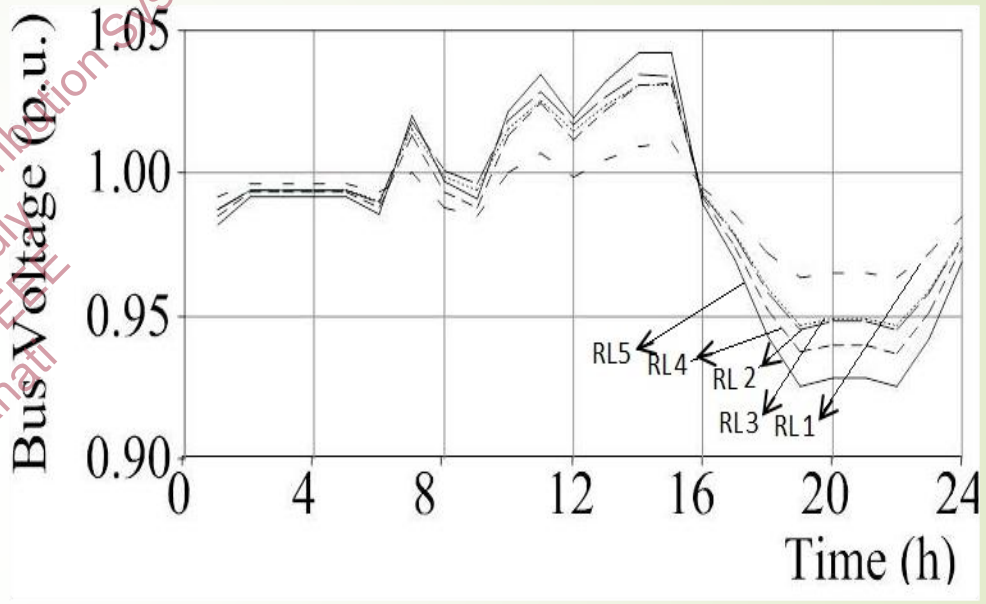
# Load voltage profile in summer




50% penetration level




100% penetration level

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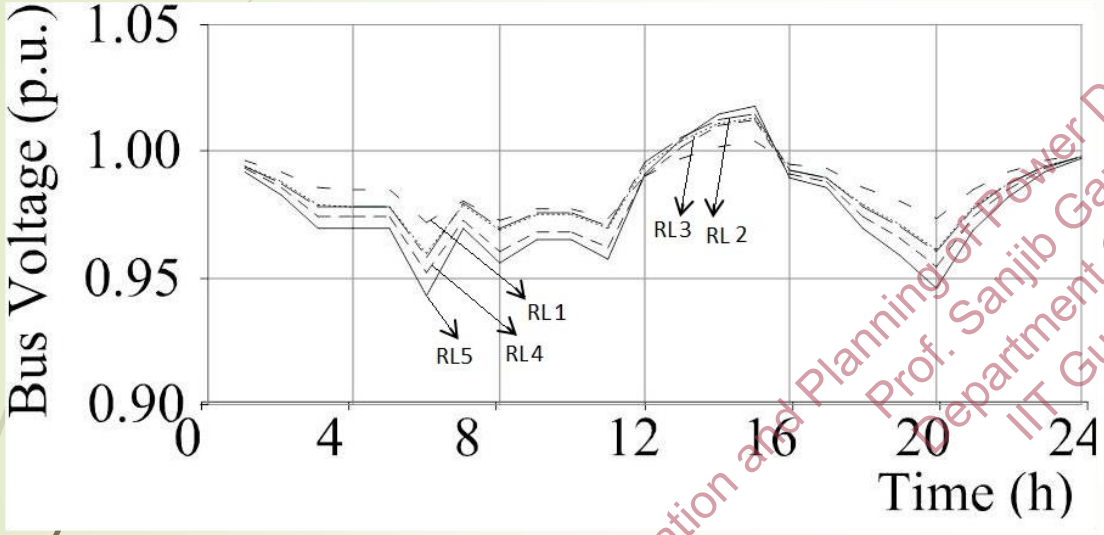
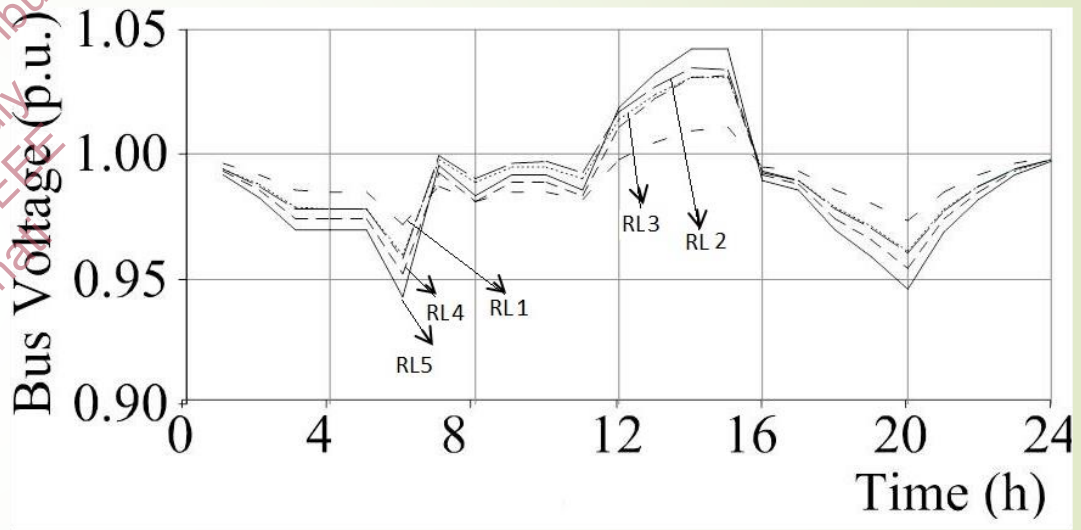
# Load voltage profile in winter




50% penetration level




100% penetration level

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# Concept of Micro-Grid

- A microgrid is basically an active distribution network and is made up of a collection of DG systems and various loads at distribution voltage level.
- They are generally small low-voltage combined heat loads of a small community.
- The examples of such small community include university or school campuses, a commercial area, an industrial site, a municipal region or a trade center, a housing estate, or a suburban locality.
- They can be connected to the main grid or can be operated in islanded mode.

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# Difference of microgrid with the conventional power network

- 1. Power generated at distribution voltage level and can thus be directly provided to the utility's distribution system.
- 2. They are of much smaller capacity with respect to the large generators in conventional power plants.
- 3. They are usually installed closer to the customers' locations so that the electric/heat loads can be efficiently served with proper voltage level and frequency and ignorable line losses.
- 4. They are ideal for providing electric power to remote locations.

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# Difference of microgrid with the conventional power network

- 5. The fundamental advantage of microgrids to a power grid is that they can be treated as a controlled entity within the power system.
- 6. The fundamental advantage of microgrids to customers is that they meet the electric/heat requirements locally. This means that they can receive uninterruptable power, reduced feeder losses, improved local reliability, and local voltage support.
- 7. The fundamental advantage to the environment is that they reduce environmental pollution and global warming by utilizing low-carbon technology.

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# Benefits of microgrid operation



- Improved energy efficiency
- Reduced environmental concerns and pollution
- Improving power utility and reliability
- Improved voltage control
- Line loss reduction etc,.

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N. Hziargiriou, G. Strbac, 'Microgrids-A Possible Future Energy Configuration', IEA Workshop 'Distributed Generation: Key issues, Challenges, Roles, Paris, 1st March 2004

# Benefits of microgrid operation

- Reducing some operational and investment issues
- Increasing cost savings
- Solving market issues
- More awareness of customers about energy
- Increased quality of service
- Reduced impact of outages

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# Concerns on microgrid deployment

- The establishment of standards and regulations for operating the microgrids in synchronism with the power utility
- Low energy content of the fuels involved
- The climate-dependent nature of the production of the DERs.
- Availability of communication infrastructure

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# Concerns on microgrid deployment

- Load and generation imbalance
- Application and control of more power electronics converters
- Multiple energy sources management
- Safety and protection

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# Concerns on microgrid deployment

- Efficient and secure power delivery  market schemes
- Congestion management methods
- New ownership and energy providers structures
- Restructuring roles and responsibilities of DISCOMs, other energy provides and consumers

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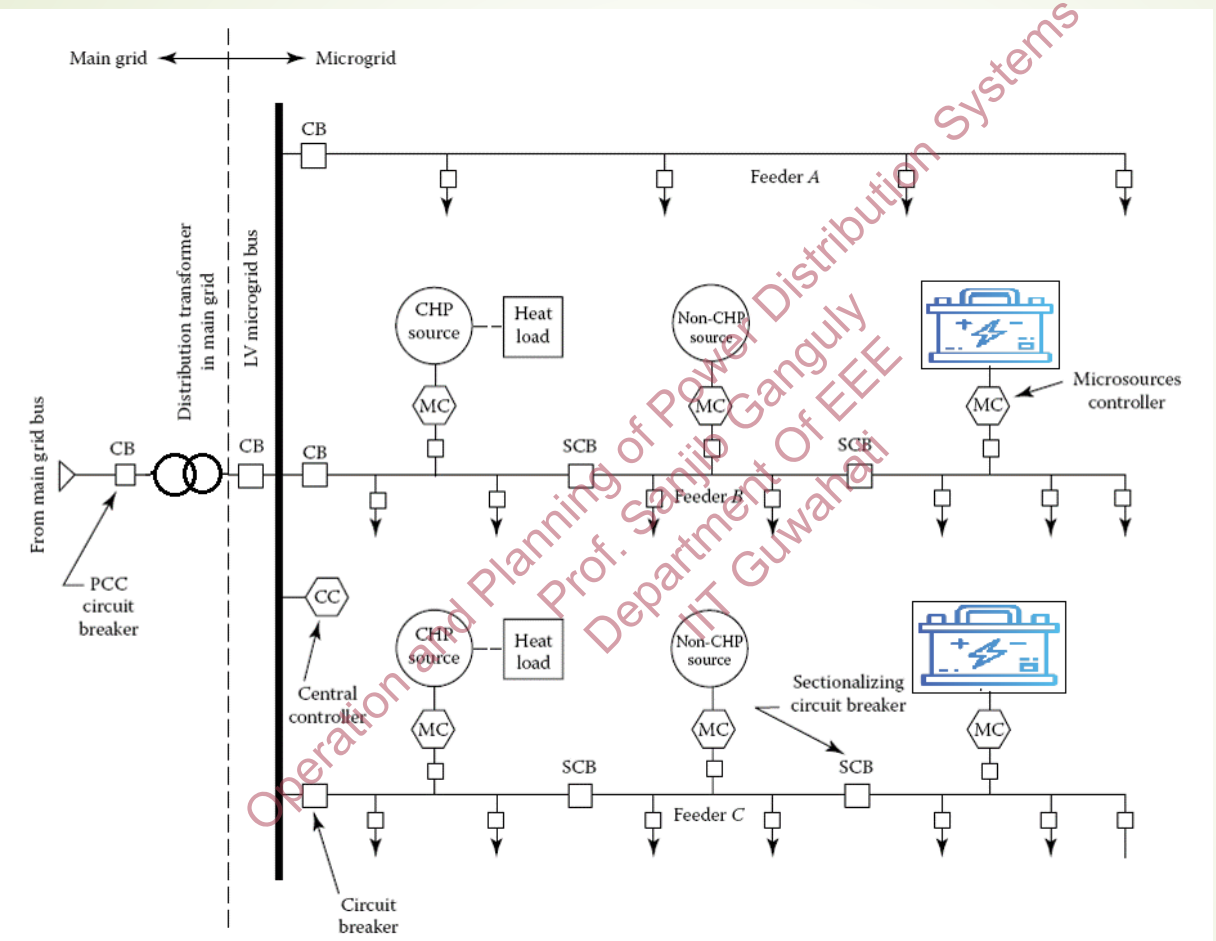
# A typical microgrid structure



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Chowdhury, S.; Chowdhury, S.P.; Crossley, P. Microgrids and Active Distribution Networks; Institution of Engineering and Technology: London, UK, 2009.

# Microgrid operation

- The microgrid has two modes of operations: (1) grid-connected and (2) stand-alone/island mode.

Grid-connected mode:

- The microgrid is connected to main grid
- Imports or exports power from or to the main grid.

Stand-alone or island mode:

- In the event of any disturbance in the main grid, the microgrid switches over to stand-alone mode but still supply power to the priority loads.
- This is achieved by opening the necessary circuit breakers. But feeder A will be left alone so that it can ride through the disturbance.

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# Microgrid Components

- Small DG sources and storage devices
- LV network
- Central Controller (CC)
- Micro Source Controller (MC)
- Load Controller (LC)

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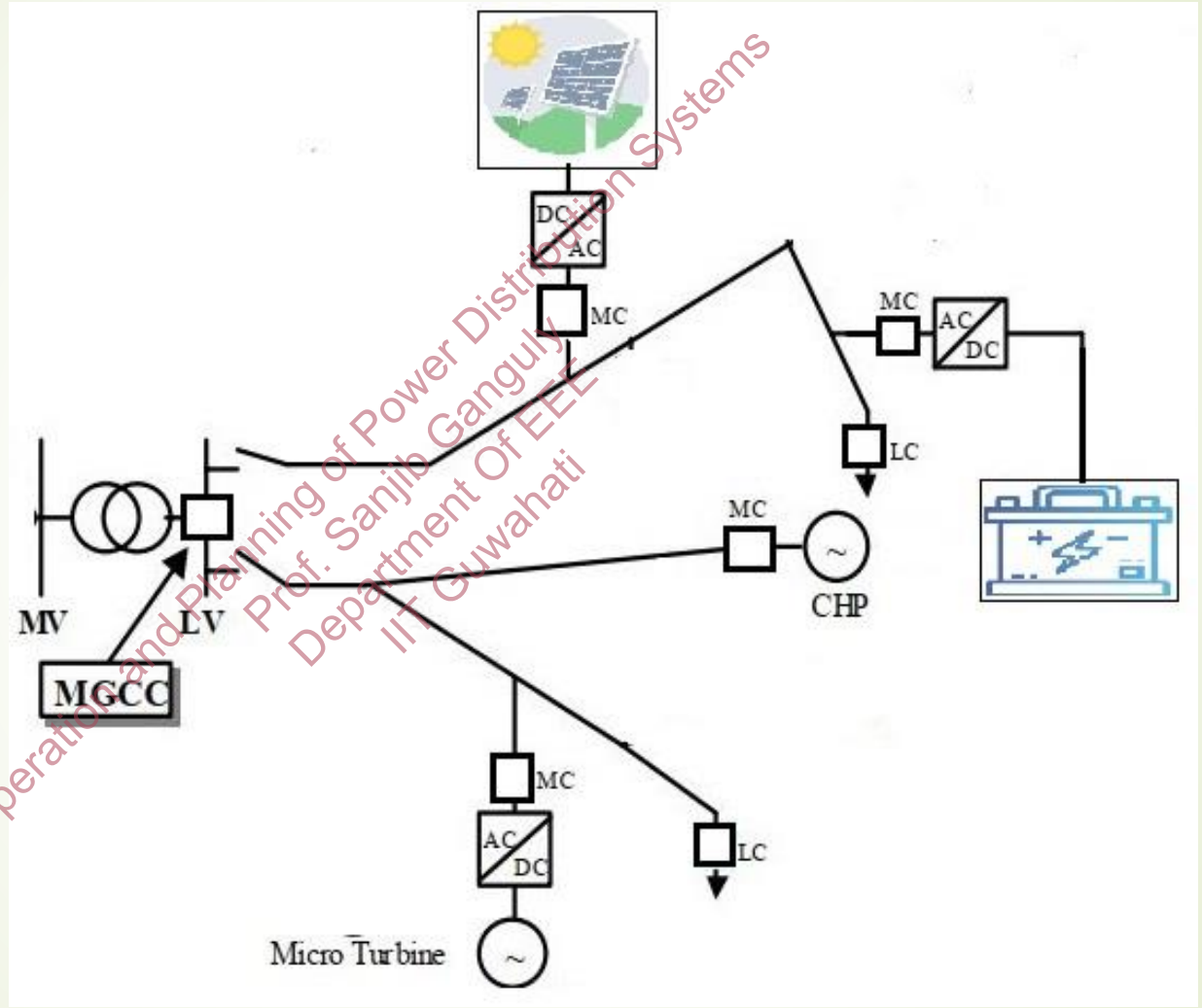
J.A. Pecas Lopes, J. Tome Saraiva, N. Hziargiriou, N. Jenkins, 'Management of Microgrids', invited to IJECC 2003, Bilbao, Spain

# Microgrid Example



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J.A. Pecas Lopes, J. Tome Saraiva, N. Hziargiriou, N. Jenkins, 'Management of Microgrids', invited to IJECC 2003, Bilbao, Spain

# Central Controller

- The main functions of central controller (CC) include *energy management module* (EMM) and *protection coordination module* (PCM).
- The EMM supplies the set points for active and reactive power output, voltage, and frequency to each MC and LC to promote technical and economical operation.
- This is done by advanced communication and artificial intelligent techniques
- The PCM supervises to microgrid and main grid faults and loss of grid situations so that proper protection coordination of the microgrid is achieved.

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# The functions of the CC in the grid-connected mode

- 1. Monitoring system diagnostics by gathering information from the microsources and loads
- 2. Performing state estimation and security assessment evaluation, economic generation scheduling and active and reactive power control of the microsources, and demand-side management functions by employing collected information
- 3. Ensuring synchronized operation with the main grid maintaining the power exchange at priori contract points.

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# The functions of the CC in the stand-alone mode

- 1. Performing active and reactive power control of the microsources to keep stable voltage and frequency at load ends
- 2. Adapting load interruption/load-shedding strategies using demand-side management with storage device support for maintaining power balance and bus voltage
- 3. Beginning a local "cold start" to ensure improved reliability and continuity of service
- 4. Switching over the microgrid to grid-connected mode after main grid supply is restored without hindering the stability of either grid

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# Micro source controller and load controller

- Set points input from CC
- Active/reactive generation control of micro sources for energy management applications such as voltage control, and economic operation of the system etc,.
- Interruptible loads control for voltage control or economical operation of the system

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# Wind energy conversion system: Advantages

- It is one of the lowest-cost renewable energy technologies that exist today.
- It is available as a domestic source of energy in many countries worldwide.
- It is energized by naturally flowing wind; thus, it is a clean source of energy. It does not pollute the air and cause greenhouse gases.
- It can also be built on farms or ranches and hence can provide the economy in rural areas using only a small fraction of the land.

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# Wind energy conversion system: Disadvantages

- The main challenge to using wind as a source of power is that the wind is intermittent and it may not provide required generation when electricity is needed.
- Although the cost of wind power has come down substantially in the past 10 years, the technology requires a higher initial investment than the solutions using fossil fuels.
- It is often that good sites are located in remote locations. Thus, the cost of transmission to the grid becomes expensive.
- There may be some concerns over the noise generated by the rotor blades.

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# Wind energy conversion system: Different types of wind turbines

- Wind turbines turn the kinetic energy of the moving air into electric power or mechanical work.
- There are various types of wind energy conversion systems. They can be classified as:
  - (1) horizontal-axis converters,
  - (2) vertical-axis converters,
  - (3) upstream power stations.

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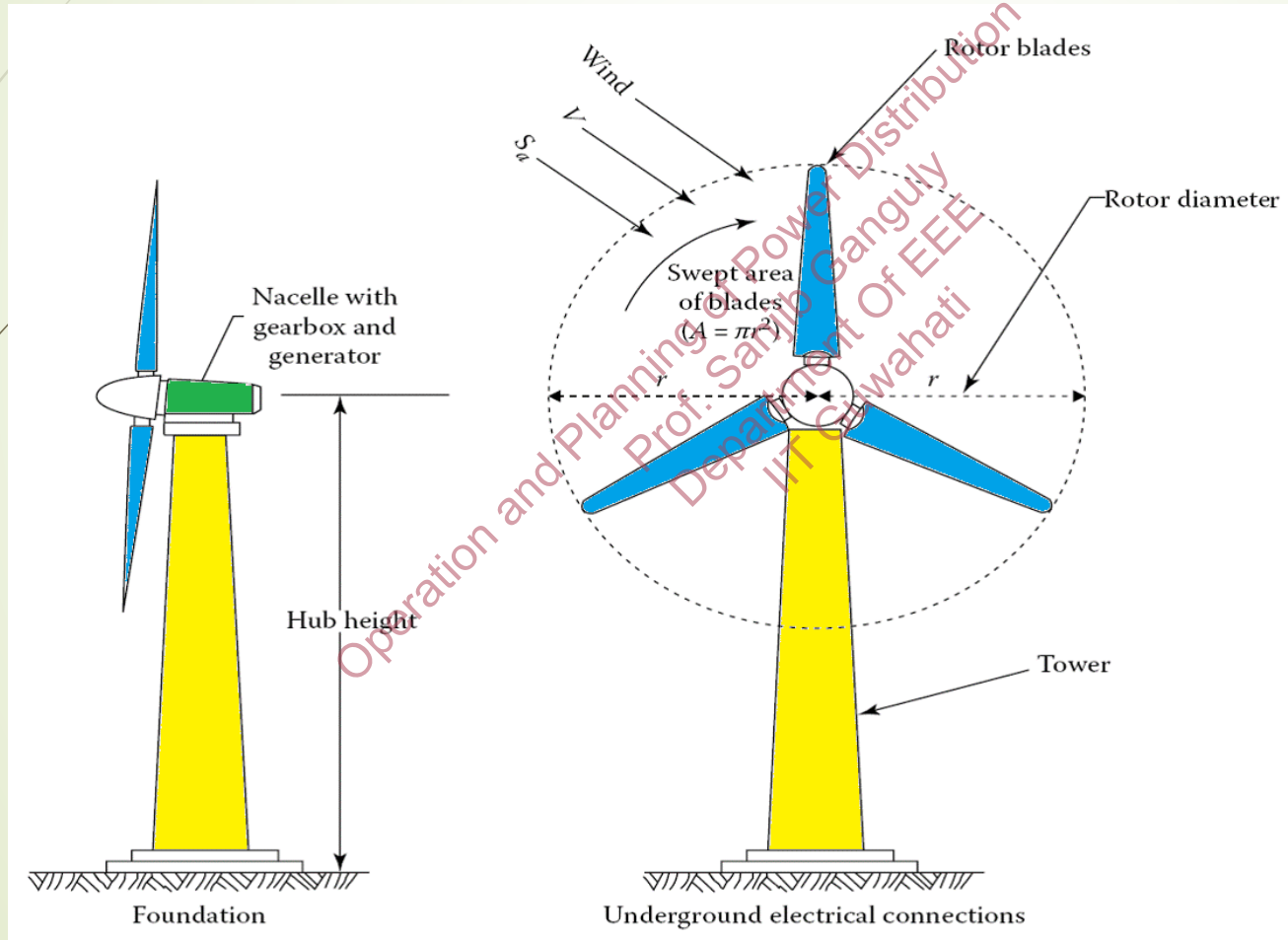
# Wind energy conversion system: Horizontal axis wind turbine

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The wind velocity increases substantially with height; as a result, the horizontal-axis wheels on towers are more economical.

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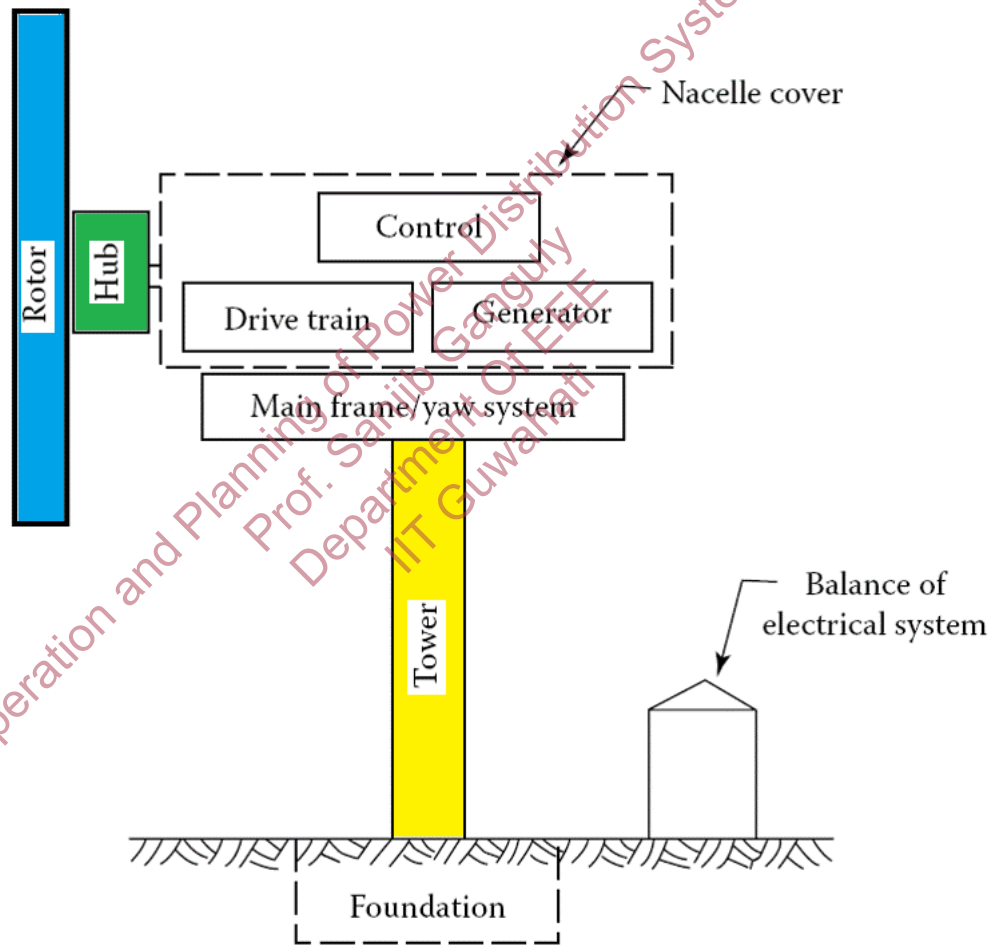
# Horizontal axis wind turbine




Major components of a horizontal-axis wind turbine.

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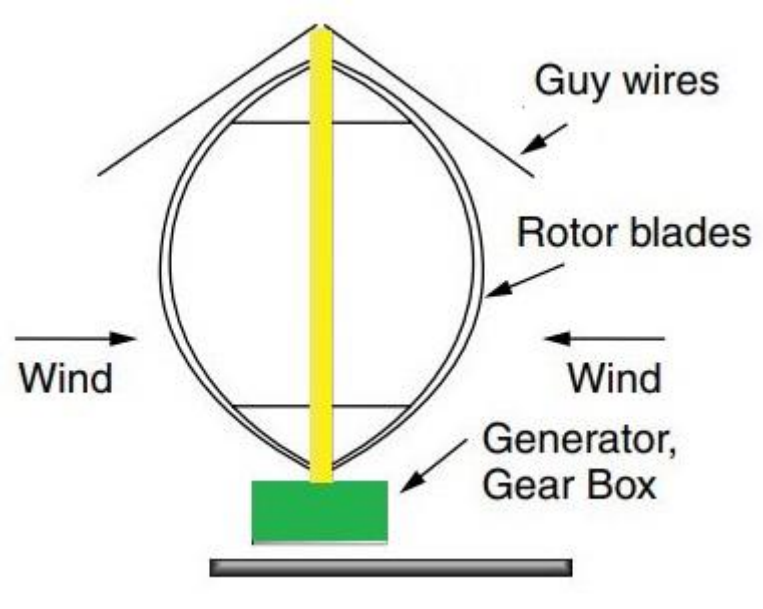
# Vertical axis wind turbine

- Wind flow through vertical blades produces rotation.
- Yaw control is not required
- Generator and gear box are located on the ground
- Tower need not be as strong as that for a horizontal axis wind turbine.
- Blades are near to ground surface where wind-speed is less

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# Wind energy conversion system: Types of Generator used

- There are three types of electrical machines that can convert mechanical power into electric power. They are:
  - the direct current (dc) generator
  - the synchronous alternator
  - the induction generator

- In the past, the shunt-wound dc generators were commonly used in small battery charging wind turbines.

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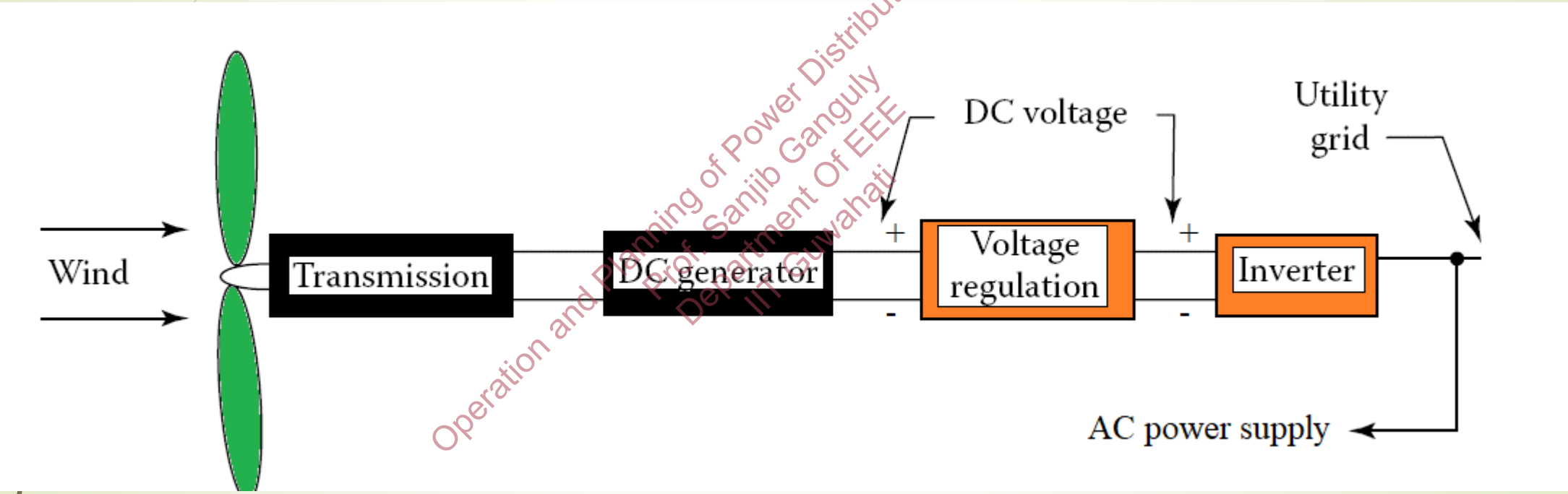
# Wind energy conversion system: DC Generator

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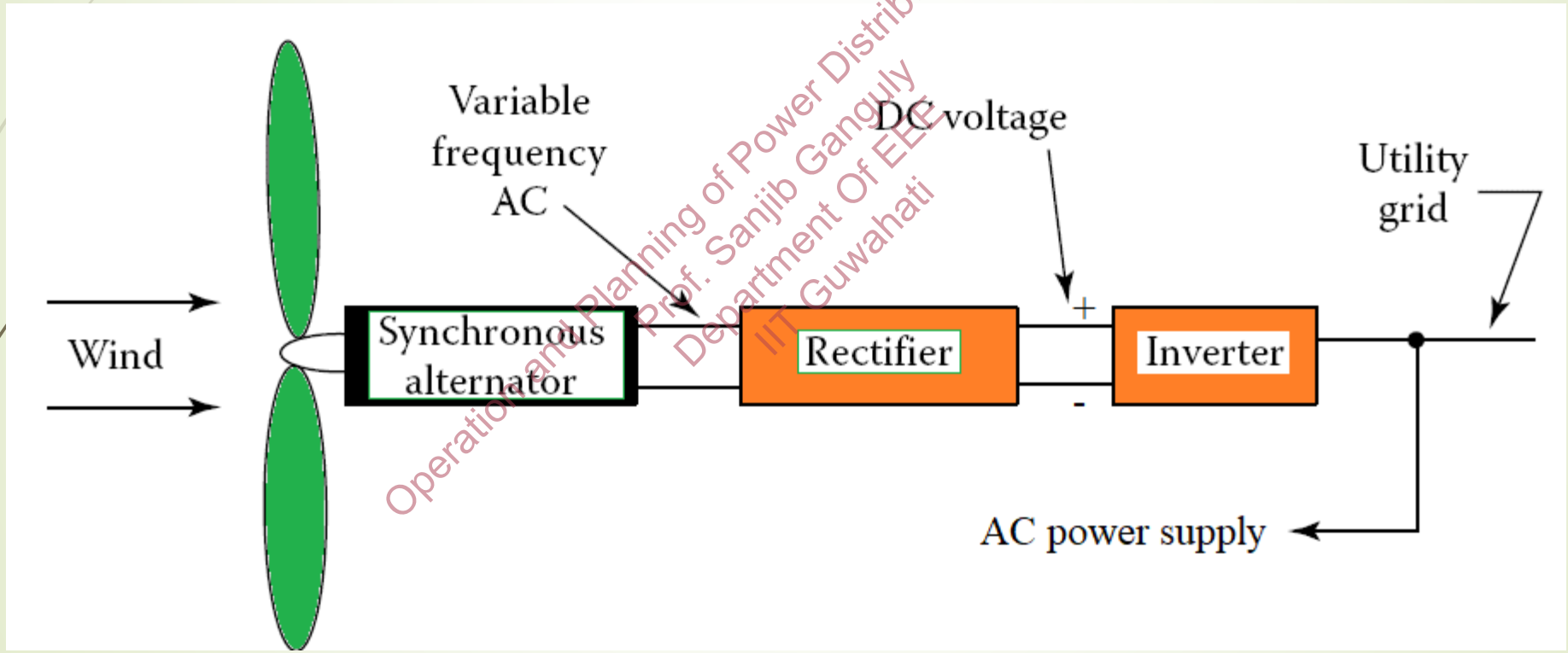
The dc generators of this type are seldom used today because of high costs and maintenance requirements (due to the commutators).

# Wind energy conversion system: Synchronous Generator

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# Wind energy conversion system: Synchronous Generator

- Permanent magnet generators are used in most small wind turbine generators, up to at least 10 kW.
- Permanent magnets provide the magnetic field. Hence, there is no need for field windings, or supply current to the field, nor there is any need for commutators, slip rings, or brushes.
- The permanent magnet generator is quite rugged, since the machine construction is so simple.
- Their operating principles are similar to that of synchronous machines, with the exception that they are run asynchronously.
- The power produced by the generator is initially variable voltage and frequency ac. This ac variable voltage is often rectified immediately to dc. The resultant dc power then either directed to dc loads or battery storage, or else it is inverted to ac with a fixed frequency and voltage.

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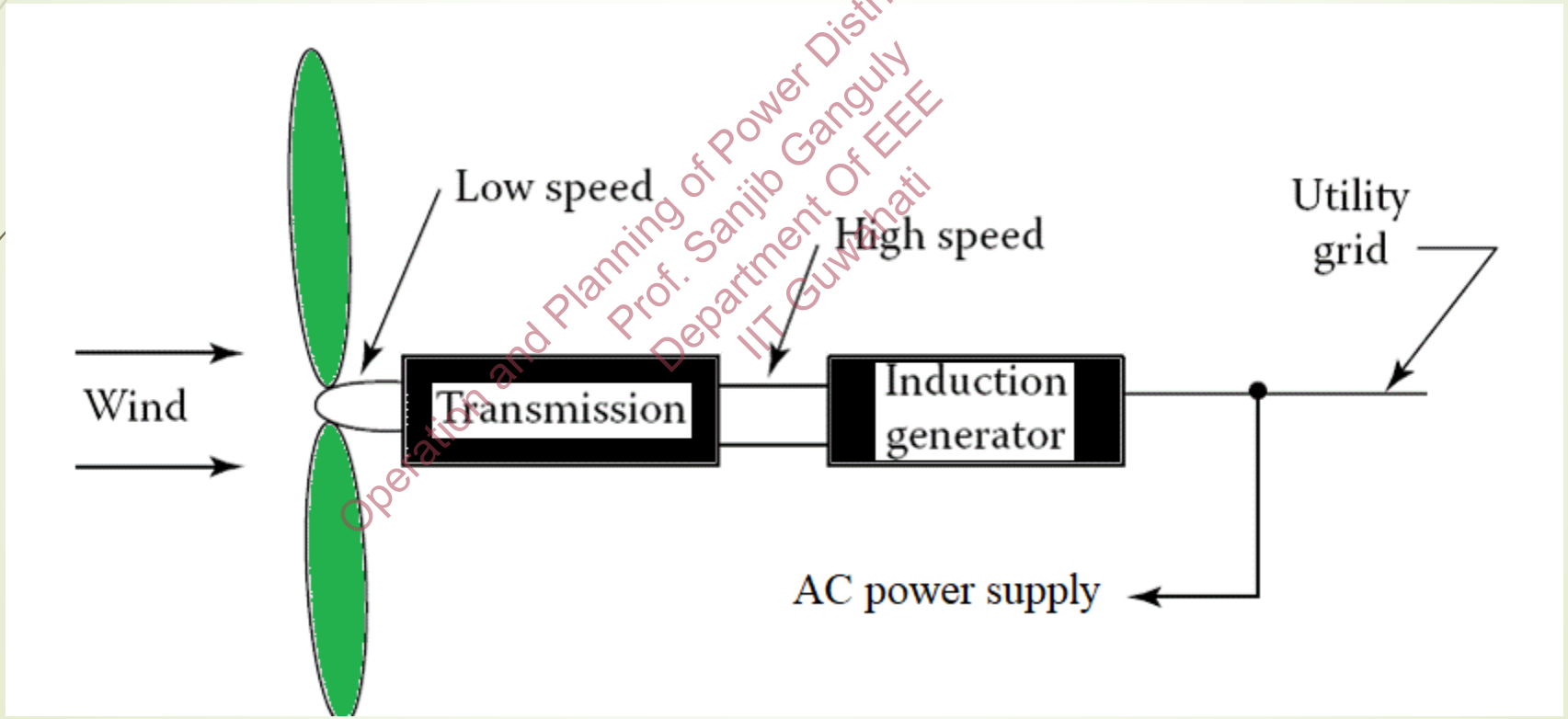
# Wind energy conversion system: Induction Generator

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# Wind energy conversion system: Induction Generator

- The induction generator is well suited for a wind energy system provided that utility power is available.
- But in order for the induction machine to operate as a generator, a separate source of reactive power is necessary to excite the machine.
- The induction generator must be driven slightly faster than synchronous speed. However, it is not necessary for the speed to be constant, merely to maintain a negative slip.
- Rated power and peak efficiency are generally achieved at about −3% slip.

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*Ref. T. Gonen. Electric Power Distribution System Engineering*

# Wind turbine operating conditions

- Depending on controllability, wind turbine operating systems are categorized as:
  - (1) constant-speed wind turbines
  - (2) variable-speed wind turbines.

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# Constant-speed wind turbines

- Constant-speed stall-regulated turbines have no options for any control input. Its turbine blades are designed with a fixed pitch to operate near the original tip speed ratio (TSR) for a given wind speed.
- When wind speed increases, it causes a reduced rotor efficiency and limitation of the power output.
- The same result can be achieved by operating the wind turbine at two distinct constant operating speeds by either changing the number of poles of the induction generator or changing the gear ratio.

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# Constant-speed wind turbines: Advantages and disadvantages

- They have the following advantages:
  - 1. They have a simple, robust construction and electrically efficient design.
  - 2. They are highly reliable, since they have fewer parts.
  - 3. No current harmonics are produced since there is no frequency conversion.
  - 4. They have a lower capital cost in comparison to variable-speed wind turbines.
- On the other hand, their disadvantages include the following:
  - 1. They are aerodynamically less efficient.
  - 2. They are prone to mechanical stress and are noisier.

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# Variable-speed wind turbines: Advantages and disadvantages

- It has two methods for controlling the turbine operation in terms of speed changes and blade pitch changes. The control strategies that are usually used are power optimization strategy and power limitation strategy.
- Power optimization strategy is used when the wind speed is below the rated value. It optimizes the energy capture by keeping the speed constant based on the optimum TSR.
- However, if speed is changed because of load variation, the generator may be overloaded for wind speeds above nominal value. To prevent this, methods like generator torque control are employed to control the speed.
- The power limitation strategy is used for wind speeds above the rated value by changing the blade pitch to reduce the aerodynamic efficiency.

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# Variable-speed wind turbines: Advantages and disadvantages

- The advantages of the variable speed wind turbine systems include the following:
  - 1. They are subjected to less mechanical stress and they have high energy capture capacity.
  - 2. They are aerodynamically efficient and have low transient torque.
  - 3. They require no mechanical damping systems since the electric system can effectively provide the damping.
  - 4. They do not suffer from synchronization problems or voltage sags because they have stiff electrical controls.
- The disadvantages of the variable-speed wind turbine systems include the following:
  - They are more expensive. They may require complex control strategies.
  - They have lower electrical efficiency.

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# Variable-Speed Doubly Fed Induction Generator

- One of the important wind energy system configurations.
- Both stator and rotor can feed energy to the grid.
- Stator is connected directly to the grid.
- Rotor is connected through power converters to the grid
- Rotor-side converter controls the torque i.e., active/reactive power of the generator
- Grid side converter controls ac side reactive power along with dc link voltage
- Separate reactive power compensation is not needed.

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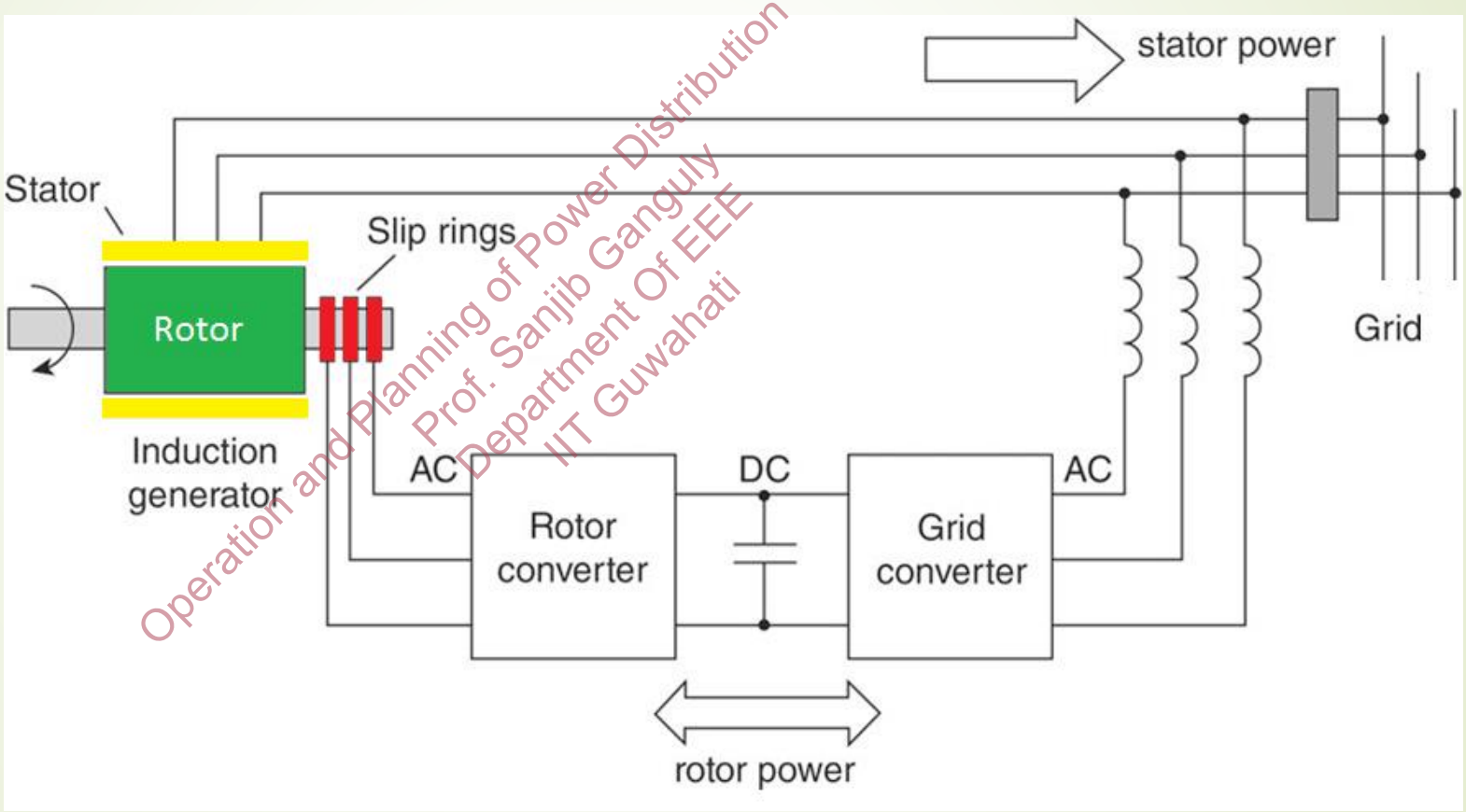
S. Muller, M. Deicke and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," in *IEEE Industry Applications Magazine*, vol. 8, no. 3, pp. 26-33, May-June 2002, doi: 10.1109/2943.999610.

# Variable-Speed Doubly Fed Induction Generator Wind Energy System

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# Power in the wind

- The wind speed is always fluctuating, and thus, the energy content of the wind is always changing.
- The variation depends on the weather and on local surface conditions and obstacles to the wind flow.
- Power output from a wind turbine will vary as the wind varies, even though the most rapid variations will to some extent be compensated for by the inertia of the wind turbine rotor.

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# Power in the wind

- A wind generator will capture only the wind power caught by the given swept area A that can be expressed in watts in SI system as:

$$P = 0.5\rho A V^3$$

Where ρ is mass density of air,

A is circular cross section area in $m^2$

V is wind velocity in m/s

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# Impact of tower height in wind power

- As general rule, a taller tower is expected to result in higher-speed winds to the wind turbine.
- However, surface winds can also be affected by the irregularities or roughness of the earth's surface or by the existing forest and/or buildings in the vicinity. The relationship between the wind speed and the height of the wind turbine can be expressed as:

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$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^a$$

Where V is wind speed at height H

$V_0$ is reference wind speed at reference height $H_0$

a Is roughness/friction coefficient

# Characteristic of wind generator

- The most important characteristic of a wind generator is its power curve. Normally, it is a graph provided by the manufacturer of a particular wind turbine. It shows the approximate power output as a function of wind speed.
- the minimum wind speed required to start the blades turning and producing a useful output is defined as the *cut-in speed*.
- The maximum power output that the wind turbine will produce is called the *rated power*.
- The minimum wind speed needed for the wind turbine to produce rated power is known as the *rated speed*.
- The *shutdown speed* is also called the *furling speed*. It is the maximum operational speed of the wind turbine. Beyond this speed, in order to prevent damage to the system from high winds, the blades are either folded back or turned to a high-pitch position.

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# Characteristic of wind generator: Typical power curve

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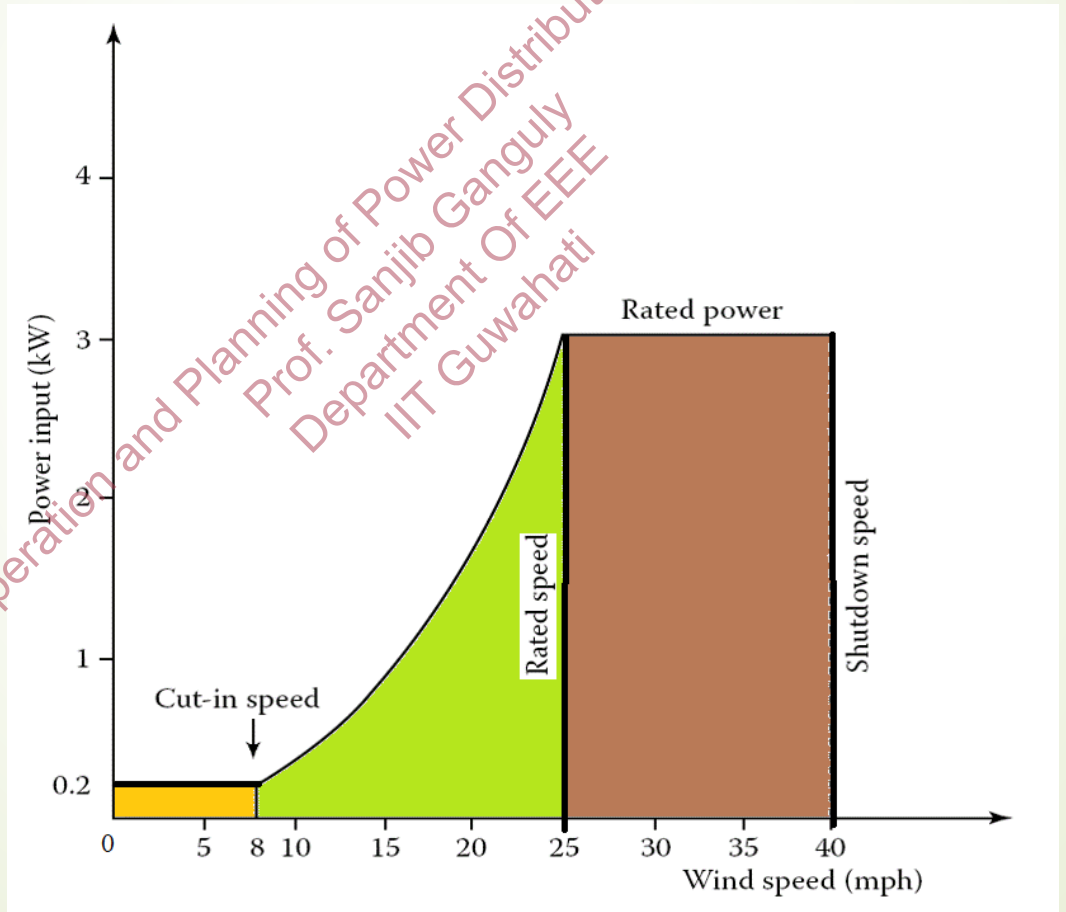


*Ref. T. Gonen. Electric Power Distribution System Engineering*

# Example 1

- Consider the wind turbine whose power curve of its generator is shown in Figure in last slide. It is rated 3 kW/25 mph, as indicated in the figure. Assume that during of 8 h period, the wind had the following average speeds: 6 mph for 2 h duration, 10 mph for 3 h duration, 15 mph for 2 h duration, and 20 mph for 1 h duration. Determine the resultant electric output for the 8 h period.

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# Solution…

- *At 6 mph*, it is below the cut-in speed in Figure; thus, the output is zero.

at 10 mph, P=0.35 kW;

$$\text{Energy} = 0.35\ \text{kW} \times 3\text{h} = 1.05\ \text{kWh}$$

at 15 mph, P=0.85 kW;

$$\text{Energy} = 0.85\ \text{kW} \times 2\text{h} = 1.7\ \text{kWh}$$

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# Solution…

at 20 mph, P=1.65 kW;

$$\text{Energy} = 1.65\ \text{kW} \times 6\text{h} = 1.65\ \text{kWh}$$

Total energy for 8 h=(1.05+1.7+1.65) kWh

= 3.855 kWh

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# Example 2

- In example 1 assume that during of 24 h period, the wind had the following average speeds: 6 mph for 6 h duration, 10 mph for 6 h duration, 15 mph for 6 h duration, and 20 mph for 6 h duration. Determine the resultant electric output for the 24 h period.

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# Solution…

*At 6 mph*, it is below the cut-in speed in Figure; thus, the output is zero.

at 10 mph, P=0.35 kW;

$$\text{Energy} = 0.35\ \text{kW} \times 6\text{h} = 2.1\ \text{kWh}$$

at 15 mph, P=0.85 kW;

$$\text{Energy} = 0.85\ \text{kW} \times 6\text{h} = 5.1\ \text{kWh}$$

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# Solution…

at 20 mph, P = 1.65 kW;

$$\text{Energy} = 1.65\ \text{kW} \times 6\text{h} = 9.9\ \text{kWh}$$

Total energy for 8 h = (2.1+5.1+9.9) kWh

= 17.1 kWh

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# Example 3

For a Blade length, $l$ = 30 m, Wind speed, $V$ = 1.6 m/sec, Air density, $\rho$ = 1.225 kg/m$^3$ calculate the wind power.

Wind power = $P = 0.5\rho A V^3 = 0.5 \times 1.225 \times 3.14 \times 30^2 \times 1.6^3$

$= 7.09$ kW

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# Example 4

For a Wind speed, $V$= 1 m/sec, Air density, $\rho$ = 1.225 kg/m$^3$ calculate the length of the blade required for producing a power of 1 kW.

Wind power = $P = 0.5\rho A V^3 = 0.5\times 1.225\times 3.14\times r^2\times 1^3$

$$r=(10^3/(0.5\times 1.35\times 3.14\times 1^3))^{1/2}$$

$r$= 22.79 m

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# Example 5

For a blade length = 30 m, Air density, $\rho$ = 1.225 kg/m$^3$ calculate the wind speed required for producing a power of 1 kW.

Wind power = $P = 0.5\rho A V^3 = 0.5\times1.225\times3.14\times30^2\times V^3$

$$V=(10^3/(0.5\times1.225\times3.14\times30^2))^{1/3}$$

$V$= 0.8327 m/s

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# Wind Generation Efficiency: Factors governing wind energy

- How much energy a wind turbine can produce is a function of a number of factors:
  - the rotor swept area,
  - the hub height, and
  - how efficiently the wind turbine can convert the kinetic energy of the wind.
- Over the years, the rotor swept area of wind turbines has increased steadily and thus so has the rated power of the wind turbines.

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# Wind Generation Efficiency

- *Generator efficiency*: A wind turbine can never utilize all the power in the wind.
- The amount of power that can be utilized by a wind turbine is given by the power coefficient *Cp*. Its value varies with *rotor design* and the Tip-speed ratio (*TSR*).
- It is known that (*based on Bets' law*) the maximum value of this coefficient is 0.59. It varies with the wind speed.

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# Tip-speed ratio *(TSR)*

- TSR is the relative speed of the rotor tip with respect to the wind. The ratio of the tip speed of the machine turbine blades to wind speed is found from the following expression:

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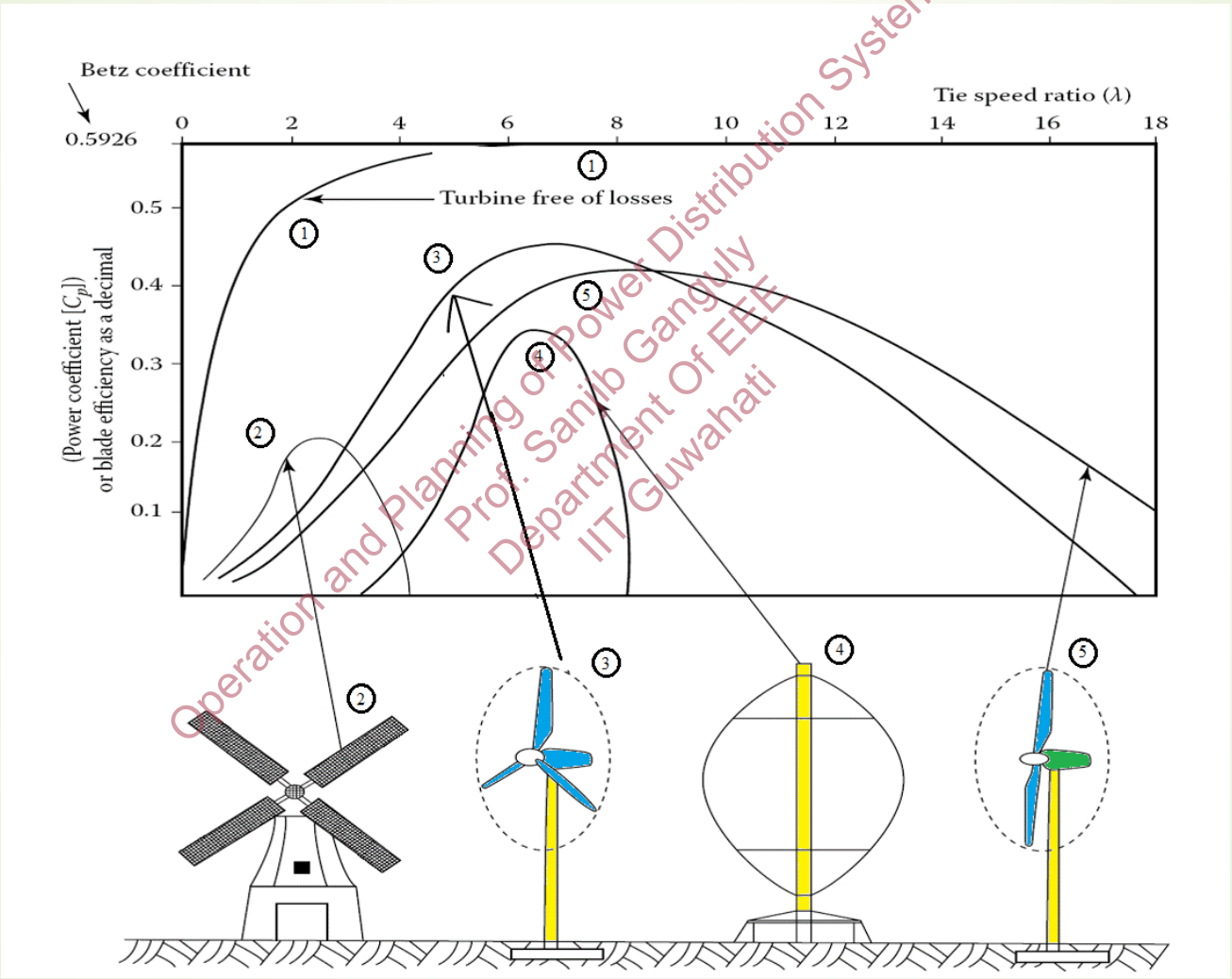
Tip-Speed-Ratio (*TSR*) = Rotor tip speed /Wind speed

$$= \frac{rpm * 2\pi r}{60 * V}$$

# TSR diagrams for various types of wind turbine

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# Example 6

For a blade radius = 30 m, *P* = 60 kW and *V* = 3 m/s. and air density = 1.225 kg/m3, determine the rpm of the rotor for a *TSR* = 4.

$$rpm = \frac{TSR * 60 * V}{2\pi r}$$

$rpm$ = 3.8197 rotations/minute

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# Example 7

For the values given in Example 6, determine the tip speed of rotor.

Rotor tip speed = (*TSR***V*)

Rotor tip speed = 4×3 =12 m/s

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# Wind Generation Efficiency

- *Gear box efficiency*: Typically on a large modern wind turbine, the rotor has a rotational speed of 20–30 rpm, while the generator will need to rotate at 1520 rpm. In order to increase the speed, a gearbox is used. If the turbine rotor runs at 30 rpm, a gear change of 30:1520 = 1:50.7 is required. That is, 1 rev of the main shaft has to be increased to 50.7 rev. Generally, a gearbox has several steps; thus, the rotational speed is increased stepwise. Losses can be estimated at 1% per step.
- The overall efficiency is the multiplication of *Cp*, efficiency of generator, and efficiency of gear box.

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# Solar energy

- The earth receives more energy from the sun in 1 h than the global population uses in an entire year.
- The average intensity of light outside the atmosphere (known as the solar irradiation/constant) is about 1300-1500 W/m2.
- There are two ways of solar energy conversion systems. They are: (i) *photovoltaic* and (ii) *concentrating solar power* (CSP).
- The former directly converts solar irradiation to electrical energy, whereas the latter converts firstly it to heat and then, to electrical energy.

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# Solar PV cell

- A solar cell will produce a voltage of 0.57 V when the sunlight shines upon it under open-circuit conditions.
- This voltage would be the same regardless of how big the size of the cell is. But its current supply is directly proportional to its surface area.
- In that sense, a solar cell can be considered a constant current source as well as a voltage source.
- The solar cell is a nonlinear device and its performance is subject to its characteristic curve.

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## Short-Circuit Current:

The maximum current produced at a given irradiation and temperature with zero output voltage .

## Open-Circuit Voltage :

The maximum voltage at a given irradiation and Temperature with zero output current.

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- Maximum power Voltage

The voltage at which maximum power is produced by a solar panel

- Maximum Power current

The current at which maximum power is produced by a solar panel

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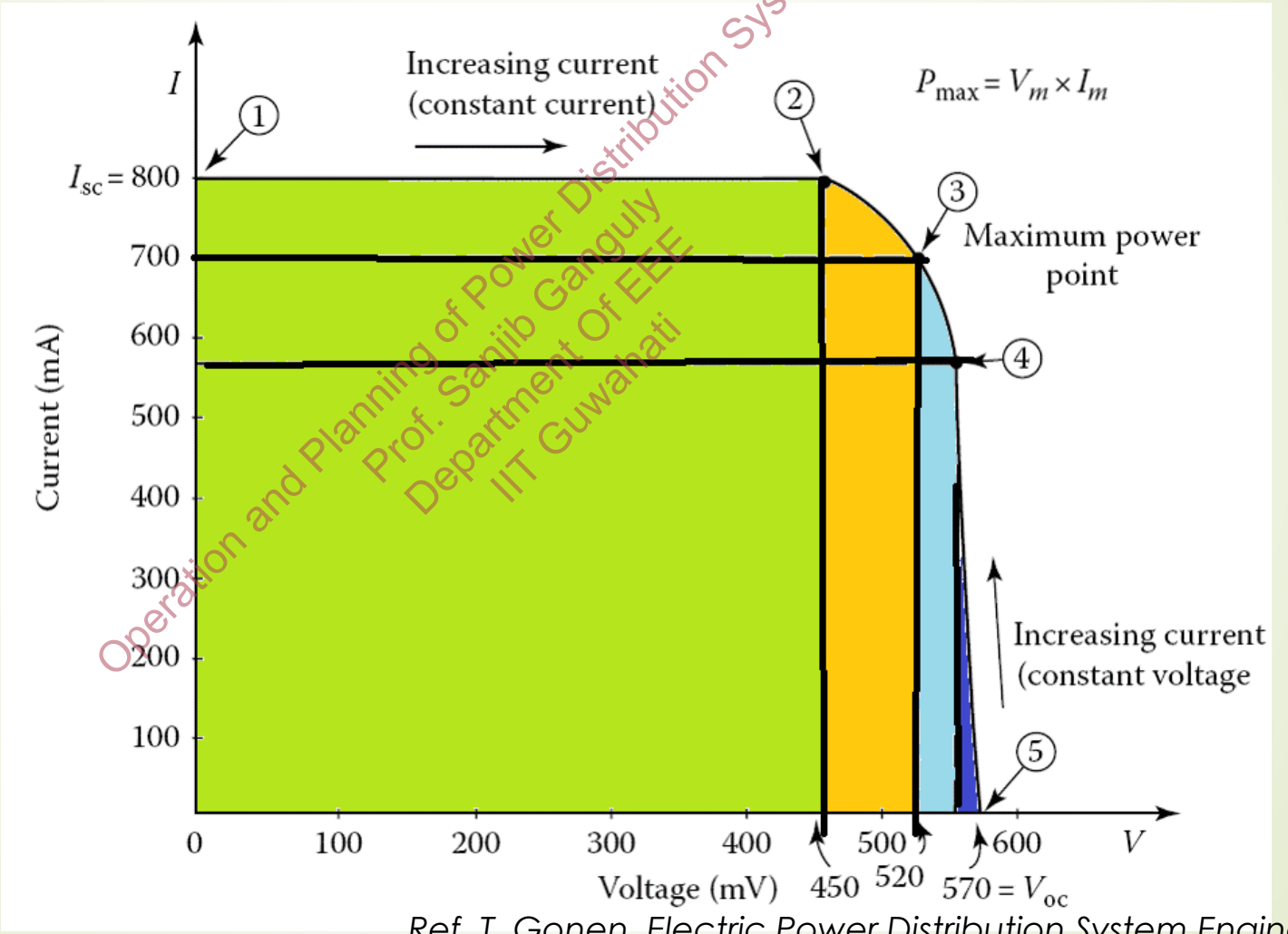
# Solar PV cell: *Typical V-I* Characteristic

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# Temperature effects on cell characteristic

- The ratings of solar cells are based on the minimum current they supply at 0.45 V under a full sun at 25°C (77°F).
- Its output is a function of its cell temperature. As temperature increases, the current will increase.
- The opposite takes place as the temperature decreases; that is, cell operates more efficiently when they are cooler.
- At other temperatures, the voltage and the current of the cell can be determined from:

$$E_o = E_R - 0.0021(T\text{-}25)$$
$$I_o = I_R + 0.025\text{A}(T\text{-}25)$$

Where $E_R$ and $I_R$ are the cell ratings in volts and mAs, respectively, at 25° C, $E_o$ and $I_o$ are the cell voltage and current at temperature T, A is cell area in $cm^2$.

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# Efficiency of solar cells

- In general, *solar cell efficiency* is defined as the ratio of the electric power output to the sunlight power it receives.
- The maximum theoretical efficiency of a silicon solar cell is about 25%.
- Today's cells have rated efficiencies of 10%–16%.
- The efficiency of a cell is a function of number of things, including the number and thickness of the wires connected to the top of the cell and light reflected from the surface of the cell. Also, when cells are connected together to form panels, the panel efficiency will be based on the cell's shape.

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# PV Cell Technology vs Efficiency

| Technology | Efficiency |
|---|---|
| Mono crystalline | 20-27% |
| Poly crystalline | 14-18% |
| Copper indium gallium selenide | 10-13% |
| Amorphous silicon | 5-7% |

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Ahmad, Zameer. (2013). Control of Grid Connected Solar Photovoltaic System. 10.13140/RG.2.1.1253.2969. .

# Cascading of multiple solar cells

- Typical solar cell output is 800 mA at 0.45 V. But most everyday applications dictate more than 800 mA at 0.45 V.
- The net voltage can be increased by connecting them in series, and the net current can be increased by connecting them in parallel.
- If many solar cells are connected in series and parallel to form a permanent unit, it is called a *solar panel*.
- In practice, solar panels are manufactured in different sizes and ratings. Such panels can be interconnected to form *solar arrays* or *modules*.

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# Components of PV system

- Solar panels
- Power conditioning circuit
- Storage
- Inverter
- Loads

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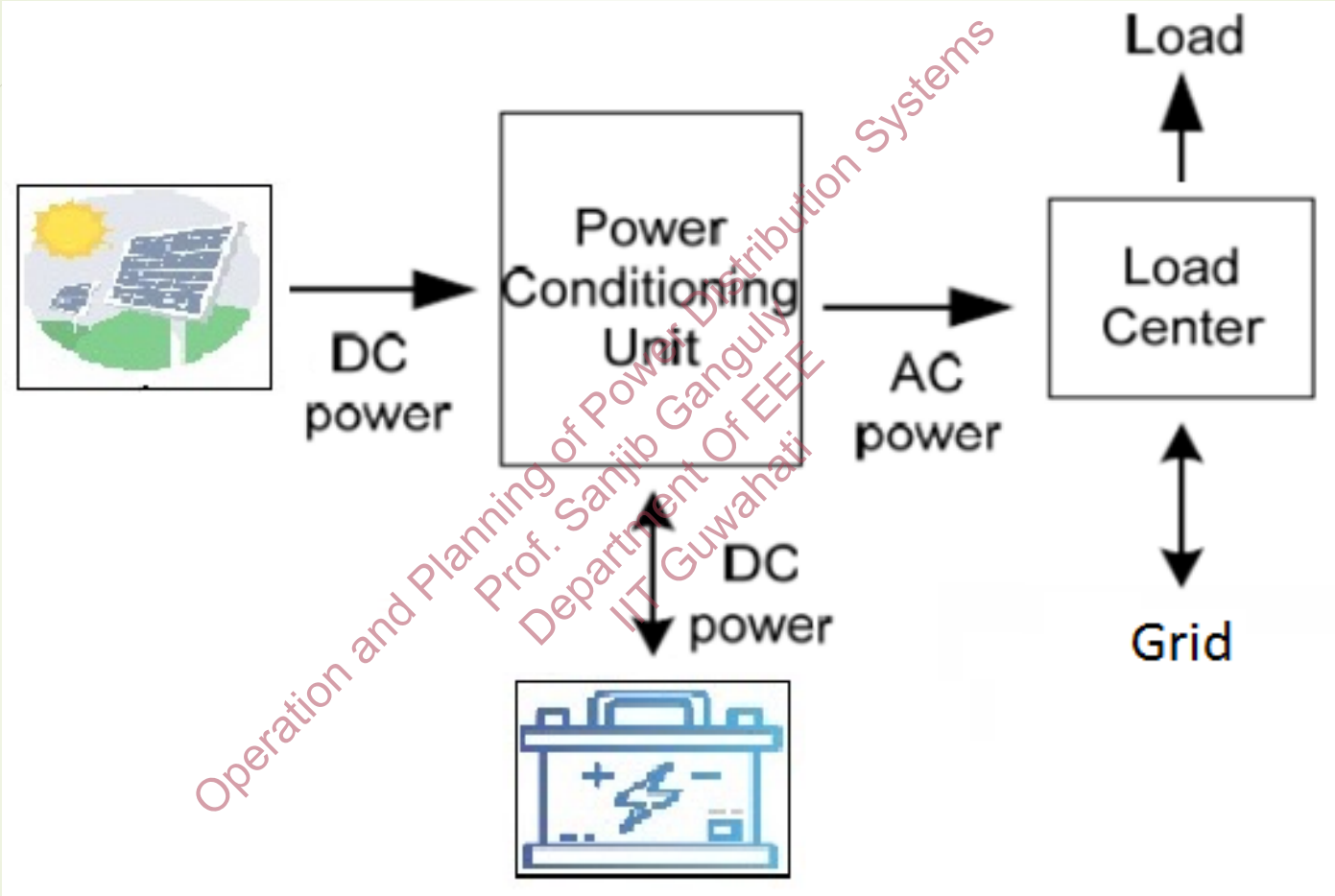


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Walid Omran, "Performance Analysis of Grid-Connected Photovoltaic Systems" Philosophy of doctorate Thesis, Electrical and Computer Engineering, Ontario, Canada, 2010

# System configuration for solar PV generation.

- There are two types of solar PV generation systems:
  - Stand-alone system
  - Grid-connected system

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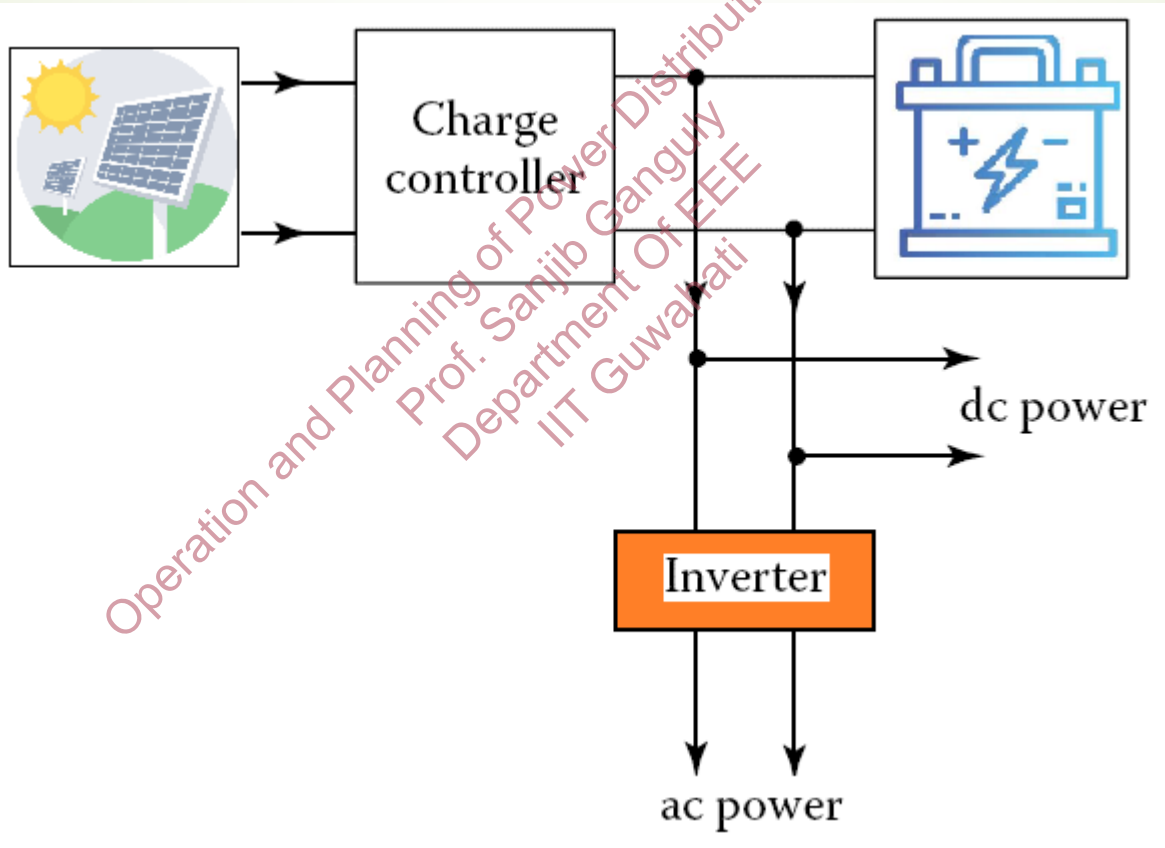
# System configuration for solar PV generation: Standalone system

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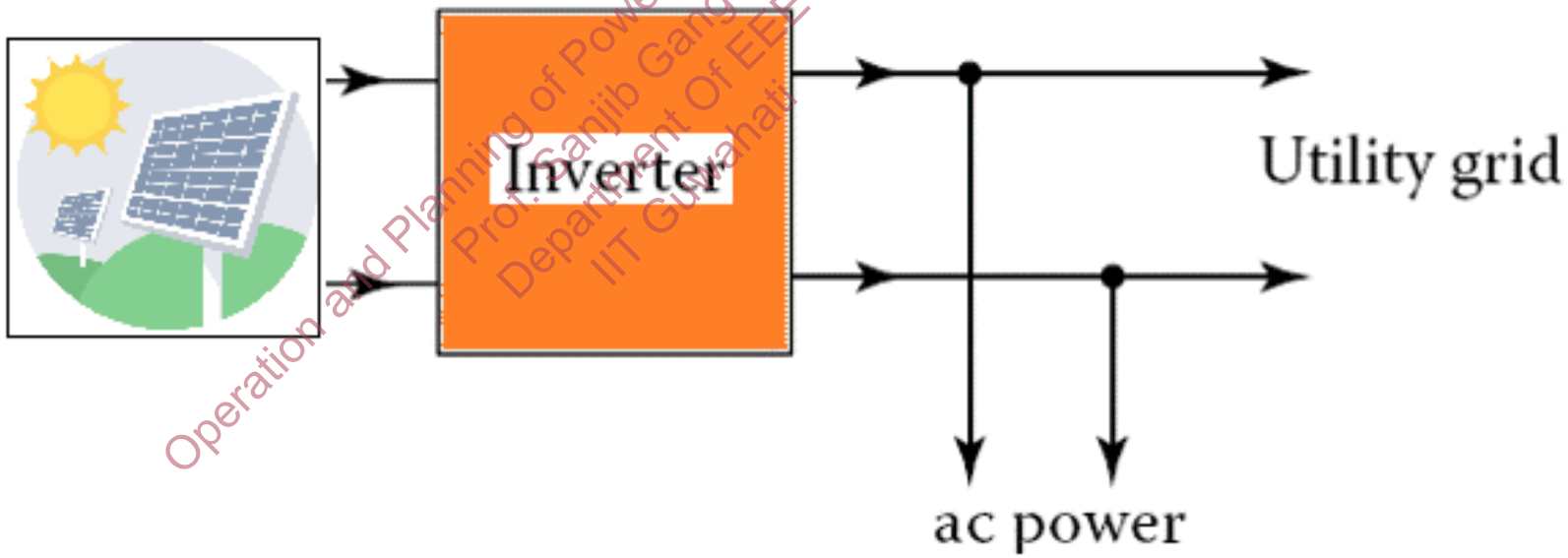
# System configuration for solar PV generation: Grid-connected system

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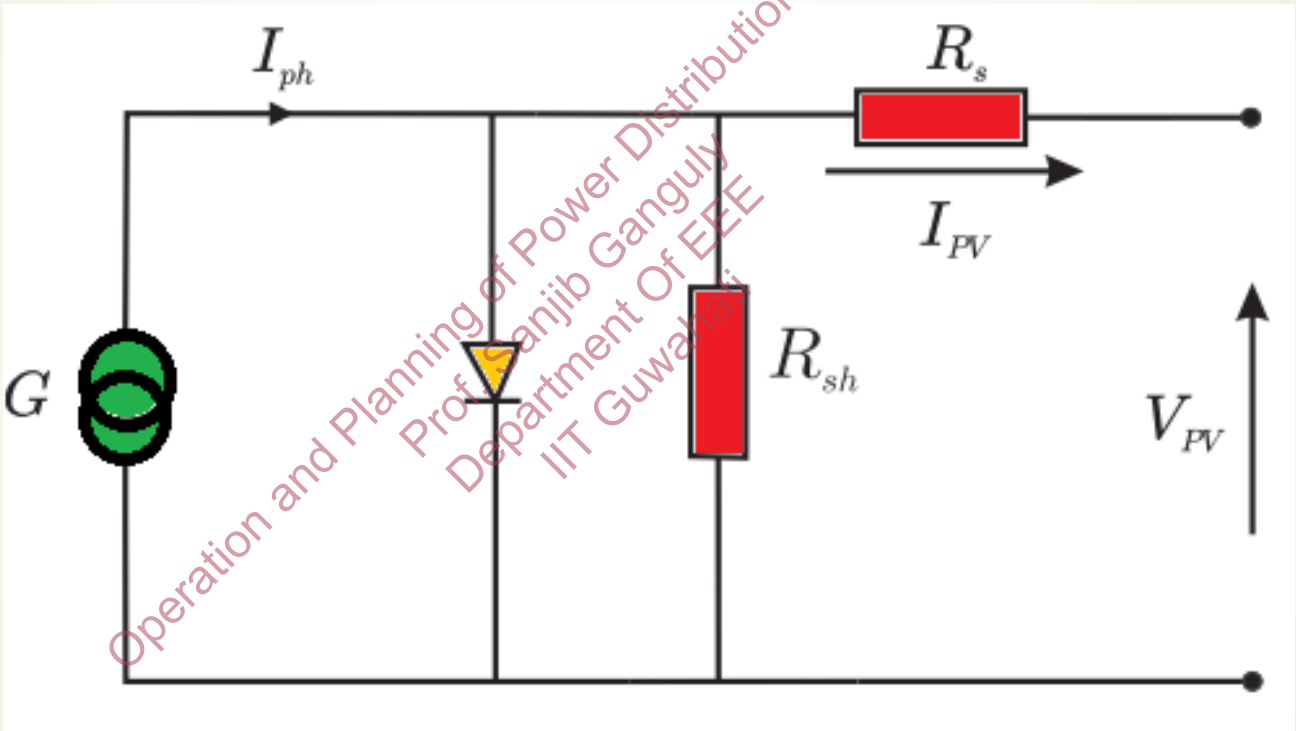
# Equivalent circuit of PV cell

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# Output current of PV cell

$$I_{pv} = I_{ph} - I_o \left[ \exp\left( \frac{q(V_{pv} + R_s I_{pv})}{K T_c A} \right) - 1 \right]$$

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$V_{PV}$ is the output voltage of PV cell,
$I_{ph}$ is the current photo generated by the solar cell,
$I_o$ is the reverse saturation current of the diode,
$q$ = electron charge= $1.602 \times 10^{-19}$ C,
$Rs$ is the internal resistance,
$K$ = Boltzmann constant = $1.381 \times 10^{-23}$ J/K,
$T_c$ is the temperature of the cell, $A$ is the diode ideality factor.

# Maximum Power Point Tracking Controller



- Maximum Power Point (MPP) is the maximum energy that can be extracted from the PV panel.
- MPPT methods are useful for tracking MPP.
- MPPT algorithms provide control signal i.e., PWM signal to power electronic converters in order to deliver maximum available power to the load.

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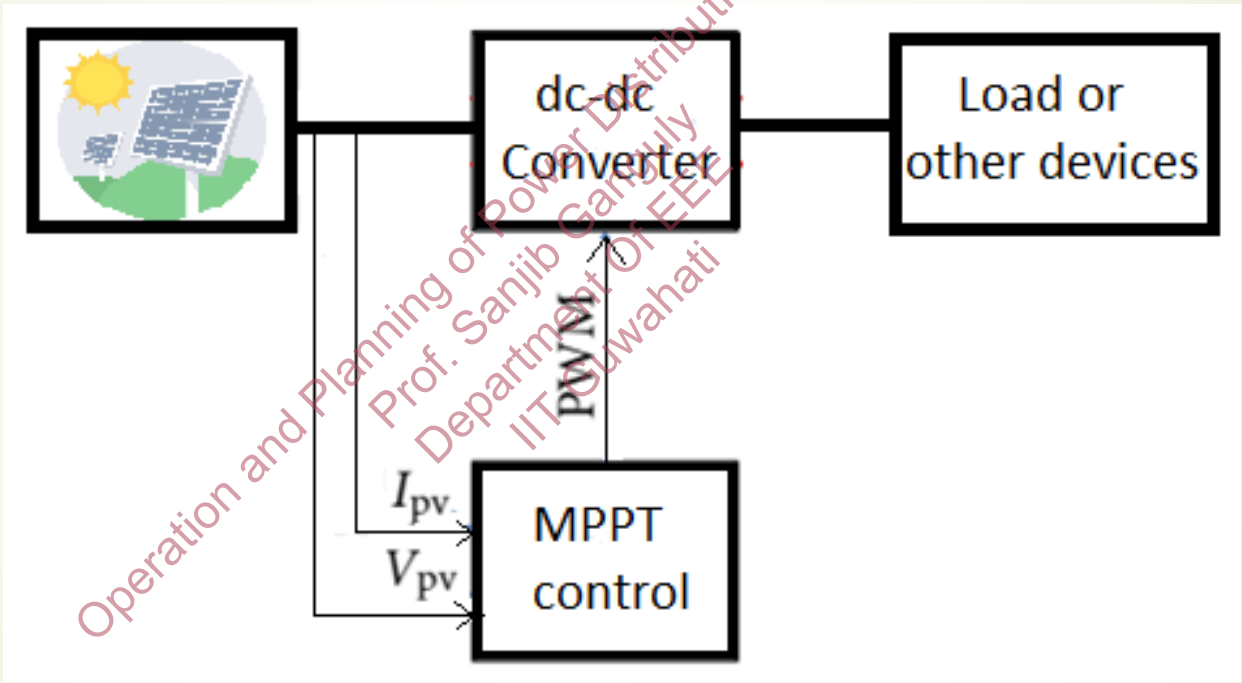
Brunton, S.L.; Rowley, C.W.; Kulkarni, S.R.; Clarkson, C. Maximum power point tracking for photovoltaic optimization using ripple-based extremum seeking control. *IEEE Trans. Power Electron.* **2010**, *25*, 2531–2540.

# Maximum Power Point Tracking Controller

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# Maximum Power Point Tracking Controller

- The current /voltage *of* PV module and output voltage of converter are the inputs to MPPT controller
- MPPT controller generates control signal for converter to maintain maximum power point as the operating point of the system.
- The perturb & observe (P&O) and Incremental Conductance (IncCond) are the most popular MPPT algorithms.

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Brunton, S.L.; Rowley, C.W.; Kulkarni, S.R.; Clarkson, C. Maximum power point tracking for photovoltaic optimization using ripple-based extremum seeking control. *IEEE Trans. Power Electron.* **2010**, *25*, 2531–2540.

# Perturb and Observe Method



- MPP is tracked using periodic measurements of current and voltage of the PV system.

## Advantages

- Simple
- Less costly.

## Disadvantages

- Oscillatory power around the MPP.
- Might Fail to track MPP during sudden changes of temperature and solar irradiance.

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Jain, S.; Agarwal, V. A new algorithm for rapid tracking of approximate maximum power point in photovoltaic systems. *IEEE Power Electron. Lett.* **2004**, 2, 16–19.

# Incremental Conductance Method

- MPP is tracked by comparing the instantaneous conductance with the incremental conductance to modify the required reference voltage.

## Advantages

- Less oscillatory power around the MPP.

## Disadvantages

- Response is slow while reaching MPP during certain conditions .

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Salas, V.; Olías, E.; Barrado, A.; Lázaro, A. Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. *Sol. Energy Mater. Sol. Cells* **2006**, *90*, 1555–1578.

# Concentrating solar power (CSP)

- It involves intermediate conversion of solar energy into thermal energy in the form of steam, which in turn is employed to drive a turbo generator.
- To have high temperatures, thermal systems invariably use concentrators by the use of mirrors either in the form of parabolic troughs or thermal towers.
- The CSP systems are essentially categorized based on how the systems collect solar energy. The three basic systems are the linear, tower, and disk systems.

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# Merits of Solar Energy

- Renewable source of energy
- Reduction of energy costs
- Low maintenance costs
- Abundantly Available
- Provides Grid support
- Extensive applications

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# Demerits

- Cost
- Intermittency
- More space requirement
- Energy storage is costly
- Less efficient

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# Example 8

- Consider a solar panel that is rated 20 W at 10 V. Determine the following:
- a. How many of these panels are needed to supply 10 A of current at 120 V?
- b. How should they be connected?
- c. The value of the necessary load resistance.
- d. The total power that can be obtained from this array of solar cells.

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# Solution…

- Since each panel produces 10 V, to get 120 V, the number of panels required in series is: Total required voltage/Each panel voltage

Number of panels in series = 120/10

= 12

Current rating of each panel = power/voltage

= 20/10

= 2 A

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# Solution…

Number of required parallel paths = Total required current/ Each panel current

= 10/2

= 5

a) panels needed for a supply of 10 A at 120 V are

= Number of series connected panels*Number of parallel paths

=12*5

= 60

b) They should be connected in five parallel paths, with each parallel path consisting of 12 panels connected in series

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# Solution…

c) Required load resistance is

$$R_L = 120/10$$

$$= 12 \text{ ohm}$$

The input resistance facilitates the maximum power conversion in a full sun. However, as the lighting changes, this impedance needs to be changed to get the maximum power conversion.

d) The total power of solar array = Voltage * Current

$$= 120*10$$

$$= 1.2 \text{ kW}$$

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# Example 9

- Consider that each solar panel is rated 20 W at 10 V. Determine the following:
- a. How many of these panels are needed to supply 20 A of current at 120 V?
- b. How should they be connected?
- c. The value of the necessary load resistance.
- d. The total power that can be obtained from this array of solar cells.

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# Solution…

- Since each panel produces 10 V, to get 120 V, the number of panels required in series is: Total required voltage/Each panel voltage

Number of panels in series = 120/10

= 12

Current rating of each panel = power/voltage

= 20/10

= 2 A

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# Solution…

Number of required parallel paths = Total required current/ Each panel current

= 20/2

= 10

a) panels needed for a supply of 20 A at 120 V are

= Number of series connected panels*Number of parallel paths

=12*10

= 120

b) They should be connected in ten parallel paths, with each parallel path consisting of 12 panels connected in series

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# Solution…

c) Required load resistance is

$$R_L = 120/20$$

$$= 6 \text{ ohm}$$

The input resistance facilitates the maximum power conversion in a full sun. However, as the lighting changes, this impedance needs to be changed to get the maximum power conversion.

d) The total power of solar array = Voltage * Current

$$= 120*20$$

$$= 2.4 \text{ kW}$$

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# Example 10

- Consider that each solar panel is rated 20 W at 10 V. Determine the following:
- a. How many of these panels are needed to supply 10 A of current at 240 V?
- b. How should they be connected?
- c. The value of the necessary load resistance.
- d. The total power that can be obtained from this array of solar cells.

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# Solution…

- Since each panel produces 10 V, to get 120 V, the number of panels required in series is: Total required voltage/Each panel voltage

Number of panels in series = 240/10

= 24

Current rating of each panel = power/voltage

= 20/10

= 2 A

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# Solution…

Number of required parallel paths = Total required current/ Each panel current

= 10/2

= 5

a) panels needed for a supply of 20 A at 120 V are

= Number of series connected panels*Number of parallel paths

=24*5

= 120

b) They should be connected in five parallel paths, with each parallel path consisting of 24 panels connected in series

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# Solution…

c) Required load resistance is

$$R_L = 240/10$$

$$= 24 \text{ ohm}$$

The input resistance facilitates the maximum power conversion in a full sun. However, as the lighting changes, this impedance needs to be changed to get the maximum power conversion.

d) The total power of solar array = Voltage * Current

$$= 240*10$$

$$= 2.4 \text{ kW}$$

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# Reference


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# Thank You…

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