

Module Outline

# GRID INTEGRATION - UTILITY-SCALE





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## Relevance and Background

Power generating plants need all kinds of protection systems for the grid as well as for the plants themselves, to ensure grid safety and health. Grid connectivity is quite standardized in many countries and newer specifications and requirements are evolving as the scale grows.

However, renewable energy sources like solar and wind power are increasingly becoming the major contributor to the grid in many countries worldwide. So, the grids, which were till date comparatively simple in operation from generation to distribution for consumption, are fast changing and becoming more complex in operation.

The major new renewable energy generation sources are variable in nature and still cannot be predicted accurately. Further, generation is also sourced at many more places along the grid than the earlier comparatively centralized locations.

Theme – Technical

Competency – Electrical

Code of the Module – To2Co3M10

## Learning Outcomes

By the end of this module, participants will be able to:

- Understand the stages in power evacuation from the PV plant to the substation.
- Identify the equipment used at different stages in the evacuation.
- Get an idea of typical specifications of switchgear equipment for a PV plant.
- Understand the effect on the grid due to increasing renewable energy capacities feeding power to the grids.
- Identify the possible challenges and their mitigation techniques in connecting higher capacity PV power plants to the grid.

## Method of Delivery

Duration	Resource Code	Resource Delivery
60 min.	M10 L01	Lecture on Grid Integration of Utility-Scale

## M10 L01: Lecture Presentation

The presentation will cover three aspects of grid connection of large-scale multi-megawatt solar PV plants. First is the process and equipment involved in evacuation and the grid connection. Secondly, it will identify some issues due to the ever-increasing presence of renewable energy sources power in the grid. Lastly, it will list the possible techniques to manage the challenges and risks.\



## Key Topics to be Covered

1. Single Line Diagram
2. Stages in Power Flow from PV Plant to Grid
3. Electric Power System
4. Evacuation System for Grid Integration
5. Typical Equipment in 5 MW Plant Evacuation Systems
6. Challenges and Mitigation of Utility-Scale Renewable Energy Grid Integration



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## 1 Introduction

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Solar photovoltaic (PV) plants generate electricity by converting sunlight into electrical energy using solar panels. To ensure effective power evacuation from the solar PV plant to the substation, it is essential to have proper switchgear and a well-designed substation.

This module aims to provide an overview of the key components and considerations for the switchgear and substation in a solar PV plant's power evacuation system, ensuring seamless integration with the grid.

## 2 Single Line Diagram

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In power engineering, the single-line diagram (SLD) serves as the simplest symbolic representation of an electric power system. This document holds paramount importance in obtaining technical approval for grid connectivity because it outlines the philosophy and design of the grid interconnection from the plant to the substation.

The SLD includes essential details such as cable sizes, protection systems, and metering setups, specifically tailored for each large-scale power plant to be connected to the grid. The execution of the evacuation process must strictly adhere to the SLD pre-approved by the grid authority or a regulatory agency.

## 3 Stages in Power Flow from PV Plant to Grid

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The following are the stages in the evacuation and grid integration of large-scale solar PV power plants.

The generation is at low tension level, but for easy and safe transmission of power it needs to be at high tension, the value of which depends on the power being carried and distances of transmission. This also reduces the costs and risks involved in transmitting the power all across the country.

- PV array to generate power in DC form.
- String combiner boxes junction boxes to manage numerous cables and introduce protections against overcurrent and surges.
- Inverter and allied equipment to convert power to AC form.
- Transformer to step up inverter output voltage (normally low tension or LT) to high or extra high voltages such as 11/22/66/132/220 kV
- High tension (HT) switchgear at the solar plant to manage high voltage cables and protections and also to monitor power flow.
- Transmission lines from plant switchyard to substation
- HT switchyard near the plant or substation for metering and protections
- Meter at grid interconnection point to record energy flow for further billing purpose

- Regular power grid with transmission and distribution network

## 4 Electric Power System

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A comprehensive understanding of electric power systems is essential, including how the grid functions in terms of generation, transmission, and distribution. Over time, global standards have been established for equipment, switchyard or substation layouts, and protection equipment like grounding to safeguard against lightning or electrical faults such as short circuits.

The majority of electrical consumption occurs in AC form at the low tension (LT) level, as equipment is designed accordingly. Some exceptions include loads such as telecom equipment or railways traction, which operate at either LT or HT. Meters must adhere to regulatory standards and are instrumental in recording energy flow at various stages while assessing losses within these stages.

## 5 Evacuation System for Grid Integration

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- **Switchgear in PV Plants**

Switchgear plays a crucial role in protecting the solar PV plant and facilitating the power evacuation process. It comprises a combination of circuit breakers, disconnectors, and protection relays. The primary functions of switchgear include:

- **Circuit breaking:** Circuit breakers are devices used to interrupt electrical currents during abnormal conditions such as short-circuits or overloads. They protect the solar PV plant and other electrical equipment from damage caused by excessive currents.
- **Disconnection:** Disconnectors provide isolation and allow the safe disconnection of individual solar PV panels, strings, or inverters from the system for maintenance or repair purposes.
- **Protection:** Protection relays monitor the electrical parameters and trigger appropriate actions, such as opening circuit breakers, in case of abnormal conditions, to protect the solar PV plant from potential damage.

- **Components of Solar PV Plant Substations**

- The substation acts as a crucial intermediate link between the solar PV plant and the main grid. It steps up the voltage of the generated electricity to match the grid requirements. A typical solar PV plant substation consists of the following components:



- Transformers step up the low-voltage DC power generated by the solar panels to a higher voltage suitable for transmission to the main grid. This process reduces transmission losses and enhances overall efficiency.



- The switchyard houses the main switchgear components like circuit breakers, disconnectors, and protection relays. It is the central point for controlling the power flow and ensuring the safety of equipment.
- Power evacuation equipment, such as power factor correction units and reactive power compensators, may be installed to improve power quality and grid stability.
- To monitor the solar PV plant's performance and electricity generation, metering and monitoring equipment, including energy meters; communication devices and data loggers are installed in the substation.
- The control room serves as the nerve center of the substation, where operators can monitor and control the entire power evacuation process.

- **Transmission line (plant to substation)**

Planning and laying out the power transmission line from a solar PV plant to the utility substation involves several crucial decision points. Each decision plays a significant role in ensuring the efficiency, reliability, and cost-effectiveness of the transmission system. Below are the key decision points in this process:





- **Route Selection:** Choosing the most suitable route for the power transmission line is essential. Factors to consider include:
  - The distance between the solar PV plant and the substation, as well as the terrain, impacts the overall cost of construction and maintenance.
  - Identifying and obtaining necessary land and right-of-way permissions are critical for the smooth implementation of the transmission line project.
  - Assessing potential environmental and social impacts helps in mitigating any adverse effects on the surrounding areas.
- **Voltage Level and Capacity:** Deciding on the appropriate voltage level and transmission capacity is crucial for efficient power evacuation. Considerations include:
  - Determining if the power needs to be stepped up or stepped down through transformers for transmission and distribution.
  - Accounting for future load growth and the potential need for capacity expansion.

- **Type of Transmission Line:** Different types of transmission lines are available, each with its advantages and disadvantages. Overhead lines are cost-effective and relatively easier to construct and maintain but may face environmental and aesthetic challenges. On the other hand, underground cables are less visually intrusive but tend to be more expensive and require additional technical considerations.
- **Line Conductor Selection:** The choice of conductors for the transmission line depends on factors such as transmission capacity, and environmental conditions such as the impact of weather, temperature, and other environmental factors on the conductors' performance.
- **Support Structures:** The selection and design of support structures (towers or poles) involve considerations like the appropriate height and spacing between towers to maintain the required clearance and stability, and accounting for the soil conditions to design stable foundations for the support structures.
- **Reliability and Redundancy:** Ensure that the transmission line layout provides a reliable power evacuation route with minimal downtime. This may involve incorporating redundancy in critical sections of the line.
- **Safety and Maintenance:** Consider safety measures during installation and design the transmission line for ease of maintenance to reduce downtime and ensure smooth operation.
- **Interconnection with Substation:** Plan the interface between the transmission line and the utility substation, ensuring compatibility and adherence to grid interconnection requirements.
- **Regulatory and Permitting Requirements:** Comply with all relevant regulations, permits, and codes necessary for the construction and operation of the transmission line.
- **Cost Analysis:** Perform a comprehensive cost analysis to assess the overall expenses involved in the transmission line project, including construction, maintenance, and operational costs.

## 5.1 Protections at PV Plant and Utility Substations

### 5.1.1 PV Plant Substation Protections:

- **Overcurrent Protection:** Overcurrent protection devices, such as fuses and circuit breakers, are installed to safeguard the PV plant equipment and the transmission line from excessive currents due to faults or overloads.
- **Ground Fault Protection:** Ground fault protection systems detect and clear ground faults to prevent electrical hazards and equipment damage.
- **Reverse Power Flow Protection:** To ensure that power flows only from the PV plant to the utility substation and not vice versa, reverse power flow protection is employed.

- **Anti-Islanding Protection:** Anti-islanding protection is essential for grid-tied PV systems to detect islanding events (when the PV plant continues to supply power during a grid outage) and disconnect from the grid to ensure the safety of utility workers.
- **Voltage Regulation and Protection:** Voltage regulation devices and protection relays maintain the voltage levels within acceptable limits and prevent voltage surges or sags that could damage the equipment.
- **Frequency Protection:** Frequency protection systems monitor the grid frequency and take corrective actions in case of frequency deviations, helping maintain grid stability.
- **Temperature Monitoring:** Monitoring the temperature of key components, such as transformers and inverters, ensures that they operate within safe limits.
- **Communications and Control Systems:** These systems enable remote monitoring and control of the PV plant substation, allowing operators to respond to events promptly.

### 5.1.2 Utility Substation Protections:

- **Transformer Protection:** This includes measures such as overcurrent protection, differential protection, and Buchholz relay for detecting and responding to transformer faults.
- **Circuit Breakers and Relays:** These provide overcurrent, overvoltage, and other protection functions for the utility substation equipment and transmission lines.
- **Busbar Protection:** This safeguards the substation's main bus from faults and overloads.
- **Distance Protection:** Distance protection relays measure fault impedance and detect faults along the transmission lines, enabling quick isolation and restoration.
- **Differential Protection:** This compares currents entering and leaving key equipment, such as transformers, to detect internal faults.
- **Frequency and Voltage Protection:** Similar to the PV plant substation, the utility substation also employs protection systems to monitor and regulate grid frequency and voltage.
- **Synchronizing Protection:** This ensures that when connecting the substation to the grid, the phase angle and voltage levels are properly synchronized before synchronization occurs.
- **Backup Protections:** Redundant and backup protection systems are in place to ensure reliability and fault clearance even if the primary protection devices fail.
- **Remote Monitoring and Control:** Advanced communication and control systems enable remote monitoring and operation of the utility substation for enhanced efficiency and reliability.

## 6 Typical Equipment in 5 MW Plant Evacuation Systems

The equipment and other work items involved in evacuation systems of solar PV plants are:

- 33/11 kV switchyard at client's end
- Ring Main Units (RMUs), HT/LT panel
- Power and auxiliary transformers
- Power and control cables
- Excavation for cable laying
- Cabling accessories
- Switchyard lighting
- Earthing
- Safety equipment
- Testing and commissioning
- Design
- Approvals



## 7 Challenges and Mitigation of Utility-Scale Renewable Energy Grid Integration

Key challenges related to grid integration of utility-scale power plants and their possible mitigation measures are:


Challenges	Explanations	Mitigation Techniques
<b>Intermittency and Variability</b>	Renewable sources like solar and wind are intermittent, posing challenges for grid stability due to unpredictable power generation patterns.	<ul style="list-style-type: none"><li>- Implement advanced forecasting and scheduling techniques to predict renewable energy generation more accurately.</li><li>- Combine multiple renewable sources to reduce the impact of intermittency.</li></ul>

Challenges	Explanations	Mitigation Techniques
<b>Variability and Rapid Changes</b>	Rapid fluctuations in renewable energy output require quick grid adjustments to maintain stability and match supply with varying demand.	<ul style="list-style-type: none"> <li>- Enhance grid flexibility by deploying energy storage systems to store excess energy and release it during high-demand periods.</li> <li>- Develop demand response programs to adjust electricity consumption based on renewable generation fluctuations.</li> </ul>
<b>Mismatch between Generation and Demand</b>	The unpredictable nature of renewables can lead to imbalances between generated energy and actual demand, affecting grid stability.	<ul style="list-style-type: none"> <li>- Invest in demand-side management programs to align electricity usage with renewable generation patterns.</li> <li>- Develop energy management systems that can dynamically adjust energy generation based on real-time demand signals.</li> </ul>
<b>Transmission and Remote Locations</b>	Renewable projects in remote areas face challenges in transmitting power to consumption centers due to inadequate transmission infrastructure.	<ul style="list-style-type: none"> <li>- Invest in grid infrastructure upgrades and build new transmission lines to efficiently transport renewable energy from remote areas.</li> <li>- Implement smart grid technologies to monitor and control energy flow, optimizing grid performance and efficiency.</li> <li>- Develop clear communication channels and collaborative platforms to share information and address integration challenges collectively.</li> </ul>
<b>Storage and Backup Needs</b>	Effective energy storage solutions are essential to store excess energy during peak generation and release it during low generation periods.	<ul style="list-style-type: none"> <li>- Deploy energy storage technologies such as batteries and pumped hydro storage to store excess energy and release it when needed.</li> <li>- Invest in research and development to improve energy storage technologies and reduce costs.</li> </ul>
<b>Grid Stability and Frequency Control</b>	Fluctuations in renewable generation can impact grid stability by causing voltage and frequency deviations, requiring advanced control methods.	<ul style="list-style-type: none"> <li>- Develop advanced grid control and management systems that can quickly respond to fluctuations in renewable energy output.</li> </ul>



Challenges	Explanations	Mitigation Techniques
		<ul style="list-style-type: none"> <li>- Integrate energy storage and flexible demand resources to provide rapid response to grid stability issues.</li> </ul>
<b>Adapting Energy Markets</b>	Energy markets need to adapt to the variable nature of renewables, requiring new pricing mechanisms and market structures to ensure efficiency.	<ul style="list-style-type: none"> <li>- Design electricity markets that offer incentives for flexible generation, demand response, and energy storage participation.</li> <li>- Implement real-time pricing mechanisms that reflect the actual supply-demand balance, encouraging efficient energy consumption.</li> </ul>
<b>Environmental and Regulatory Concerns</b>	Large-scale renewable projects can face regulatory challenges and environmental concerns related to land use, wildlife, and community impact.	<ul style="list-style-type: none"> <li>- Collaborate with regulatory authorities to develop streamlined permitting processes for renewable projects without compromising safety.</li> <li>- Implement community engagement strategies to address concerns and build local support for renewable energy initiatives.</li> </ul>
<b>Investment and Funding</b>	Developing large-scale renewables requires significant upfront investment and proper funding models to ensure successful project implementation.	<ul style="list-style-type: none"> <li>- Provide financial incentives such as tax credits, grants, and subsidies to attract investment in large-scale renewable projects.</li> <li>- Develop innovative financing models, including public-private partnerships, to share the financial burden of renewable integration.</li> </ul>
<b>Flexibility and Rapid Adjustment</b>	Unlike conventional power plants, renewables lack rapid controllability, which can impact grid stability during sudden demand or supply changes.	<ul style="list-style-type: none"> <li>- Combine renewable energy sources with flexible backup generation, such as natural gas plants, to provide stable grid support.</li> <li>- Invest in grid modernization and automation technologies to enable quick adjustments and response to rapid changes in demand.</li> </ul>





Challenges	Explanations	Mitigation Techniques
<b>Effective Coordination and Communication</b>	Successful integration of renewables relies on effective communication and coordination among stakeholders to manage the complexities involved.	- Establish cross-sector partnerships involving government agencies, utilities, developers, and communities to coordinate integration.

Understanding the impact on the grid due to increasing renewable energy capacities and identifying the potential challenges and their mitigation techniques in connecting higher-capacity PV power plants to the grid are crucial for effective and seamless power generation and transmission.



## Reading Material

1. *Utility Scale Solar Power Plants – A Guide for Project Developers and Investors* by International Finance Corporation  
<https://documents1.worldbank.org/curated/en/868031468161086726/pdf/667620WP00PUBLo05BoSOLARoGUIDEoBOOK.pdf>
2. *Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition* by National Renewable Energy Laboratory  
<https://www.nrel.gov/docs/fy18osti/68469.pdf>