

# Renewable Energy and Distributed Generations

## Lecture 11

### Grid-Connected PV System Configurations

Lecturer: Teshome Goa (Assist. Prof.)

## ***Lecture learning outcomes:***

At the end of this lecture, you will be able to:

- i. Understand the configuration of Grid connected PV systems
- ii. Identify the modeling of PV generators and its importance in MPPT
- iii. Identify some controlling approach of boost converters for maximum power harvesting
- iv. Know the Grid code and Regulation of PV system

# Outlines

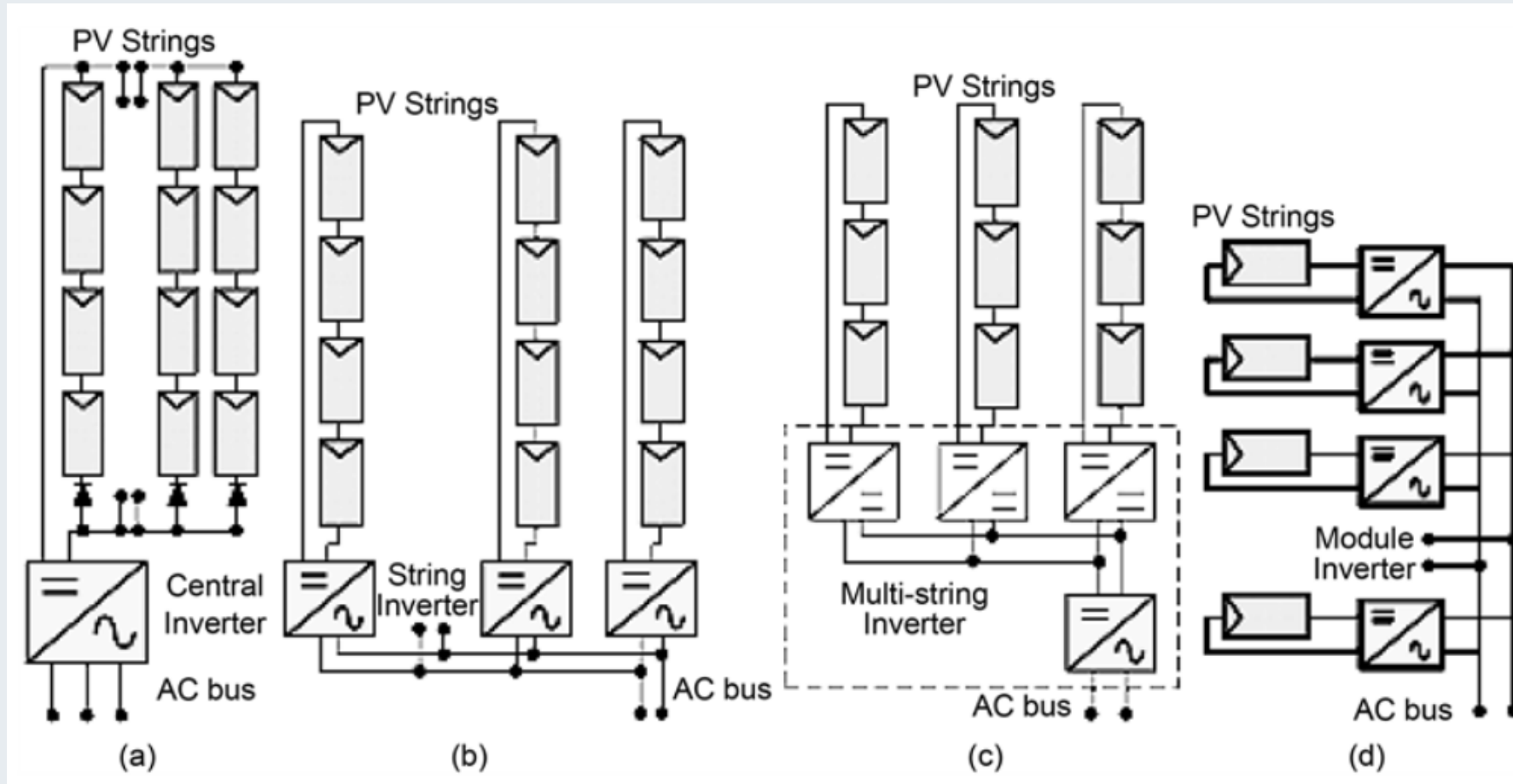
1. **Grid-Connected PV System Configurations**
2. **Controlling Of Grid Connected PV systems**
3. **Photovoltaic Generator Model**
4. **Modeling & Control of grid connected Converters**
5. **Control Strategy of Grid Connected PV Inverter**
6. **Grid Codes and Regulations**

**Summary**

**References**

# 1. Grid-Connected PV System Configurations( GCPVC )

- Solar panels or arrays that are connected to the utility grid via a power inverter unit enable them to function in parallel with the electric utility grid.
- *Grid-connected PV energy conversion* systems can be grouped into four different types of configurations:
  - ✓ Centralized configuration for large-scale PV plants , specifically for 3-phase
  - ✓ String configuration for small and medium-scale PV systems , common for single-phase & 3-phase systems
  - ✓ Multi-string configuration for small- to large-scale systems
  - ✓ AC-module configuration for small-scale systems (commonly single phase).
- Simplified diagrams of each of these configurations are given in Fig.1.



**Figure 1.** Grid-connected PV system configurations[1]: a. Centralized configuration b. String Configuration c. Multi-string configuration d. AC-module configuration.

<https://www.scirp.org/journal/paperinformation?paperid=72028>

- The centralized topology uses a single three-phase voltage source inverter (VSI) to connect the whole PV plant to the grid as presented in Fig.1.a
- Here, as presented earlier, the PV system is formed by the series connection of modules or string to reach the desired output power.
- The advantages of this configuration is that its simple structure, single transformer and single control system that needs single set of sensors, control platform and grid monitoring unit.
- This comes at the expense of reduced power generation because of a single MPPT algorithm for the whole PV system. Also, diode conduction losses are introduced by the string series blocking diodes.
- Currently, the central configuration is the most widely used topology for large-scale PV plants.

- The string configuration presented in Fig.1.b uses one inverter per PV string; hence there is no need for a **series blocking diode**.
- In addition, for a PV plant consisting of several string inverters instead of a single central inverter, there will be more individual MPPT available, increasing the total energy yield.
- Partial shading and mismatch are reduced at a string level and not at an array level.
- The string configuration also increases modularity, since additional PV strings and string inverters can be added to the power plant without affecting existing strings.

However, compared to a central inverter, the string configuration has:

- A higher component count, multiple transformers if isolation is required and a need for several individual grid control systems
- Thus, it needs several number of the sensors, control platforms, grid monitoring units and others for a power plant of the same size of centralized inverter type PV systems
- Accordingly, for the large PV plants, the investment cost of a string inverter configuration can reach up to 60% higher than that of a central inverter configuration.
- Therefore, the string topology is widely adopted as a solution for small- and medium-scale PV systems like rooftop and residential systems.

- Figure 1.c presents the multi-string configuration of grid connected PV system, which merges the benefits of the centralized and string systems.
- It introduces the distributed MPPT capability of the string configuration through individual DC–DC converters interfacing each string to the centralized inverter
- The DC–DC stage also serve for voltage elevation and isolation
- Accordingly, the system utilizes the major benefits centralized structure of the grid connected system like simple structure and single grid-side control system
- But, the multi-string structure gains higher energy yield and modularity compared to the central topology

- In terms of component count: the multi-string configuration is above the central topology, because of additional DC–DC converters, and below the string inverter, since the DC–DC stage requires fewer components compared to the grid-tied inverters.
- Among the disadvantages are higher DC-cable losses, which are necessary to connect smaller parts of the PV system and DC–DC converters to the central inverter
- The multi-string configuration is popular for small- and medium-scale PV systems such as rooftop ones
- More recently, it has also been introduced for large- or utility-scale PV plants.

- Finally, the AC-module or module-integrated topology, commonly referred to as micro-inverter is presented in Fig.1.d
- Which is the most distributed power converter architecture for grid-connected PV systems, since it features one inverter per PV module.
- Therefore, it has the best MPPT capability of all configurations.
- Because PV modules usually generate a low voltage, which is less than 50 V, voltage elevation is required for grid connection of this configuration.
- Generally, AC-module topologies usually include a DC–DC boosting stage to elevate the voltage of the module.
- Therefore, this topology is intended for small-scale PV systems and more domestic use.

## 2. Controlling Of Grid Connected PV systems(CGCPVs)

- Controlling of grid connected PV system is mandatory for all the configurations though the controlling parameters, number of variables and method of controlling varies with the configuration.
- The increased number of grid connected PV inverters gave rise to problems concerning the stability and safety of the utility grid, as well as power quality issues. The main problems in all configuration of grid connected systems are:
  - Voltage rise problem
  - Frequency
  - Increased harmonics
  - Increased voltage unbalance
  - Anti-islanding

## Voltage raise[2]:

- The integration of large amounts of PV systems in the LV networks increases the generation of active power leading to voltage rise along the feeders though it's playing a bigger role in the electricity market because of its capacity to reduce greenhouse gas emissions, support the grid, and provide stand-alone power.
- The typical LV grid's behavior has been impacted by protection concerns, higher losses, transformer and cable rating issues, unexpected voltage rises, and reverse power flow.
- In order to reduce voltage rise issues, communication with PV and voltage control devices must be incorporated.
- The negative effects of high PV penetration have compromised the operation of on load tap changers (OLTC) and automatic voltage regulation.
- At the moment, the voltage rise should not exceed the 2% limit imposed by the old GC

- The **volatile** characteristic of PV type renewable energy sources' power production leads to the grid frequency problems.
- In particular, frequency variation is caused by a temporal disparity between generation and demand brought on by the typical volatility of PV power output though the super-capacitors and other frequency control is adopted
- As a result, it is now essential to take the grid's frequency into account at high PV penetration levels.
- Accordingly, it's better to control the grid-connected photovoltaic system, frequency regulation like battery storage and others. Thus, it's important to maintain the energy balance

- A small PV system linked to the LV grid side must function correctly within the frequency range of 59.3 Hz (98.83%) - 60.5 Hz (100.83%) based on a nominal frequency of 60 Hz, per IEEE 929-2000[3],[4].
- Accordingly, when the frequency falls to 59.2 Hz (98.66%) or rises to 60.6 Hz (101%), the PV plant must trip.
- Within six cycles, the inverter shall stop energizing the utility wires when the frequency drops below the permitted range.
- However, according to IEC 61727, the frequency range is 49 Hz (98%) to 51 Hz (102%) based on a system frequency of 50 Hz[5].
- Means, the PV system must be unplugged **within 0.2 Hz** if the system frequency falls outside of these bounds.

# CGCPVs

# Cont.....

- While the PV system is connected to the power grid side, the frequency deviation is required to meet the requirements.
- For instances , the Germany, France and Spain grid codes for frequency is presented in Table.1

Table 1. grid connected PV system frequency tolerances[5]

| Country                         | Germany           | France        | Spain           |
|---------------------------------|-------------------|---------------|-----------------|
| Frequency tolerance             | $47.5 < f < 51.5$ | $48 < f < 51$ | $47.5 < f < 52$ |
| Over frequency trip time (sec.) | 10 cycles         | N/A           | N/A             |
| Under-frequency trip time(sec.) | 10 cycles         | N/A           | N/A             |

# CGCPVs

# Cont.....

- Accordingly, controlling several grid connected systems, from PV up to Grid is needed to maintain the network stability and reliability
- Thus, the penetration of PV into the smart grid and vice versa requires studies in variability and conversion technology.
- Needs the mathematical modeling of PV systems , converters and controlling devices
- The tracking method based on modern AI based mechanisms to obtain enough power at PV systems and its delivery to grid is needed.
- The control system and modulation schemes depend on the topology and vary from one topology to another.
- Nevertheless, the main control objectives are universal and include MPPT of the PV system, grid synchronization, DC-link voltage control, active and reactive power control and grid Monitoring including anti-islanding detection.

### 3. Photovoltaic Generator Model(PVGM)

- Models of photovoltaic cells have long been used to describe the behaviors of photovoltaic cells.
- The single diode circuit model, which is shown in Fig.2, is the most often used model for predicting energy generation in solar cell modeling.
- A current source/photon current  $I_{ph}$  is included in this model; it is dependent on *cell temperature and solar radiation*.
- A diode in which, after accounting for resistive losses, the inverse saturation current  $I_0$  depends mostly on the *operating temperature, a series resistance  $R_s$ , and a shunt resistance  $R_{sh}$* .
- The current–voltage relationship of a photovoltaic cell is given by:

$$I = I_{ph} - I_0 \left( \exp\left(\frac{V + R_s I}{A}\right) - 1 \right) - \frac{V + R_s I}{R_{sh}} \quad \text{eqn.(1)}$$

# PVGM

# Cont.....

- This eqn.1 can be solved by different iterative mechanisms.

Where,  $A = nkT/q$  modified ideality factor,  $n$  the diode ideality factor,  $k$  the Boltzmann constant ( $1.38 \cdot 10^{-23} \text{ JK}^{-1}$ ),  $q$  the electronic charge ( $1.602 \cdot 10^{-19} \text{ C}$ ),  $T$  the cell temperature (K),  $V_t$  the thermal voltage ( $V_t = kT/q$ , V),  $R_s$  the series resistance ( $\Omega$ ) and  $R_{sh}$  is the shunt resistance ( $\Omega$ ).

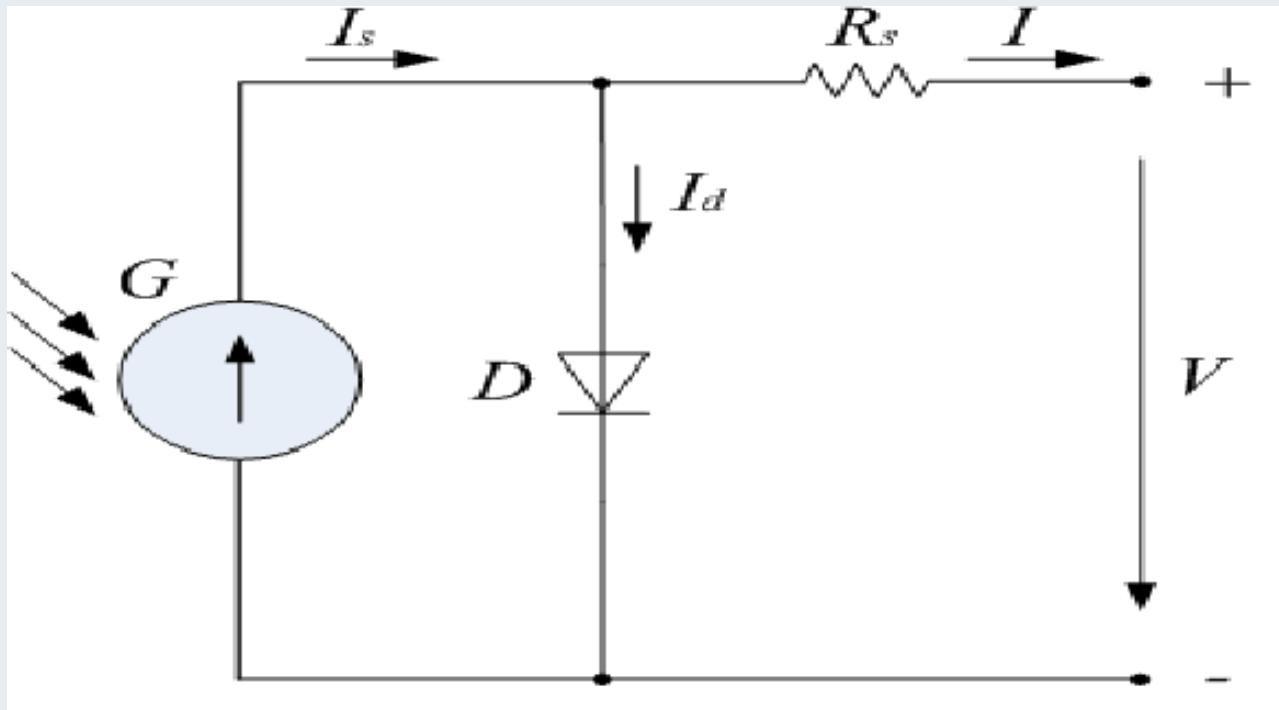


Figure 2. The single diode circuit model representation PV system[7] .

URL. <https://api.semanticscholar.org/CorpusID:14288298>

- The cell temperature, the incident solar irradiance, and their reference values are the three factors that affect the five parameters in Eqn.(1).
- PV module manufacturers typically supply these reference values for specific operating conditions like STC.
- The standard conditions and real operating conditions are never the same, and mismatch factors may also have an impact on the real values of these mean parameters.
- Therefore, it is crucial to assess the five characteristics *under actual working conditions in order to produce a mathematical model of a PV module that is accurate.*
- The above reference value can be changed using different operating conditions as given by[8]:

$$I = I_{ph(ref)} - I_{0(ref)} \left( e^{\left( \frac{V + R_{s(ref)} * I}{A_{ref}} \right)} - 1 \right) - \frac{V + R_{s(ref)}}{R_{sh(ref)}} \quad \text{eqn.(2)}$$

# PVGM

Cont.....

## A. short circuit condition

- Thus, at short ckt condition  $I=I_{sc}$  and  $V=0$ , then eqn.2 is rewritten as:

$$I_{SC(ref)} = I_{ph(ref)} - I_{0(ref)} \left( e^{\left( \frac{R_s(ref) * I_{SC(ref)}}{A_{ref}} \right)} - 1 \right) - \frac{R_s(ref)}{R_{sh(ref)}} \quad \text{eqn.(3)}$$

## B. open circuit condition

- $I=0$ , and  $V=$  open circuit voltage ( $V_{OC}$ ), Then:

$$I_{ph(ref)} - I_{0(ref)} \left( e^{\left( \frac{V_{OC(ref)}}{A_{ref}} \right)} - 1 \right) - \frac{V_{OC(ref)} + R_s(ref)}{R_{sh(ref)}} = 0 \quad \text{eqn.(4)}$$

## C. at maximum power point (MPP), $V=V_{max}$ and $I=I_{max}$ ). Then:

$$I_{m(ref)} = I_{ph(ref)} - I_{0(ref)} \left( e^{\left( \frac{V_m(ref) + R_s(ref) * I_m(ref)}{A_{ref}} \right)} - 1 \right) - \frac{V_m(ref) + R_s(ref)}{R_{sh(ref)}} \quad \text{eqn.(5)}$$

- Then, the derivation of original eqn., eqn.1 at  $V=V_{oc(ref)}$  and  $I=I_{sc(ref)}$ , respectively is given as :

$$\left. \frac{\partial V}{\partial I} \right|_{V=V_{OC(ref)}} = -R_{s0} \quad \text{eqn.(6)}$$

$$\left. \frac{\partial V}{\partial I} \right|_{I=I_{SC(ref)}} = -R_{sh0} \quad \text{eqn.(7)}$$

- Where,  $R_{s0}$  and  $R_{sh0}$  are the slopes of the I-V curve in open circuit and short circuit points, respectively
- Thus, the series and shunt resistances of the semiconductor can be easily determined using the above equations for initial conditions.

- Normally, the outdoor measurements of multiple I-V curves for a standard module can be combined to determine  $I_{sc(ref)}$ ,  $V_{oc(ref)}$ ,  $I_{m(ref)}$  and  $V_{m(ref)}$ . This can be expressed mathematically as;;

$$I_{sc(ref)} = I_{sc(mes)} * \frac{G_{ref}}{G_{mes}} + \alpha(T_c - T_{ref}) \quad \text{eqn.(8)}$$

$$V_{OC(ref)} = V_{OC(mes)} - \beta(T_c - T_{ref}) + V_t \ln\left(\frac{G_{ref}}{G_{mes}}\right) \quad \text{eqn.(9)}$$

$$I_{m(ref)} = I_{m(mes)} * \frac{G_{ref}}{G_{mes}} + \alpha(T_c - T_{ref}) \quad \text{eqn.(10)}$$

$$V_{m(ref)} = V_{m(mes)} - \beta(T_c - T_{ref}) - R_{s(mes)}(I_{m(mes)} - I_{m(ref)}) + V_t \ln\left(\frac{G_{ref}}{G_{mes}}\right) \quad \text{eqn.(11)}$$

Where,  $G_{ref}$  and  $G_{mes}$  are the reference and measured irradiances,  $\alpha$  is the temperature coefficient of the short circuit current,  $T_{ref}$  and  $T_{mes}$  are the reference and measured Temperature,  $\beta$  is the temperature coefficient of the module Voltage

- Then, by introducing the parameters from eqn. 8 to eqn.11 into eqn.2 , the five reference parameters are determined as;

$$A_{ref} = \frac{V_{m(ref)} + I_{m(ref)}R_{so} - V_{oc(ref)}}{[\ln[I_{sc(ref)} - \frac{V_{m(ref)}}{R_{sh(ref)}} - I_{m(ref)}] - \ln[I_{sc(ref)} - \frac{V_{oc(ref)}}{R_{sh(ref)}}] + [\frac{I_{m(ref)}}{I_{sc(ref)} - \frac{V_{oc(ref)}}{R_{sh(ref)}}}]]} \quad \text{eqn.(12)}$$

$$I_{o(ref)} = (I_{sc(ref)} - \frac{V_{oc(ref)}}{R_{sc(ref)}}) e^{(\frac{-V_{oc(ref)}}{A_{ref}})} \quad \text{eqn.(13)}$$

$$R_{sh(ref)} = R_{sh0} \quad \text{eqn.(14)}$$

$$R_{s(ref)} = R_{s0} \quad \text{eqn.(15)}$$

$$I_{ph(ref)} = I_{sc(ref)} (1 + \frac{R_{s(ref)}}{R_{sh(ref)}}) + I_{o(ref)} * \{e^{(\frac{I_{sc(ref)} * R_{s(ref)}}{A_{ref}})} - 1\} \quad \text{eqn.(16)}$$

**B. Then, for real conditions, the equations can be rewritten as;**

- Model ideal factor:

$$A = A_{ref} \left( \frac{T}{T_{ref}} \right) \quad \text{eqn.(17)}$$

- Saturation current of the diode:

$$I_0 = I_{0(ref)} \left( \frac{T}{T_{ref}} \right) \exp \left[ \frac{E_g N_s}{A_{ref}} \left( 1 - \frac{T_{ref}}{T} \right) \right] \quad \text{eqn.(18)}$$

where,  $E_g$  is the band-gap energy of semiconductor and  $N_s$  is the total number of cell connected radial

- Photo current is:

$$I_{ph} = \left( \frac{G}{G_{ref}} \right) [I_{ph(ref)} + \alpha(T - T_{ref})] \quad \text{eqn.(19)}$$

- Series resistance is:

$$R_s = R_{S(ref)} - \left[ \frac{A}{I_0} \exp \left( - \frac{V_{oc}}{A} \right) \right] \quad \text{eqn.(20)}$$

- Shunt resistance is:

$$R_{sh} = R_{Sh(ref)} \left( \frac{G_{ref}}{G} \right)$$

eqn.(21)

- Short circuit current and open circuit voltage at any operating condition is given by:

$$I_{sc} = I_{sc(ref)} \left( \frac{G_{ref}}{G} \right) + \alpha(T - T_{ref})$$

$$V_{oc} = V_{oc(ref)} - \beta(T_{ref} - T) + A * \ln\left(\frac{G}{G_{ref}}\right)$$

eqn.(22)

- The current and voltage at maximum power point are given by:

$$I_m = I_{m(ref)} \left( \frac{G_{ref}}{G} \right)$$

$$V_m = V_{m(ref)} - \beta(T_{ref} - T)$$

eqn.(23)

## 4. Modeling & Control of grid connected Converters (MCGC)

- The significant advancements in the photovoltaic industry have presented novel obstacles for inverters, which are now expected to enhance grid stability through the provision of support functions[9]. **The main challenges which inverters faces are:**

Stage 1: Current control, harmonics, synchronizations and voltage unbalance

Stage 2: Power control(active and reactive power) and power quality

Stage 3: Grid Interaction with optimal support of power interaction

As observed in Fig. 3, controlling stage one leads to controlling stage 2 and the grid integration comes after stage three.

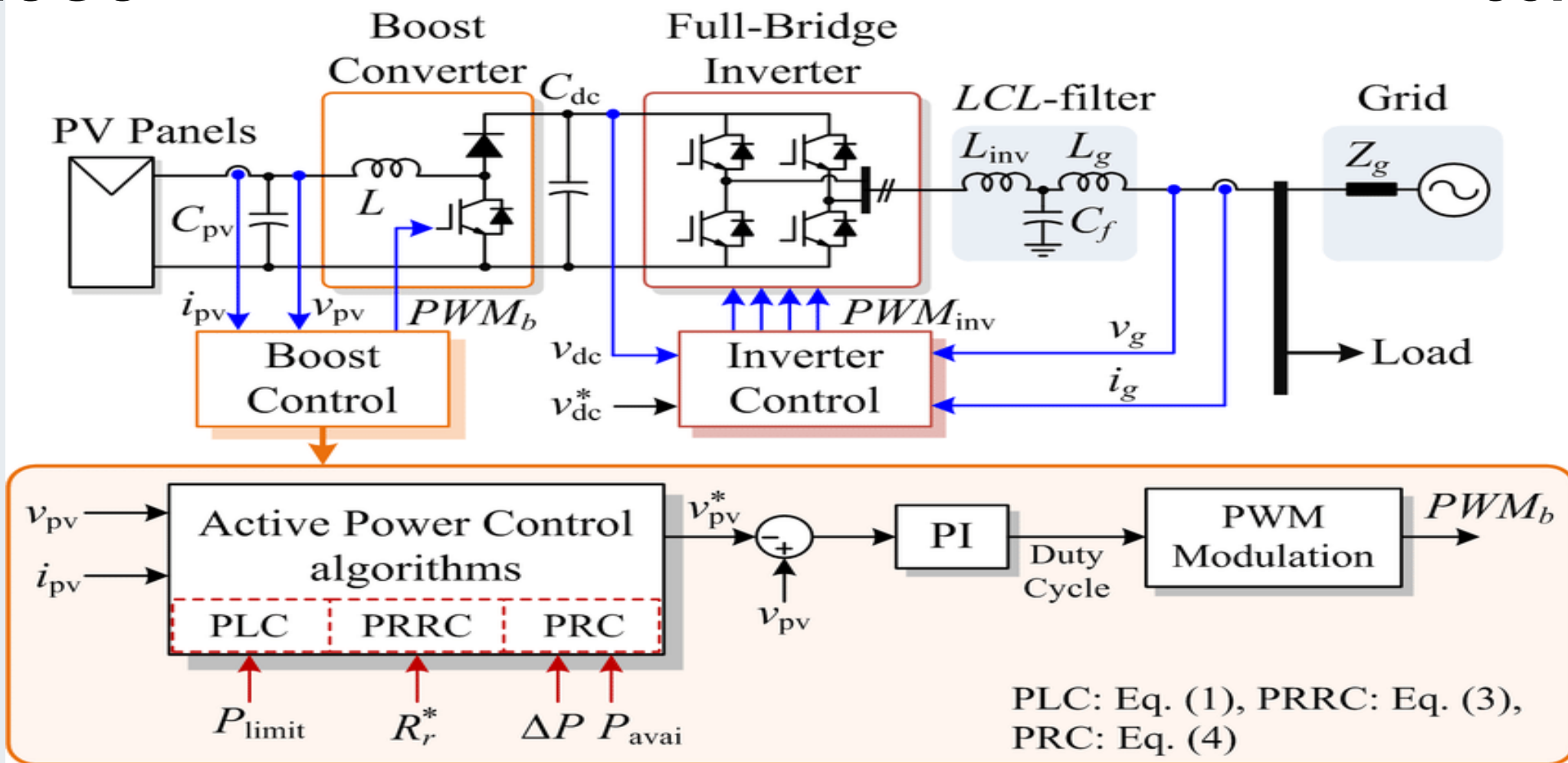


Figure 3. Grid connected configuration and control scheme of PV system with active power control strategies [10]. Url: <https://www.researchgate.net/publication/318762121>

- For example, as observed in Fig.3, harmonics and overall power of the system is easily controlled while integrating with grid using chopper based on the three principles:
  1. Power Limiting Control (PLC) Algorithm
  2. Power Ramp-Rate Control (PRRC) Algorithm
  3. Power Reserve Control (PRC) Algorithm
- In this control scheme, the PV power extraction is controlled by the boost converter through the regulation of PV voltage  $V_{pv}$  while the **full-bridge inverter transfers the extracted** PV power to the AC grid by regulating the dc-link voltage  $V_{dc}$  to be constant.

- The active power control strategy is then implemented in the boost stage, which is achieved by determining an appropriate reference PV voltage  $V_{pv}$  for a certain active power control strategy: power limiting control(PLC), power ramp-rate control(PRRC), power reserve control(PRC) as presented below [11]:

## a. Power Limiting Control (PLC) Algorithm.

- Regulating the operating voltage of the PV arrays  $V_{pv}$  along the PV voltage (Horizontal line) is necessary to limit the PV output power to a specific level  $P_{limit}$ .
- As shown in Fig. 4, the reference PV voltage  $V_{pv}$  is constantly perturbed towards the left side of the MPP during the power limiting operation (i.e.,  $P_{pv} > P_{limit}$ ) until  $P_{pv} = P_{limit}$ .
- The PV system **injects the maximum** amount of power into the grid if the PV output power falls below the power limit level ( $P_{pv} < P_{limit}$ ).
- The reference PV voltage,  $V_{pv}$ , is determined by the MPPT algorithm, which is based on P&O.

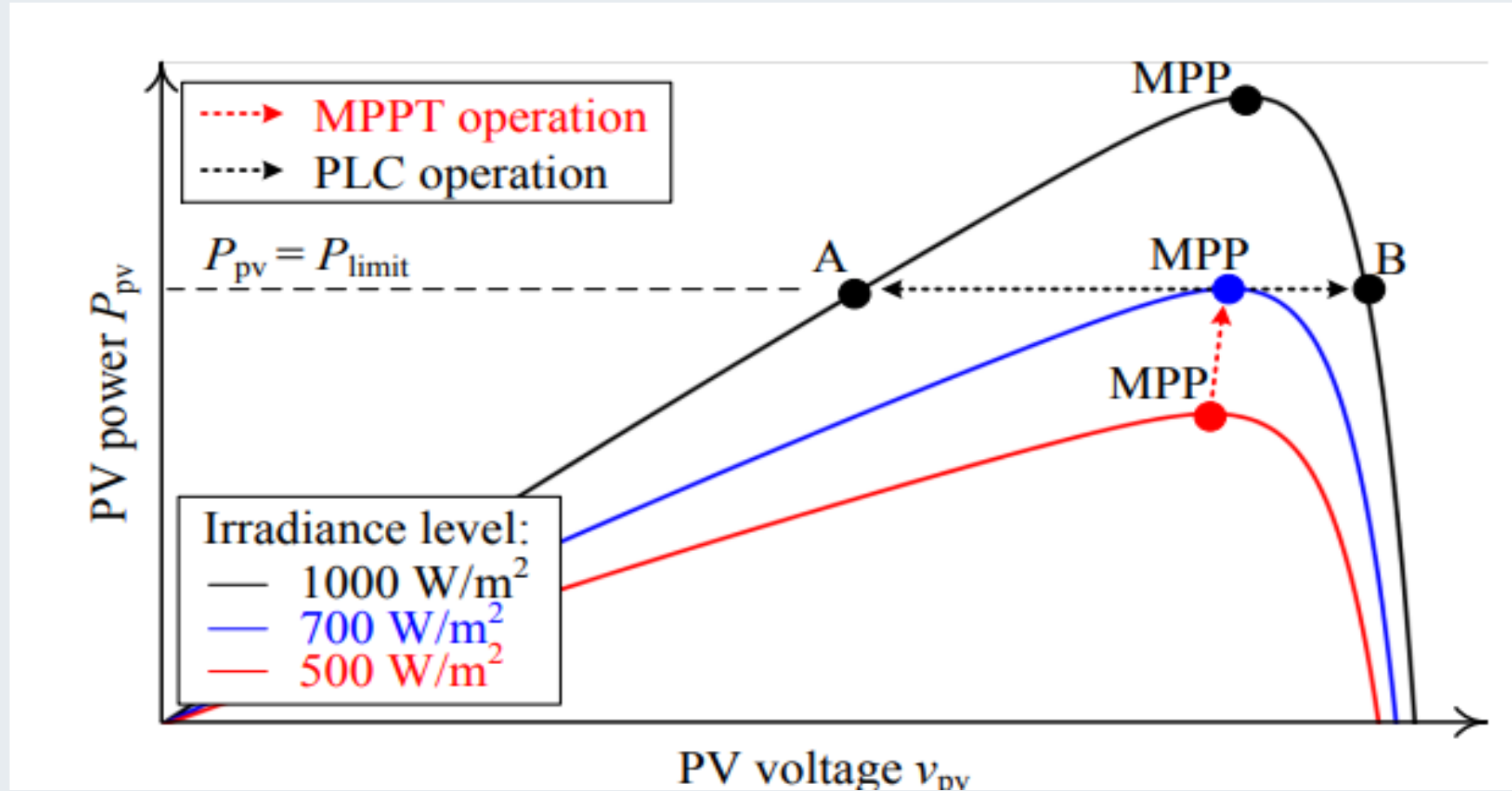


Figure 4. Operating principle of the PLC algorithm. [https://www.researchgate.net/figure/Operational-principle-of-the-Power-Limiting-Control-PLC-algorithm-where-the\\_fig4\\_327509824](https://www.researchgate.net/figure/Operational-principle-of-the-Power-Limiting-Control-PLC-algorithm-where-the_fig4_327509824)

**b. Power Ramp-Rate Control (PRRC) Algorithm:** The principle of PRRC is similar to the PLC.

- In this case, the criterion to curtail the PV power is coming from the change rate of the PV power, instead of an absolute PV power.
- Specifically, the PV power ramp-rate  $R_{r(t)}$  is first calculated as:

$$R_{r(t)} = \frac{\partial P_{PV}}{\partial t} \quad \text{eqn.(24)}$$

- Then, if the change rate of the PV power  $R_{r(t)}$  is above a certain limit  $R_r$ , the PV voltage  $V_{pv}$  is perturbed towards the left side of the MPP, in order to reduce the change rate of the PV power to a certain value ;  $R_{r(t)} = R_r$ .
- The operational principle of the PRRC algorithm is given in Fig.5

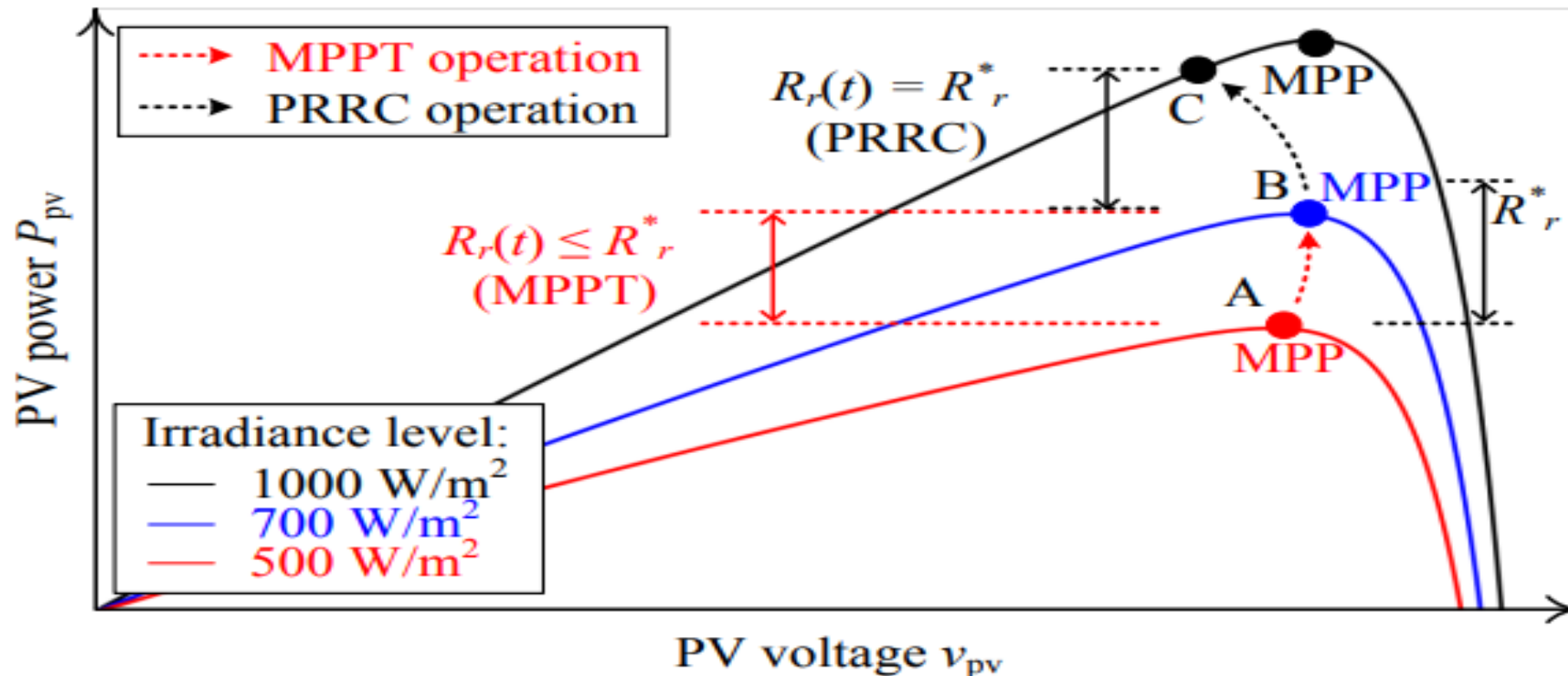


Figure 5. Operational principle of the Power Ramp-Rate Control (PRRC) algorithm: MPPT mode (A to B) and PRRC mode (B to C), where  $R_r(t)$  is the PV power ramp-rate and  $R_r$  is the ramp-rate limit. [https://www.researchgate.net/figure/Operational-principle-of-the-Power-Ramp-Rate-Control-PRRC-algorithm-the-operating\\_fig5\\_327509824](https://www.researchgate.net/figure/Operational-principle-of-the-Power-Ramp-Rate-Control-PRRC-algorithm-the-operating_fig5_327509824)

### C. Power Reserve Control (PRC) Algorithm

- PV power must be regulated below the MPP with a specific power reserve level  $P$  in order to implement power reserve control.
- This control functionality can actually be thought of as a specific instance of power limiting control, in which a predetermined power reserve level  $P$  is attained by dynamically varying the power limit level  $P_{\text{limit}}$  during operation.
- As a result, to determine the power limit level  $P_{\text{limit}}$ , deduct the required amount of power reserve from the available PV power  $P_{\text{avai}}$ , using the formula  $P_{\text{limit}} = P_{\text{avai}} * P$ .
- Fig. 6 illustrates the power reserve control strategy's working theory.

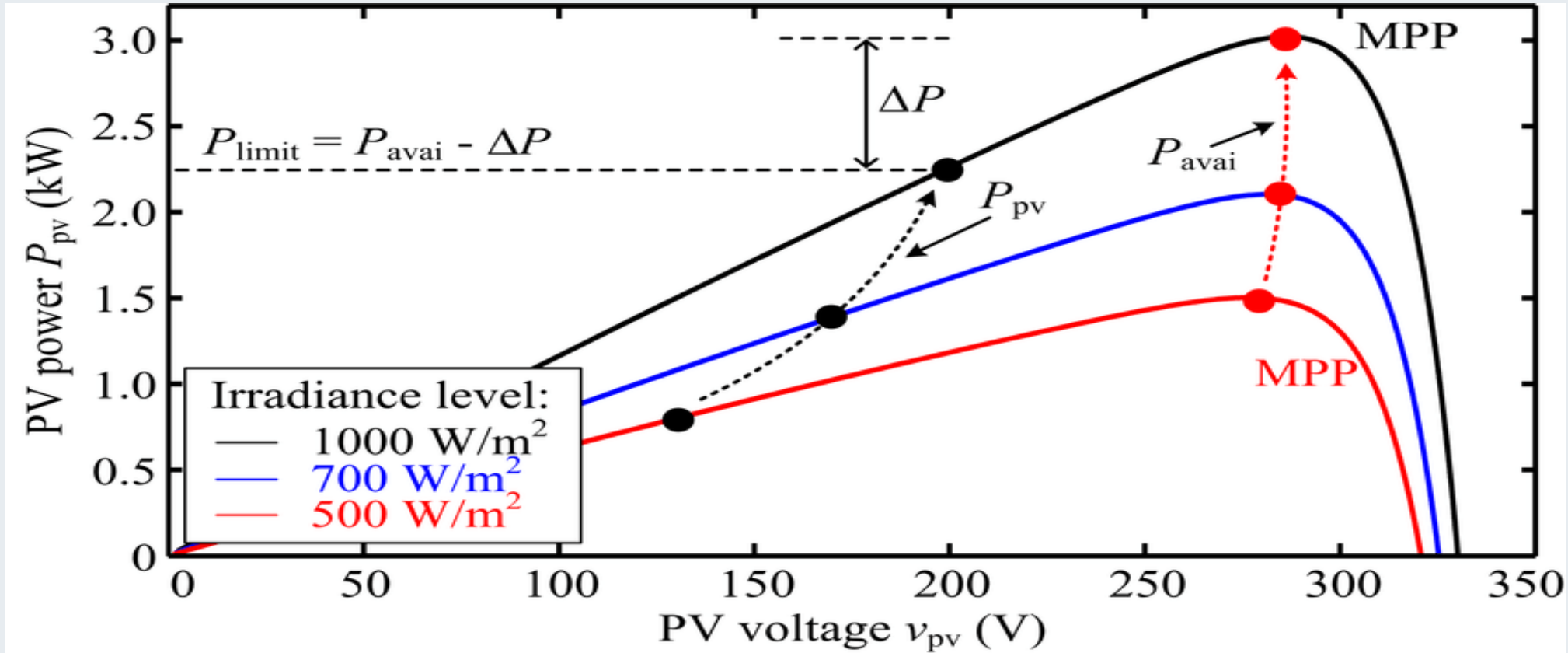


Figure 6. Operational principle of the Power Reserve Control (PRC) algorithm. [https://www.researchgate.net/figure/Operational-principle-of-the-Power-Reserve-Control-PRC-algorithm-where-P-avai-is-the-figure4\\_318762121](https://www.researchgate.net/figure/Operational-principle-of-the-Power-Reserve-Control-PRC-algorithm-where-P-avai-is-the-figure4_318762121)

# 5. Control Strategy of Grid Connected PV Inverter (CSGCPVI)

- The equivalent circuit, output voltage and current relationship of PV module is expressed in previous eqns.
- One of the essential devices in CSGCPVI control strategy is given in Fig.6
- The control circuit is divided into two control loops named as an inner current loop for controlling duty ratio and outer voltage loop to track the maximum power point to stabilize DC-link voltage
- Two currents are involved in inner loop control: active current ( $I_d$ ) and reactive current ( $I_q$ ).
- In normal operation, the output of the voltage loop (active current,  $I_{dr}$ ) is used as a reference while the reference of reactive current ( $I_{qr}=0$ ).
- Therefore, CSGCPVI operates at a nearly **unity** power factor.
- To control the grid current and dc-link voltage, typical different control approaches are utilized.

- For the generation of inverter switching pulses, it is necessary to produce active reference and the reactive reference voltage from the inner loop, and these are transformed into  $V_{dq}$ , and then to  $V_{abc}$ .
- The obtained  $V_{abc}$  is applied to PWM generator to produce required switching pulses to an inverter
- The mathematical modeling of three phase grid connected PV system as follows for conventional inverter

model.

$$V_{ai} = Ri_a + L \frac{\partial i_{ai}}{\partial t} + e_{ga}$$

$$V_b = Ri_b + L \frac{\partial i_{bi}}{\partial t} + e_{gb}$$

$$V_{ci} = Ri_c + L \frac{\partial i_{ci}}{\partial t} + e_{gc}$$

eqn.(25)

By rearranging the state space and time variant analysis the real and reactive power can be given by:

$$P = \frac{3}{2} E_{gd} I_d$$

$$Q = -\frac{3}{2} E_{gd} I_q$$

eqn.(26)

## 6. Grid Codes and Regulations

- The primary goal of connecting large number of renewable energy devices to the grid in recent years has been to boost the output of renewable energy contribution to the environment, economy and SDGs.
- However, due to the imperfections in the utility grid and volatile characteristics of RE , it is possible for the grid's voltage and frequency to surpass the established boundaries, which is unwanted and intolerable.
- Maintaining the voltage and frequency regulation, power quality enhancement, and energy balancing are necessary for the effective and dependable operation of electrical power networks.
- The grid operator of a power system is in charge of ensuring proper functioning and has the ability to buy auxiliary services straight from the PV generators. Until recently, inverters had to disconnect and wait for the fault to clear in the event of unexpected grid circumstances or breakdowns.

# Summary

- In conclusion, the grid connected configuration PV systems based on their advantage and disadvantage, application and control strategies are well discussed in this lecture
- The modeling of grid connected system, specifically the power generation takes paramount for better harvesting of power from PV system.
- In line with this, controlling the current and voltage of PV generator is the dominant factor in harvesting maximum power.
- Besides, different controlling strategies of boost converter for MPPT is observed in this lecture.
- Finally, the grid code for better synchronization of power between grid and PV is also discussed.

# References

- [1]. K. Kirubasankar and A. Senthil Kumar. "Inverter Power Stage Connected with PV-Grid". Circuits and Systems. Vol.7 (13), 2016.
- [2]. K. Aina and F. Komla. "Voltage Rise Issue with High Penetration of Grid Connected PV". IFAC Proceedings . V.47(3).2014. <https://doi.org/10.3182/20140824-6-ZA-1003.01989>
- [3]. "IEEE Recommended Practice for Utility Interface of Photovoltaic(PV) Systems," IEEE Std 929-2000 , vol., no., pp.i., 2000
- [4]. International Electrotechnical Commission, "IEC 61727 -Photovoltaic (PV) systems – Characteristics of the utility interface",2004.
- [5] B. Crăciun. "Overview of Recent Grid Codes for PV Power Integration," 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp. 959-965, 2012.
- [6]. H. Khairy; M. EL-Shimy and G. Hashem. "Overview of Grid Code and Operational Requirements of Grid-connected Solar PV Power Plants". Industry academia collaboration conference(IAC). 2015. Egypt.
- [7]. B. Jitendra; P. Surya and R. Ankita R. Joshi. "Modeling and Simulation of PV Cell using One-diode model". International Journal of Scientific and Research Publications. V. 3(10,), 20123. <https://api.semanticscholar.org/CorpusID:14288298>.
- [8]. Ch. Aissa; S. Santiago; S. Nawel and etl. "Modeling and simulation of a grid connected PV system based on the evaluation of main PV module parameters". Simulation Modelling Practice and Theory. V.20(2012).
- [9]. B.I. Craciun, E.A. Man, V.A. Muresan, D. Sera, T. Kerekes, and R. Teodorescu, Improved Voltage Regulation Strategies by PV Inverters in LV Rural Networks, accepted for publication, The 3rd International Symposium on Power Electronics for Distributed Generation Systems, Aalborg June 2012, Denmark
- [10]. Sangwongwanich, A., Yang, Y., & Blaabjerg, F. (2017). Development of Flexible Active Power Control Strategies for Grid-Connected Photovoltaic Inverters by Modifying MPPT Algorithms. In Proceedings of IFEEC 2017 -ECCE Asia (pp. 87-92). IEEE Press. <http://dx.doi.org/10.1109/IFEEC.2017.7992423>
- [11]. K. Rajasekhara Reddy; V.Nagabhaskar Reddy; M.Vijaya Kumar and etl. "Configurations and Control Strategy of a Single Stage Grid Connected PV System". E3S Web of Conferences , ICMED 2020. <https://doi.org/10.1051/e3sconf/202018401074>

Thank you !