TAMPEREEN TEKNILLINEN YLIOPISTO

Aspects on designing switched-mode power electronic converter for photovoltaic application

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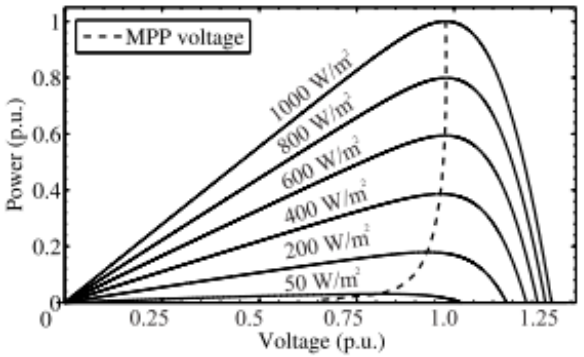
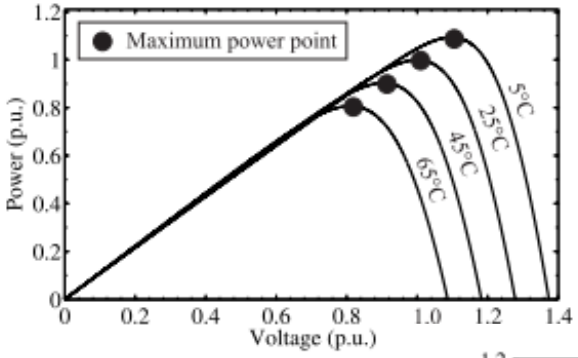
Co-funded by the Erasmus+ Programme of the European Union

MPP

- The output power is maximized at a certain operating point called maximum power point (MPP) located between these conditions.





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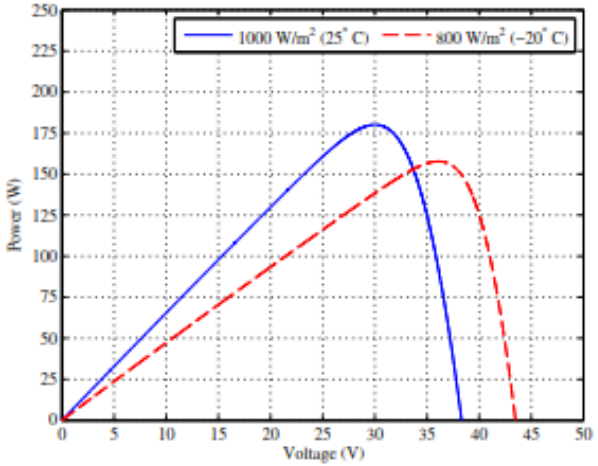
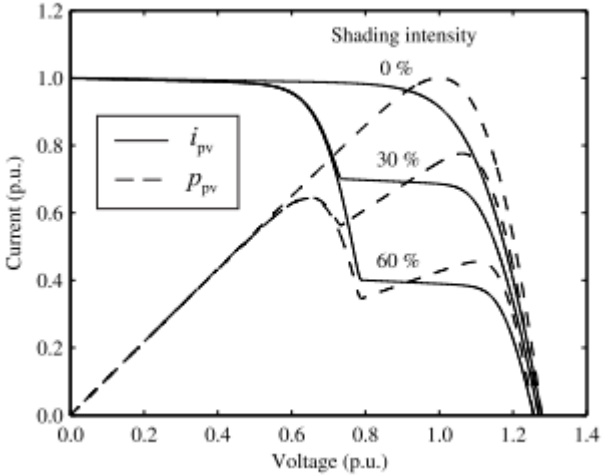




Picture: PhD Jukka Viinamäki

MPPT

- The performance of MPPT is one of the most important concerns in any PV system and it has been observed to have significant contribution to the reliability problems in photovoltaic energy systems.

- The most of the developed MPPT techniques usually measure both voltage and current values. Temperature and irradiance sensors are avoided due to their high costs, especially in large PV plants where each panel requires own sensor.

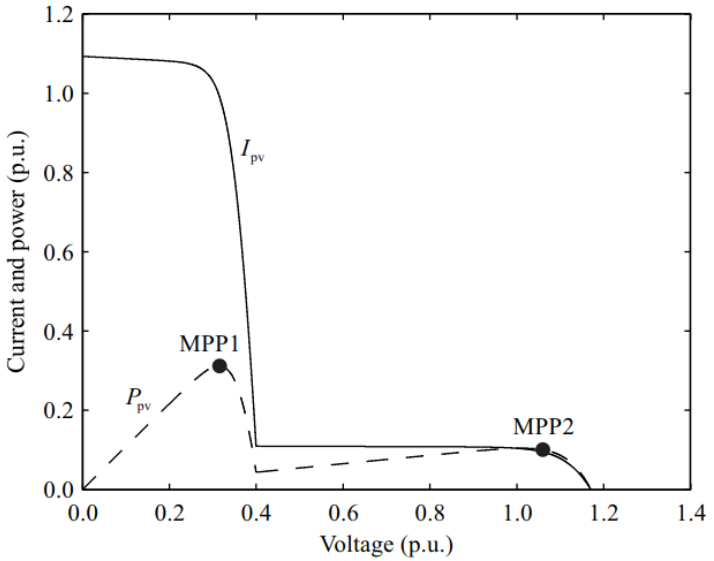
- The appearance of multiple MPPs on PVG characteristics have created a requirement to develop MPPT algorithms that can separate **global** maximum power point from the **multiple local** maximum power points.

- MPPT can be implemented either by using analog or digital circuitry. The simplest algorithms can be designed with microcontrollers, whereas the more advanced techniques require digital signal processors (DSP) or field-programmable gate array (FPGA) systems.

Properties of a photovoltaic generator

- Typically, the size of the cell group is around 20 cells yielding 3 bypass diodes in 190 W panel.
- In this kind of PV panel, 3 separate maximum power points can occur if the irradiance level is different for each group.

- The MPP locates at the lowest voltage level, when 2 out of 3 cell groups are shaded. The irradiance of the non-shaded cell is 1000W/m^2 and 100W/m^2 for the shaded cells.
- The voltage of the MPP is 1/3 of the MPP voltage in non-shaded condition. If the maximum power is to be extracted also in this situation, the input voltage range of the interfacing converter should be wide, as it should be able to handle also the maximum OC voltage of the PVG.



Picture: PhD Jukka Viinamäki

MPPT algorithms

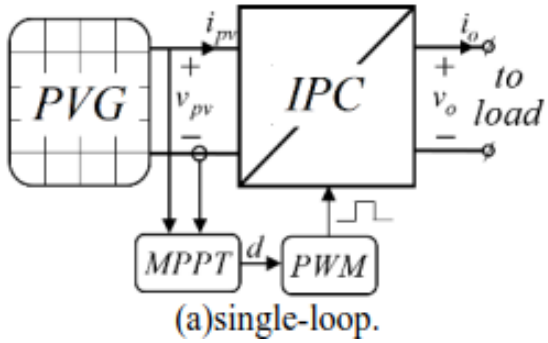
- When operating in MPPT mode, the DC/DC converter can operate either in open loop or closed loop.
- Two main MPPT control structures are typically adopted.

1. Single-loop

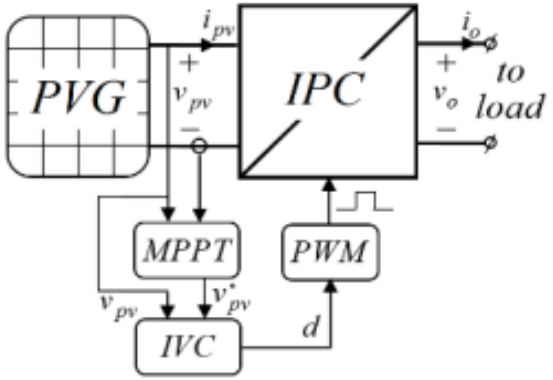
- Direct perturbation of the power converter duty cycle
- The system operates in open loop
- Simple implementation and usually faster for the same control bandwidth, relatively good performance

2. Multi-loop

- MPPT algorithm perturbs the PVG reference voltage
- Input voltage controller ensures correct tracking by appropriately varying the duty cycle
- Preferred due to improved robustness to irradiation changes



(a)single-loop.



(b) multi-loop.

Picture: PhD Jyri Kivimäki

Single loop: Indirect MPPT Techniques

- The developed MPPT techniques can be divided into indirect and direct technique referring to the method, how MPP is evaluated.

- The indirect methods are based on the prior knowledge of the PV generator and they do not usually measure the extracted power directly from PVG.

- They estimate the MPP based on a single measurement of voltage or current with predefined data from PVG.
- MPP is determined by predefined mathematical models
  -> MPP can be only approximately tracked.
  -> Significant errors can occur in MPPT if atmospheric conditions deviate too much from those predicted in models

- However, suitable for low-cost applications, since complex hardware is not required.

Single loop: Indirect MPPT Techniques

1. The constant voltage method

- Also known as fractional open-circuit method, one of the simplest MPPT methods.
- The MPP voltage is relatively close to a fixed percentage of the OC voltage. OC voltage is measured in certain time intervals and the operation point can adjusted based on the measurement.
- The problem is to find a proper coefficient to describe the relation between MPP and OC voltage.

2. Look-up table

- The measured voltage and current values of the PVG are compared with those stored in the control system. Based on the saved data, the operation point is forced to the predetermined MPP.
- Large memory capacity is required for storing data

3. Curve fitting

- The nonlinear behavior of PV cell is calculated by using mathematical models. For example, following third-order polynomial is used in curve-fitting technique to characterize the P-U curve.
- Requires a lot of calculation capacity, need huge amount of parameters from manufacturer

Direct MPPT Techniques

- Direct techniques are used if high MPPT efficiency is important in all environmental conditions

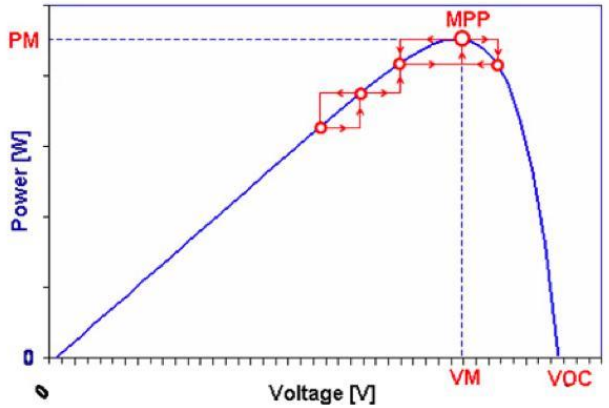
- Include techniques that use voltage and current measurements of PVG for tracking the MPP.
  -> independent from the prior knowledge of the PVG characteristics.
  -> better performance compared to indirect methods in varying atmospheric conditions

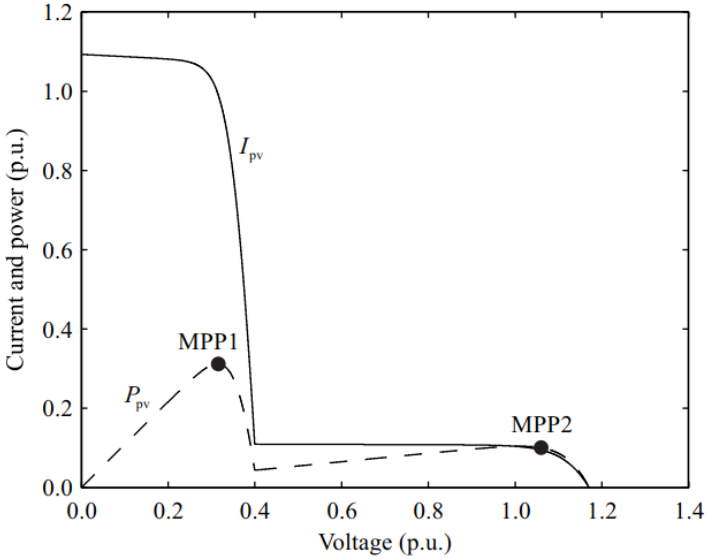
- Perturb-based MPPT techniques are most widely utilized in PV applications.
  1. perturb and observe (P&O)
  2. incremental conductance techniques (IC)

which are based on the injection of small perturbation into the system and observing the effect to locate the MPP. After the MPP is reached, the operation point is oscillating around the MPP causing mismatch losses by natural behavior of the algorithm.

Single-loop: Perturb & Observe

- Perturb & Observe is simple and **one of the most widely used methods**, where the operation point is changed in small steps.
- If the power level was increased, second step is made to the same direction, but if the power level was decreased, the direction of the step is changed.
- One of the drawbacks of this algorithm is that it can locate only local MPP but fails to locate global MPP.
- For example, if P&O algorithm starts from OC voltage, it goes to lower voltage levels step-by-step. Once it obtains MPP2, it starts to oscillate around it and will not go down to MPP1 even if the power level would be higher. For this reason, also algorithms for tracking the global MPP has been developed.

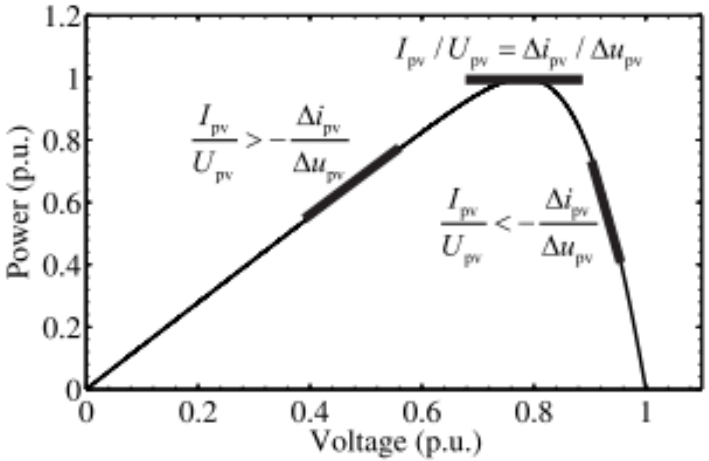




Picture: PhD Jyri Kivimäki

Single-loop: Incremental conductance

- The basic idea of incremental conductance method on a curve for a PV module.
- The slope of the PV power curve is zero at MPP, decreasing on the right of the MPP and increasing on the left hand side of the MPP.
- It is theoretically possible to know when the MPP has been reached, whereas in the P&O implementation the operating point oscillates around the MPP.
- However, because of noise and measurement and quantization errors, the condition is in practice never exactly satisfied, but it is usually required that such condition is approximately satisfied within a given accuracy.



Direct MPPT Techniques

- More intelligent perturb-based algorithms have been introduced. The main idea over the traditional P&O is to reduce the steady-state oscillation around the MPP.

1. Particle swarm optimization (PSO) is a population-based stochastic optimization technique.

2. Extremum seeking (ES) techniques is based on the detection of low-frequency oscillating components of a converter. In grid-connected PV applications, DC-link voltage fluctuation can end up to PVG terminals, where ES can use the 100 Hz voltage ripple component for tracking the MPP. Using the information that the amplitude of sinusoidal disturbance minimizes at MPP, the operation point can be forced to MPP by observing the amplitude of the ripple.

3. Ripple correlation control (RCC) utilizes the high-frequency ripple generated by the switching action to perform MPPT. Since the time derivative of the power is related to the time derivative of the current or of the voltage, the power gradient is driven to zero indicating that the operation point matches the MPP.

Global Maximum Power Point Tracking

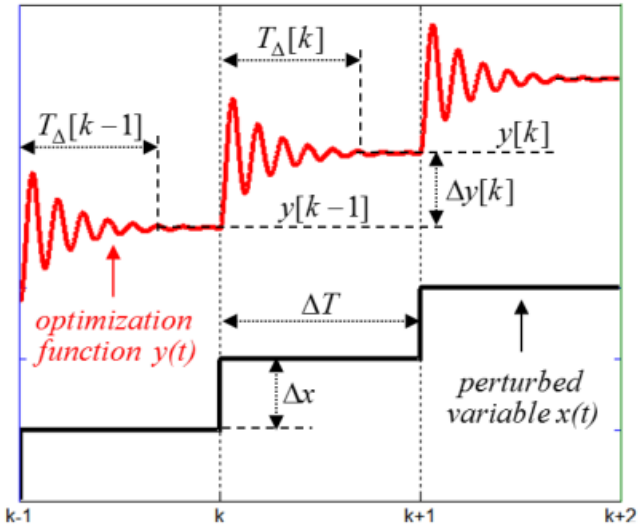
- Most of MPPT techniques are only able to track a local MPP, since they are designed to find the closest MPP in respect to a present operation point.
- However, in partial shading conditions multiple MPPs can occur on the electrical characteristics of the PV generator. Thus the local MPPT algorithms cannot distinguish the local MPP from the global one yielding reduced energy yield.

- The global MPPT algorithms are typically based on scanning the whole P-U curve and then alternatively using a local MPPT algorithms such as perturbative algorithms for fine adjusting.
- The scanning can be performed by using the current sweep method to sweep the operation point from open-circuit to short-circuit condition.
- The major disadvantage is that energy is lost every time the search is performed. The more intelligent approaches to perform P-U curve scanning can be done when utilizing the knowledge about the system and operation conditions.

Single-loop control

- If the converter is operating in open loop, the tracker speed must be small.
- The two design parameters to be decided on are perturbation period ΔT and step size Δx.
- In case of fixed-step MPPT algorithms, the two are determined once a priori and remain unchanged during the operation.

- Perturbation period should be higher than the longest settling time of the PVG output power transient induced by injected perturbation (i.e. ΔT > TΔ must hold throughout the whole operation range).
- Otherwise the algorithm may be deceived and the operating point can enter a chaotic behavior.

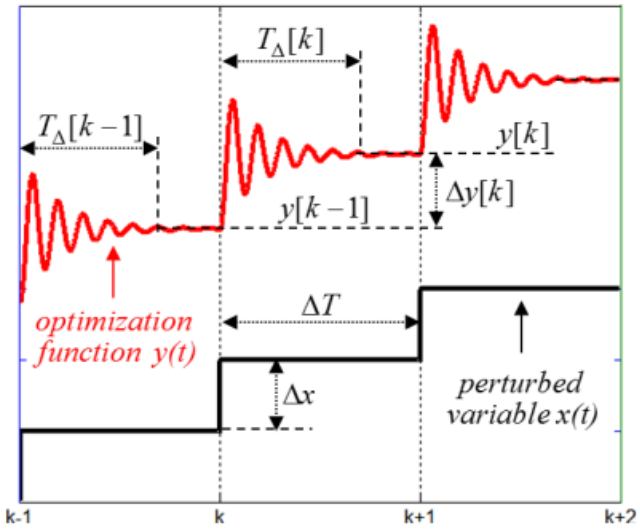


Picture: PhD Jyri Kivimäki

Single-loop control

- Perturbation step size influences the MPPT algorithm performance in both stationary and time-varying atmospheric conditions. In general, perturbation step size should be reduced to increase the efficiency under stationary environmental conditions.
- However, it must remain high enough so that corresponding optimization function change would be higher than that caused by the maximum possible irradiation variation to prevent convergence failure

- It was shown that dynamic resistance of the photovoltaic generator, significantly affects the combined energy conversion system settling time.



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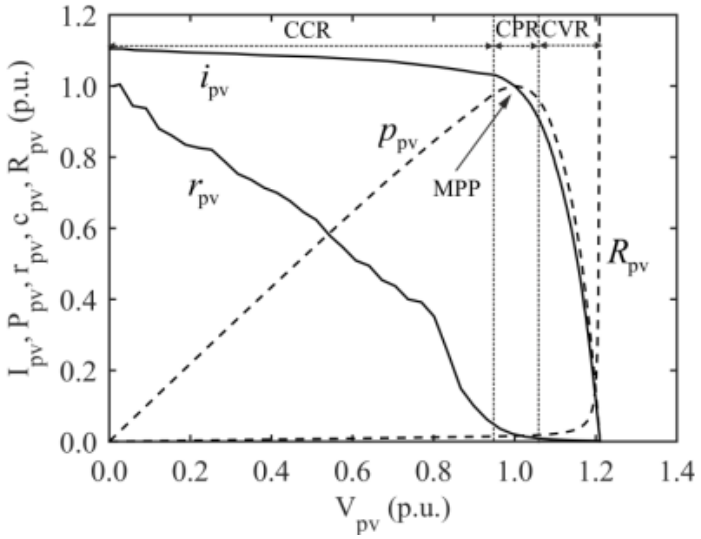
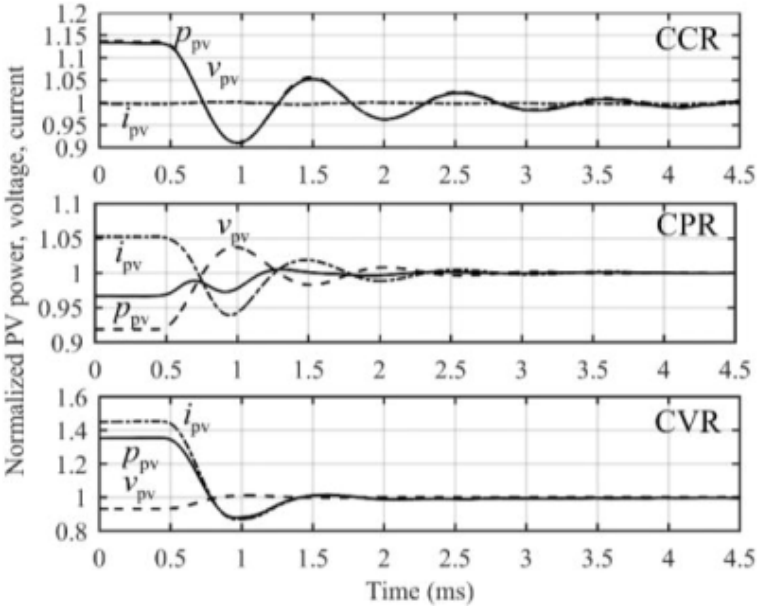
Constant-power region

- Due to finite resolution of digitally controlled measurement systems, MPP is a region rather than a single point.
- Therefore, I-V curve section at the vicinity of MPP may be entitled as constant-power region (CPR).





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Control in closed-loop

- Using closed loop operation, higher speed and better MPPT efficiency can be obtained.
- The voltage of the PVG is usually controlled instead of the current as the rate of change is much bigger in current than in voltage.
- This means that the PVG must be modeled as a current source in this case.
- As the source is conventional applications has usually been voltage source, also PVG is still often modeled as voltage source.
- It is shown that while perturbation step size design is similar to that of single-loop structures, perturbation frequency design is quite different.

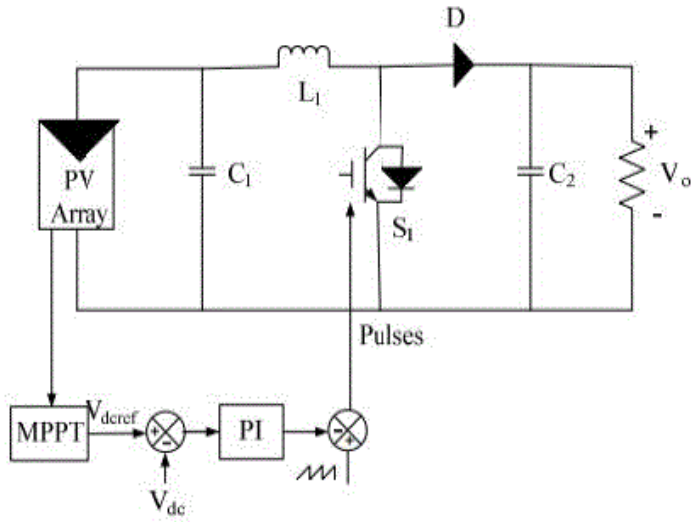

Fig.3 closed loop control for boost converter

Change between the operating modes

- In Energy Storage System (ESS) applications, the DC/DC converter must be able to operate in MPPT mode, when the voltage of the battery is below the set limit. After the voltage exceeds this limit, operation mode is changed to constant voltage charging. This means that the converter bust be able to quickly change between MPPT mode and output voltage control mode.
- The control problem is the same for DC/DC converter in two-stage PV inverter, which must be able to operate in grid-feeding and grid-forming operating modes.
- It is important to understand how the operation in both of these modes affects the control design and component selection of the converter.