DC Microgrid and Control System

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Lecture - 14
Modeling of Renewable Energy Resources (Modeling of Photovoltaic System)

Welcome to our lecture on DC Microgrid and Control System. Today we shall discuss about modeling of the solar photovoltaic cell as well as the solar element together. So, this will be more physics.

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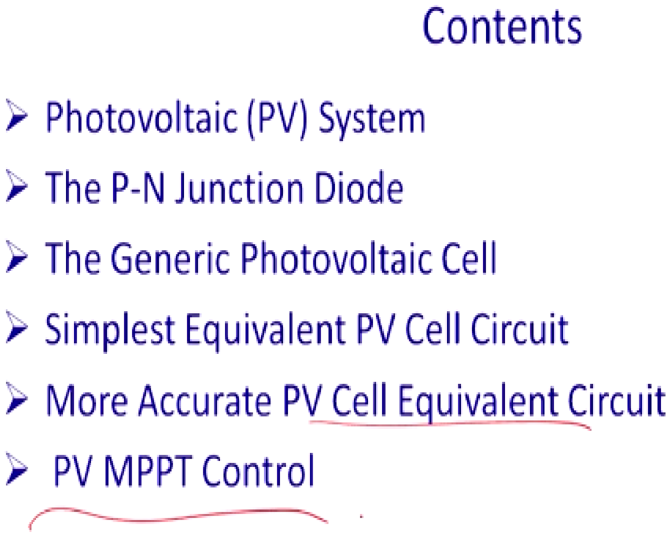

Contents

- Photovoltaic (PV) System
- The P-N Junction Diode
- The Generic Photovoltaic Cell
- Simplest Equivalent PV Cell Circuit
- More Accurate PV Cell Equivalent Circuit
- PV MPPT Control

Photovoltaic systems, thereafter P-N junction diode, now thereafter generic photovoltaic cells, and thereafter we shall discuss about simplest equivalent PV cell circuit and more accurate PV cell equivalent and the MPPT control of the solar photovoltaic.

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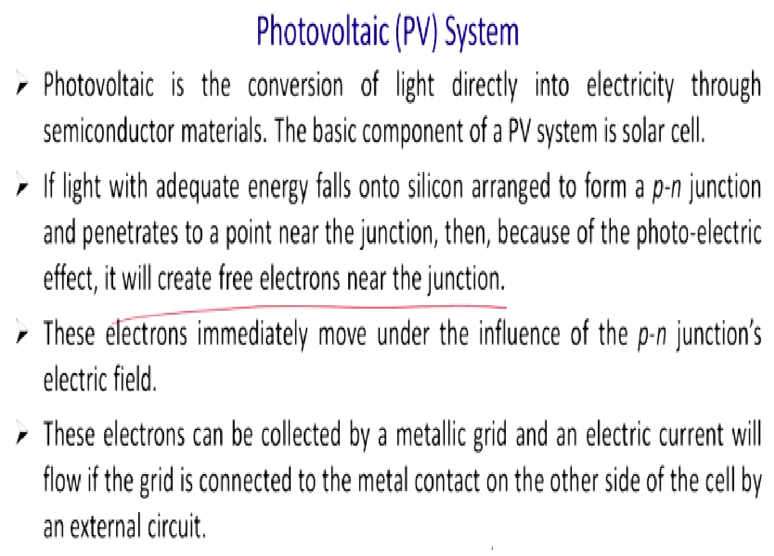

Photovoltaic (PV) System

- Photovoltaic is the conversion of light directly into electricity through semiconductor materials. The basic component of a PV system is solar cell.
- If light with adequate energy falls onto silicon arranged to form a *p-n* junction and penetrates to a point near the junction, then, because of the photo-electric effect, it will create free electrons near the junction.
- These electrons immediately move under the influence of the *p-n* junction's electric field.
- These electrons can be collected by a metallic grid and an electric current will flow if the grid is connected to the metal contact on the other side of the cell by an external circuit.

As you know that it is needless to say that photovoltaic is a conversion of the light directly into the electricity through a semiconductor material. The basic component of a PV of a PV system is a solar cell. If light with the adequate energy falls into the silicon arranged to form a p-n junction and penetrates to a point near to the junction, then because of the photoelectric effect, it will create free electron near the junction.

These electrons immediately move under the influence of the p-n junction electric field, it is quite you are familiar with this phenomenon. These electrons can be collected by the metallic grid and the electric current will flow if the grid is connected to the metal contact on the other side of the cell by the external circuit.

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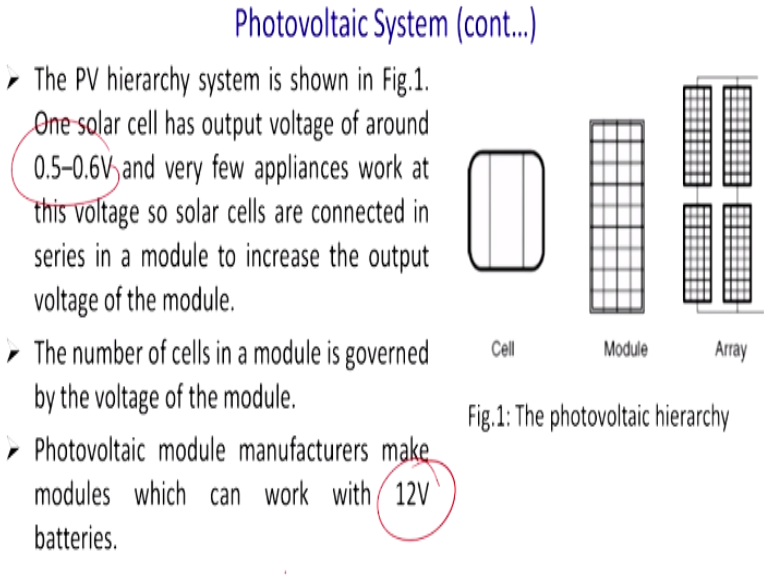

Photovoltaic System (cont...)

- The PV hierarchy system is shown in Fig.1. One solar cell has output voltage of around 0.5–0.6V and very few appliances work at this voltage so solar cells are connected in series in a module to increase the output voltage of the module.
- The number of cells in a module is governed by the voltage of the module.
- Photovoltaic module manufacturers make modules which can work with 12V batteries.

Fig.1: The photovoltaic hierarchy

So, essentially this is called cell. Ultimately you have a combination of the cell that is called the module and ultimately these are the parallel module that makes it an array, so PV hierarchy system as shown in the figure 1. One solar cell has output and around a diode that is 0.5 to 0.6 volt. A very few application works at this at this voltage. So solar cells are connected in series in a module to increase the output of the voltage of the module.

The number of cells in a diode the number of the cells in a module is governed by the voltage of the module. Photovoltaic modules manufactures manufacturers make module such as it works at 12 volt batteries depending on that different kind of setup, you can have a different voltage, you can have a 35 volt or 38 volt MPPT voltage making them into the form of array.

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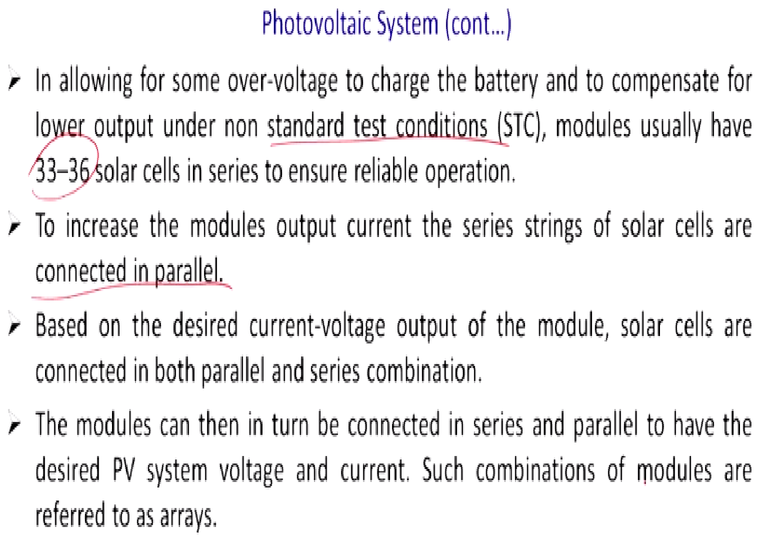

Photovoltaic System (cont...)

- In allowing for some over-voltage to charge the battery and to compensate for lower output under non standard test conditions (STC), modules usually have 33–36 solar cells in series to ensure reliable operation.
- To increase the modules output current the series strings of solar cells are connected in parallel.
- Based on the desired current-voltage output of the module, solar cells are connected in both parallel and series combination.
- The modules can then in turn be connected in series and parallel to have the desired PV system voltage and current. Such combinations of modules are referred to as arrays.

So, allowing some of the over-voltage to charge the battery and to compensate for the output under non-standard state condition, that is actually the we generally prefer 27 or original 25 degree centigrade, 0 degree uh and the 1000 watt per metre square divisions. Modules usually have 30 to 36 solar cells in series to ensure reliable operation. To increase the module output current, the series strings of the solar cells are connected in parallel.

Based on the desired current and the voltage output of the module, solar cells are connected in both series and parallel combinations. The modules can then intern be connected in series or parallel to have the desired PV voltage and current. Such combinations of modules are referred as arrays, so that is called array.

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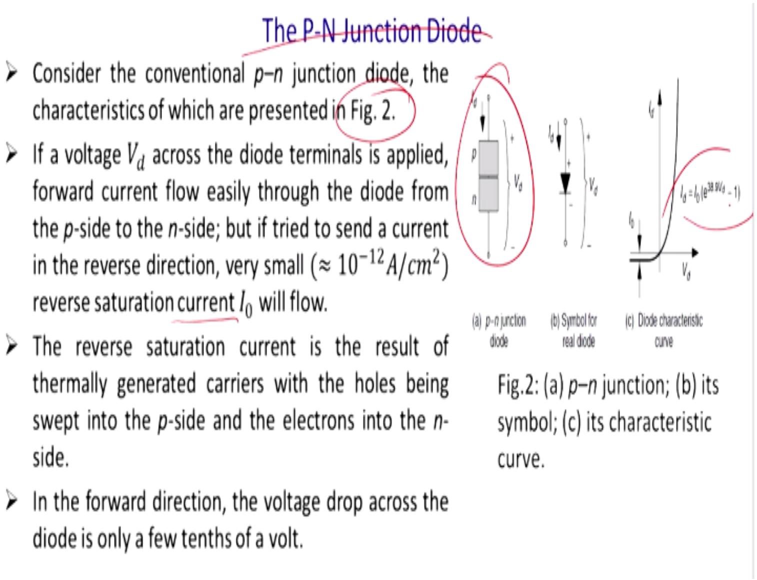

The P-N Junction Diode

- Consider the conventional *p–n* junction diode, the characteristics of which are presented in Fig. 2.
- If a voltage V_d across the diode terminals is applied, forward current flow easily through the diode from the *p*-side to the *n*-side; but if tried to send a current in the reverse direction, very small ($\approx 10^{-12} A/cm^2$) reverse saturation current I_0 will flow.
- The reverse saturation current is the result of thermally generated carriers with the holes being swept into the *p*-side and the electrons into the *n*-side.
- In the forward direction, the voltage drop across the diode is only a few tenths of a volt.

Fig.2: (a) *p–n* junction; (b) its symbol; (c) its characteristic curve.

Now let us come to the p-n junction diode, so it is quite familiar, I have nothing to be discuss much. Consider the conventional p-n junction diode, the characteristics of which are represented in Figure 2. If the vol if a voltage Vd across the diode terminal is applied, forward current flows easily through the diode from the p-side to the n-side, but if tried to send a current in the reverse direction, very small, that is 10 to the power -12 ampere per centimeter square, reverse saturation current, I0 will flow.

The reverse saturation current is the current is the result of the terminally generated carrier carriers with the hole being swept into the p-side and electron into the n-side, quite familiar the diode which phenomena. In the forward direction, the forward direction, the voltage drop across the diode is only few tenths of the volt, that is around 0.7 volt or 0.6 volt for the silicon. This is the p-n junction diode. This is the symbol of the p-n junction diode.

This is iv characteristics of the diode and that is id = i0, where reverse saturation current e to the power, this will be the Boltzmann's constant, constant and another constant comes into the picture vd-1 and this will make it a p-n junction diode.

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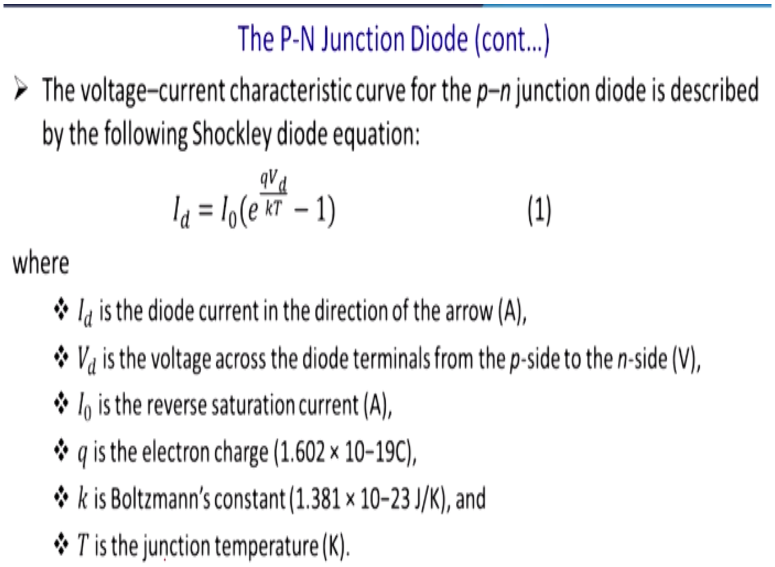

The P-N Junction Diode (cont...)

- The voltage–current characteristic curve for the *p*–*n* junction diode is described by the following Shockley diode equation:

$$I_d = I_0\left(e^{\frac{qV_d}{kT}} - 1\right) \qquad (1)$$

where

- I_d is the diode current in the direction of the arrow (A),
- V_d is the voltage across the diode terminals from the *p*-side to the *n*-side (V),
- I_0 is the reverse saturation current (A),
- q is the electron charge (1.602 × 10−19C),
- k is Boltzmann's constant (1.381 × 10−23 J/K), and
- T is the junction temperature (K).

Now you can see that the voltage and current characteristics of the p-n junction diode is described by the following Shockley diode equation that is Id = I0 e to the power qvd kt, k is the Boltzmann's constant, t is the temperature in Kelvin and -1. So that is Id is the diode current, Vd is voltage across the diode terminal, I0 is the a reverse saturation current, q is the charge of the electron, k is the Boltzmann's constant, and t is the absolute temperature.

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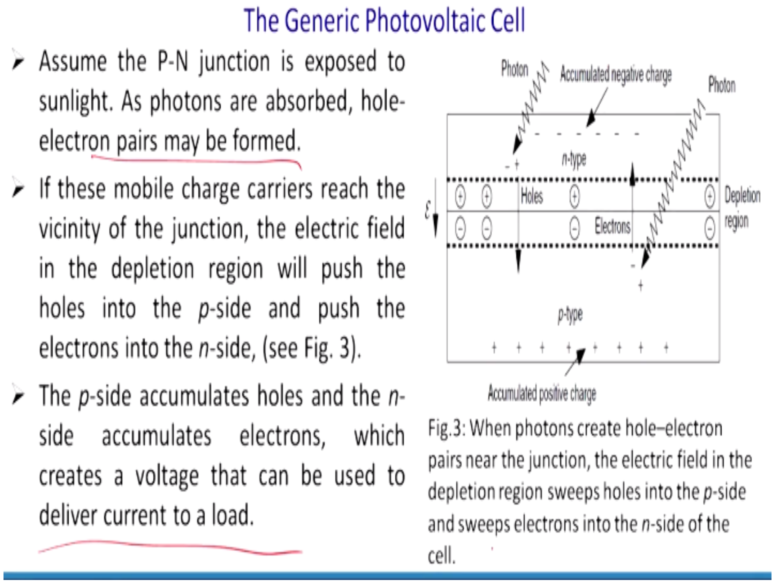

The Generic Photovoltaic Cell

- Assume the P-N junction is exposed to sunlight. As photons are absorbed, hole-electron pairs may be formed.
- If these mobile charge carriers reach the vicinity of the junction, the electric field in the depletion region will push the holes into the *p*-side and push the electrons into the *n*-side, (see Fig. 3).
- The *p*-side accumulates holes and the *n*-side accumulates electrons, which creates a voltage that can be used to deliver current to a load.

Fig.3: When photons create hole–electron pairs near the junction, the electric field in the depletion region sweeps holes into the *p*-side and sweeps electrons into the *n*-side of the cell.

Let us assume that p-n junction is exposed to the sunlight. As photons are absorbed, hole-electron pairs are formed. So, this will be photon you know actually what happens then and there will be an electron in the conduction band and holes will be there in the valence band. If this mobile charge carrier reaches the facility of the junction, the electric field in the depletion region will push the hole into the p-side and push the electron in the n–side. This is the actually the layer.

This is the n-type, and this is the p-type, ultimately they will change over and that is what happens. The p-side accumulates holes and the n-side accumulates electrons, which creates a voltage and that can be used to drive the current to the load. That is the principle operation of the this p-n junction diode. When photons created the holes electron pairs near to the junction the electric filed in the depletion region sweeps hole into the p-side and sweeps electron into the n-side of the cells.

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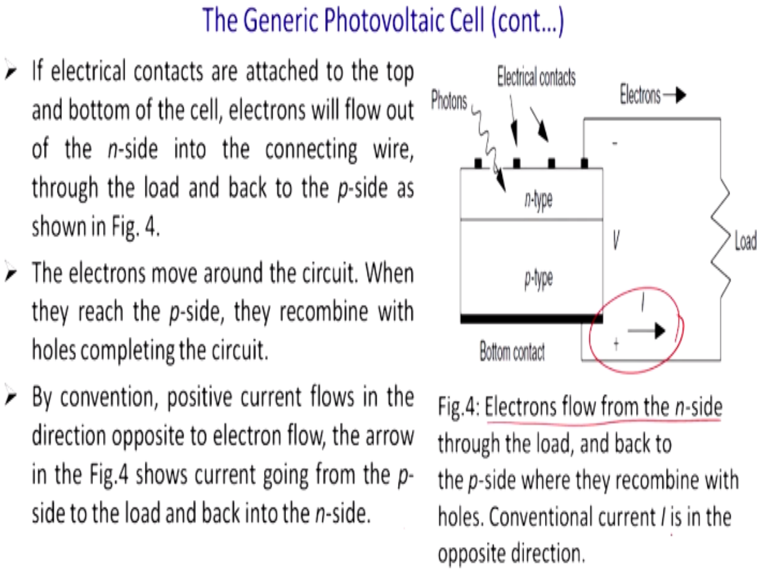

The Generic Photovoltaic Cell (cont...)

- If electrical contacts are attached to the top and bottom of the cell, electrons will flow out of the *n*-side into the connecting wire, through the load and back to the *p*-side as shown in Fig. 4.
- The electrons move around the circuit. When they reach the *p*-side, they recombine with holes completing the circuit.
- By convention, positive current flows in the direction opposite to electron flow, the arrow in the Fig.4 shows current going from the *p*-side to the load and back into the *n*-side.

Fig.4: Electrons flow from the *n*-side through the load, and back to the *p*-side where they recombine with holes. Conventional current *I* is in the opposite direction.

Now if electrical contacts are attached at the top and the bottom of the cell, electron will flow out from the inside into the connecting wire to the lot and back to the p-side as shown. The electron moves around the circuit, when they reach the p-side and they combine with the holes completing the circuit. So that is something like that battery.

By convention, positive charge, positive current flow the direction opposite to the electron flow and the arrow in the figure 4, this is the current shows that current going from the p-side to the p-side to the load to the back to the n-side. So this is the electron flow from the n-side to the load and back to the p-side, where they recombine with the holes. Conventional current I is in the positive direction.

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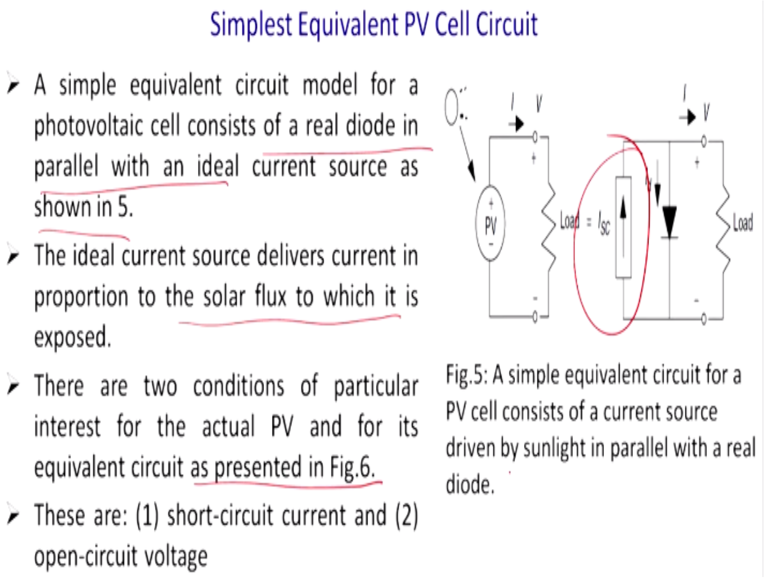

Simplest Equivalent PV Cell Circuit

- A simple equivalent circuit model for a photovoltaic cell consists of a real diode in parallel with an ideal current source as shown in 5.
- The ideal current source delivers current in proportion to the solar flux to which it is exposed.
- There are two conditions of particular interest for the actual PV and for its equivalent circuit as presented in Fig.6.
- These are: (1) short-circuit current and (2) open-circuit voltage

Fig.5: A simple equivalent circuit for a PV cell consists of a current source driven by sunlight in parallel with a real diode.

Now let us make an equivalent circuit of it. The simplest equivalent circuit is the PV cell and the load and that can be think of as a you know current source and a diode parallel to it and the load. So simplest equivalent circuits of the model for a photovoltaic cells consist of a real diode in parallel with the ideal current source as shown in the figure 5. The direct current source delivers a current in proportion to the solar flux to which it is exposed, where there are 2 conditions of particular interest for the actual PV and for its equivalent circuit as presented in the figure 6.

These are short-circuit current and the open-circuit voltage, we will see later, but you know you know there is a problem short circuiting a current source, but those kind of problem will not be here fortunately.

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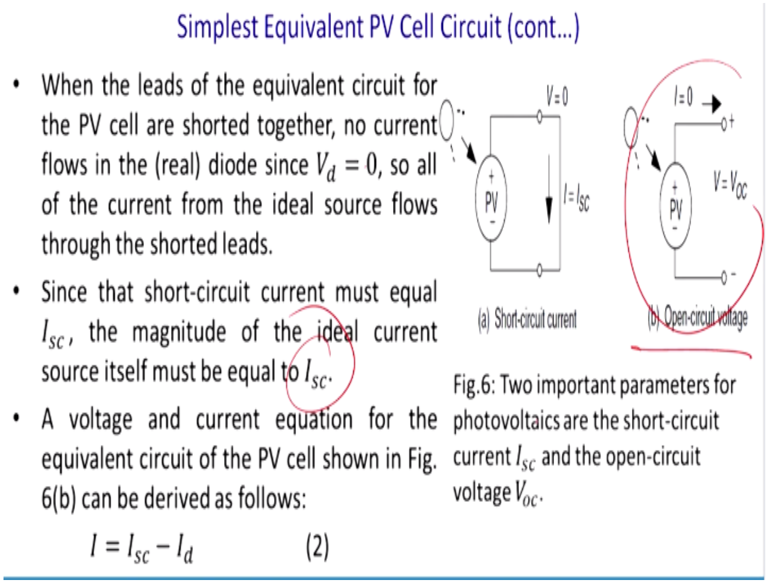

Simplest Equivalent PV Cell Circuit (cont...)

- When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since $V_d = 0$, so all of the current from the ideal source flows through the shorted leads.
- Since that short-circuit current must equal I_{sc}, the magnitude of the ideal current source itself must be equal to I_{sc}.
- A voltage and current equation for the equivalent circuit of the PV cell shown in Fig. 6(b) can be derived as follows:

$$I = I_{sc} - I_d \qquad (2)$$

Fig.6: Two important parameters for photovoltaics are the short-circuit current I_{sc} and the open-circuit voltage V_{oc}.

When the leads to the equivalent circuits for the PV cells are shorted together, no current flows in the real diodes since Vd equal to 0, so all the current from the ideal source ideal uh ideal source flows through the shorted leads. Since the short circuit current must equal to Isc, the magnitude of the ideal current source itself must be equal to the Isc. Similarly, voltage and current equation of this equivalent circuit of the PV cell are shown in the figure 6b and where I = Isc – Id. So, this is basically the open circuit and this is basically the short circuit.

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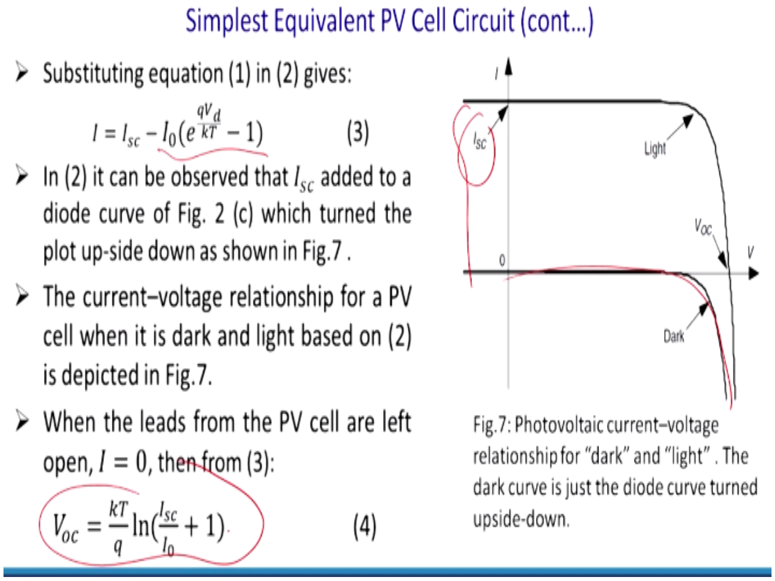

Simplest Equivalent PV Cell Circuit (cont...)

- Substituting equation (1) in (2) gives:

$$I = I_{sc} - I_0(e^{\frac{qV_d}{kT}} - 1) \qquad (3)$$

- In (2) it can be observed that I_{sc} added to a diode curve of Fig. 2 (c) which turned the plot up-side down as shown in Fig.7 .
- The current–voltage relationship for a PV cell when it is dark and light based on (2) is depicted in Fig.7.
- When the leads from the PV cell are left open, $I = 0$, then from (3):

$$V_{oc} = \frac{kT}{q}\ln(\frac{I_{sc}}{I_0} + 1) \qquad (4)$$

Fig.7: Photovoltaic current–voltage relationship for "dark" and "light". The dark curve is just the diode curve turned upside-down.

Now considering this to equation and we know that actually subtracting this equation I = Isc – I0, this is essentially the Id, so I0 to the power q kt vd -1 and observing this equation and the equation 2, we can observe that Isc is added to a diode curve of the figure 2c. So, this is the curve and the current voltage relationship for a PV cell when it is dark and the light based on 2 is depicted in the figure 7.

This is the dark condition and current will go back and this is the light condition where Isc will be positive and this is the case, and when the leads from the PV cells are left open, that is I = I0, so this open circuit voltage will be V0c = kt/q ln Isc/I0 + 1 and thus you can calculate the open circuit voltage in a lighting case.

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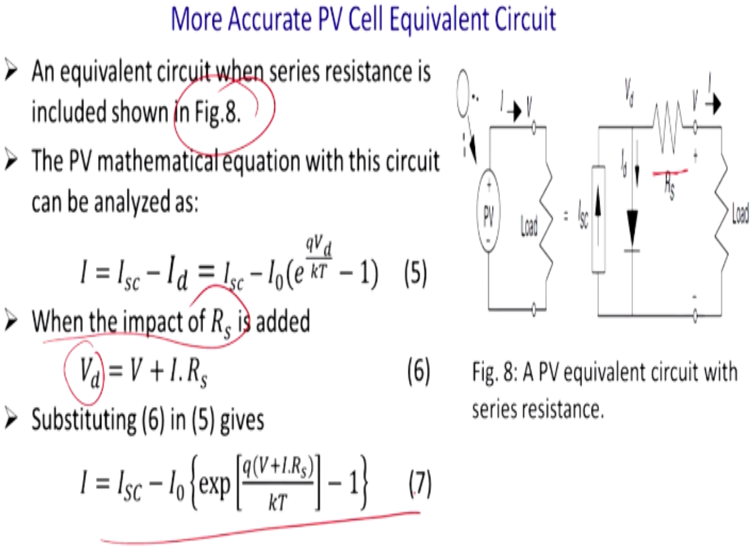

More Accurate PV Cell Equivalent Circuit

- An equivalent circuit when series resistance is included shown in Fig.8.
- The PV mathematical equation with this circuit can be analyzed as:

$$I = I_{sc} - I_d = I_{sc} - I_0\left(e^{\frac{qV_d}{kT}} - 1\right) \quad (5)$$

- When the impact of R_s is added

$$V_d = V + I.R_s \quad (6)$$

- Substituting (6) in (5) gives

$$I = I_{SC} - I_0\left\{\exp\left[\frac{q(V+I.R_S)}{kT}\right] - 1\right\} \quad (7)$$

Fig. 8: A PV equivalent circuit with series resistance.

An equivalent circuit you know circuit when series resistance is included as shown in the figure 8, this is the figure 8, so ultimately you have a resistance here, thereafter the load. This PV mathematical equation with its circuits can be analyzed by I = Isc – Id = Isc – I0 e to the power this one where the impact of Rs is added so that is basically the intrinsic resistance. So Vd = V + I x Rs and the substituting you get this results and that is what happened.

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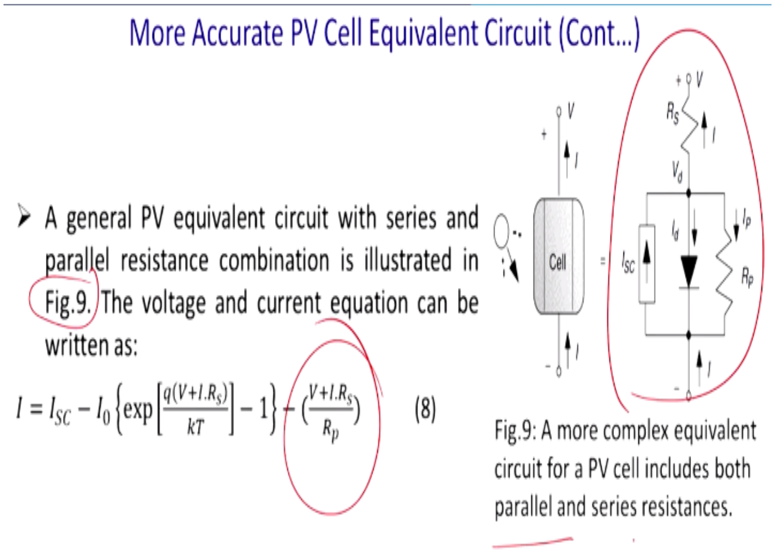

More Accurate PV Cell Equivalent Circuit (Cont...)

- A general PV equivalent circuit with series and parallel resistance combination is illustrated in Fig.9. The voltage and current equation can be written as:

$$I = I_{SC} - I_0\left\{\exp\left[\frac{q(V+I.R_S)}{kT}\right]-1\right\} - \left(\frac{V+I.R_S}{R_p}\right) \qquad (8)$$

Fig.9: A more complex equivalent circuit for a PV cell includes both parallel and series resistances.

The general equivalent circuits with the series and the parallel resistance combinations is illustrated in the figure 9. So this will be the figure overall this is Vd and ultimately there will be a resistance parallel to the diode and overall circuit will be looking like this and thus you can write I = Isc – I0, this is exponential, thereafter the drop due to this part of it furthermore more complex equivalent circuit.

Now by analyzing it, so you can choose a different kind of equivalent circuit for suitable for taking your model and instead of the taking actually this (( )) (14:18) symbolic model, you can make your own model if you know these values and it is not difficult to finding out their values. Circuits for the PV cells includes both parallel and the series resistance.

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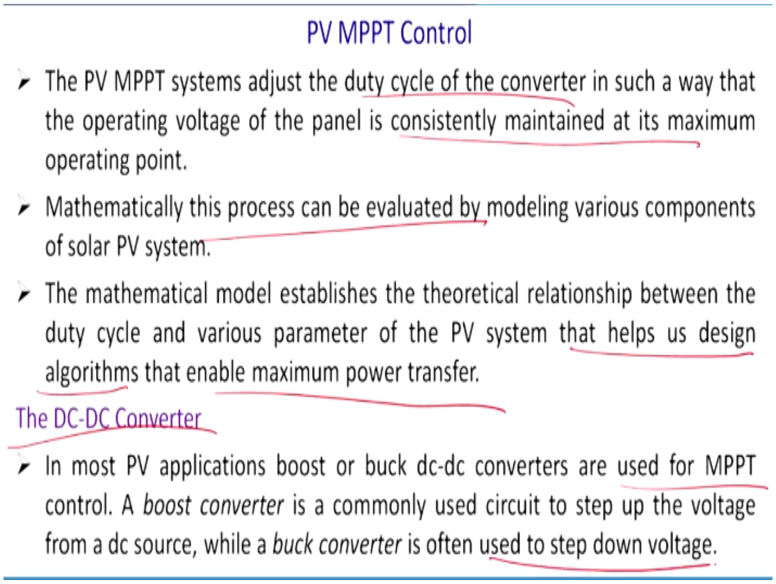

PV MPPT Control

- The PV MPPT systems adjust the duty cycle of the converter in such a way that the operating voltage of the panel is consistently maintained at its maximum operating point.
- Mathematically this process can be evaluated by modeling various components of solar PV system.
- The mathematical model establishes the theoretical relationship between the duty cycle and various parameter of the PV system that helps us design algorithms that enable maximum power transfer.

The DC-DC Converter

- In most PV applications boost or buck dc-dc converters are used for MPPT control. A *boost converter* is a commonly used circuit to step up the voltage from a dc source, while a *buck converter* is often used to step down voltage.

So, now we require to track the MPPT voltage. The MPPT system, PV solar MPPT we have seen the wind MPPT and now we do have solar MPPT, system adjusts the duty cycle of the converter in such a way that operating voltage of the panel is consistently maintained at its maximum operating point. Maximum operating point generally changes due to the temperature and irradiation. Mathematically, this process can be evaluated by modeling the various component of the solar system.

The mathematical model establishes the the theoretical relationship between the duty cycle and various parameter of the PV system that help us designing the algorithms and that enables the maximum power transfer. So, you have a DC to DC converter. The most PV application boost or the buck DC to DC converters are used for MPPT control. A boost converter is a is a commonly used circuit to step up the voltage from the DC source while a buck \converter is often used to step down the voltage.

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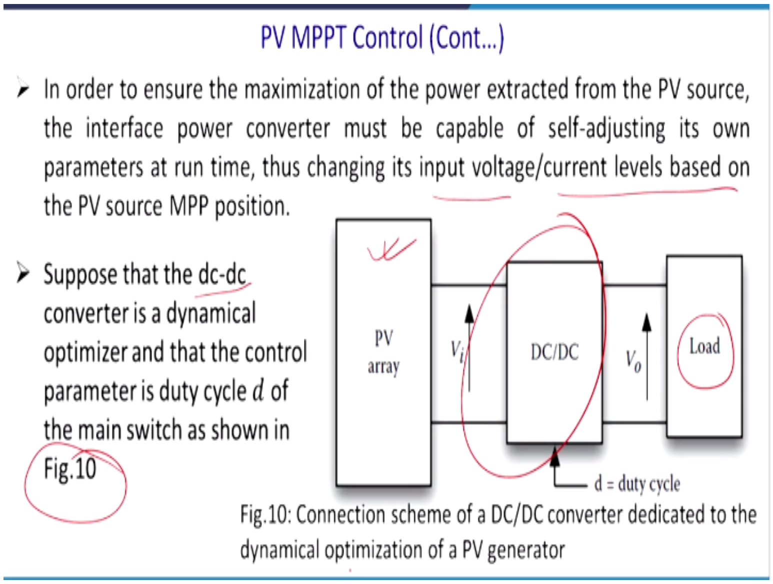

PV MPPT Control (Cont...)

- In order to ensure the maximization of the power extracted from the PV source, the interface power converter must be capable of self-adjusting its own parameters at run time, thus changing its input voltage/current levels based on the PV source MPP position.
- Suppose that the dc-dc converter is a dynamical optimizer and that the control parameter is duty cycle d of the main switch as shown in Fig.10

Fig.10: Connection scheme of a DC/DC converter dedicated to the dynamical optimization of a PV generator

So, for this reason you have a DC to DC converted in between and that will feed the load and generally it will be maintained at the MPPT voltage. In order to ensure the maximum it is called as device converter because you wanted to fix up the input voltage and output voltage will be remained in constant. In order to ensure the maximization of the power extracted from the PV source, the interface power converter must be capable of self-adjusting its own parameter at run time thus changing its input voltage current level based on the PV source of the MPP position.

Suppose that the DC to DC converter is a dynamical optimizer and that the control parameter is duty cycle of d, the main switch as shown in the figure 10, then what happens. The connection scheme of DC to DC converter dedicated to the dynamical optimization of the PV generator.

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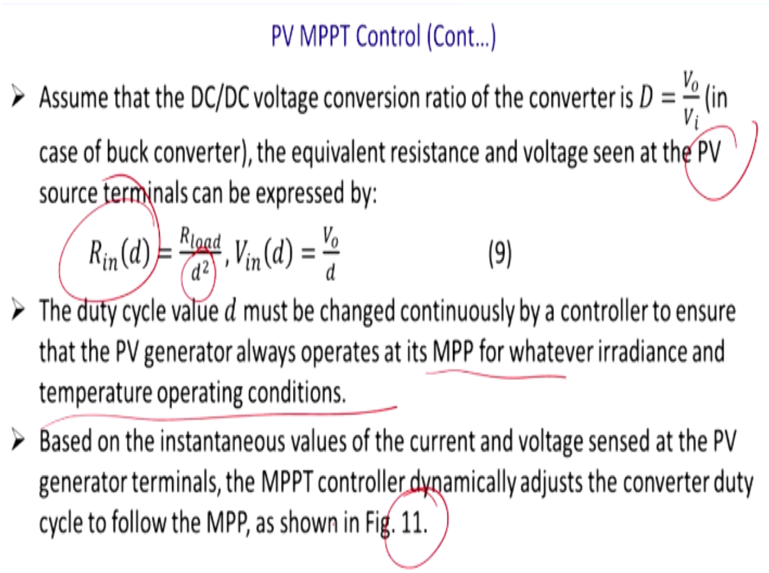

PV MPPT Control (Cont…)

- Assume that the DC/DC voltage conversion ratio of the converter is $D = \frac{V_o}{V_i}$ (in case of buck converter), the equivalent resistance and voltage seen at the PV source terminals can be expressed by:

$$R_{in}(d) = \frac{R_{load}}{d^2}, V_{in}(d) = \frac{V_o}{d} \qquad (9)$$

- The duty cycle value d must be changed continuously by a controller to ensure that the PV generator always operates at its MPP for whatever irradiance and temperature operating conditions.
- Based on the instantaneous values of the current and voltage sensed at the PV generator terminals, the MPPT controller dynamically adjusts the converter duty cycle to follow the MPP, as shown in Fig. 11.

Assume that the DC to DC voltage conversion ratio of the converter is d = V0/Vi in case of the buck converter for the continuous mode of induction. The equivalent resistance of the voltage seen by the PV source terminal can be expressed by that is basically on depends on its duty ratio. So that will be (( )) (17:30) early R load x d square and where d is less than 1, thus you have an effective more resistance and similarly Vn = V0/d.

The duty ratio, the duty cycle value d must be changed continuously by a controller to ensure that the PV generator always operate at its MPPT for whatever the irradiation in the temperature and other operating conditions. Based on the instantaneous values of the current and voltage sense at the PV generator terminals, the MPPT controllers dynamically adjust the converter's duty cycle to follow them MPPT as shown in the figure 11, that we will show in this figure.

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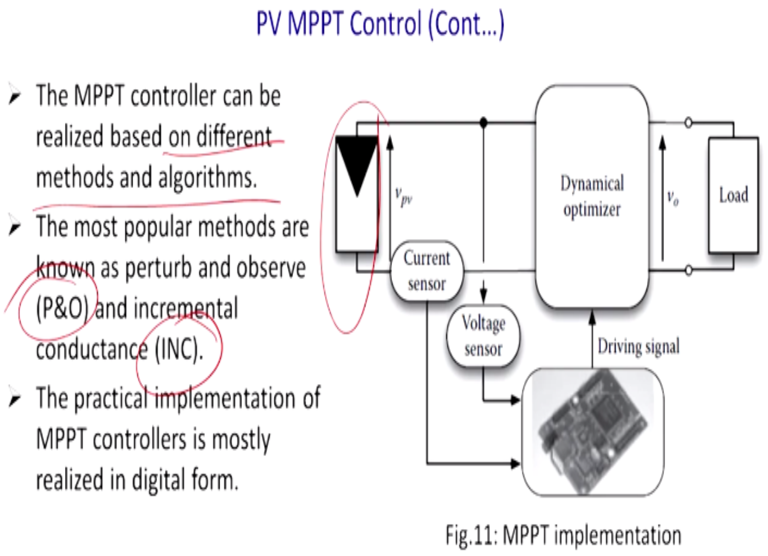

PV MPPT Control (Cont...)

- The MPPT controller can be realized based on different methods and algorithms.
- The most popular methods are known as perturb and observe (P&O) and incremental conductance (INC).
- The practical implementation of MPPT controllers is mostly realized in digital form.

Fig.11: MPPT implementation

So you have a solar panel, you have a current sensor, you have voltage sensors and it will try to have a different kind of algorithm are there, for namely perturb and observe, you have trans-conductance method and that will be a digital implementation and it will try this this DC to DC converter and ultimately it will track the maximum voltage. So the MPPT controller can be realized based on different methods and algorithms.

Most popular methods are known as or it is well estab or PO method that is called perturb and observe and the incremental conductance or IMC. The practical implementation of MPPT controller is mostly digital in in a digital domain we will have to have a now a days microcontroller. Simple microcontroller will can do that job, otherwise you can have also a complex APG and all those things, you can also use that.

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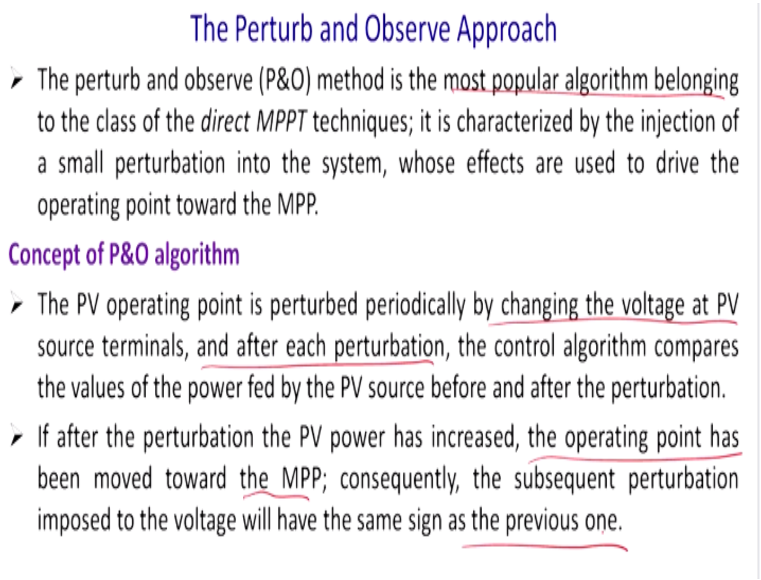

The Perturb and Observe Approach

- The perturb and observe (P&O) method is the most popular algorithm belonging to the class of the *direct MPPT* techniques; it is characterized by the injection of a small perturbation into the system, whose effects are used to drive the operating point toward the MPP.

Concept of P&O algorithm

- The PV operating point is perturbed periodically by changing the voltage at PV source terminals, and after each perturbation, the control algorithm compares the values of the power fed by the PV source before and after the perturbation.
- If after the perturbation the PV power has increased, the operating point has been moved toward the MPP; consequently, the subsequent perturbation imposed to the voltage will have the same sign as the previous one.

So perturb and observe methods are the most popular algorithm belonging to the class of the direct MPPT technique and its characteristics by the injections of the small perturbation into the system, whose effect is used to drive the operating point. So, it is if you generally you change it, if you see that power increasing, you go on that direction, it will continue go on that direction, the multiplexion on the voltage and current gives you the more power. Otherwise you actually track reverse.

So the PV operating point is perturbed periodically by changing the voltage at the PV sources terminal and after each perturbation, control algorithm compares the values of the power fed by the PV sources before and after the perturbation. If after the perturbation PV power has increased, the operating point has been moved forward the MPP, consequently and subsequently, the perturb imposed to the voltage will have the same sign as that of the previous one.

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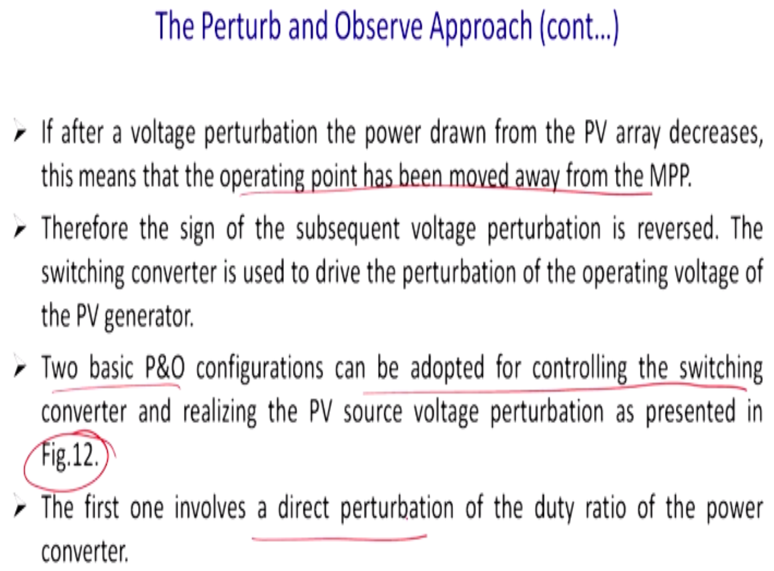

The Perturb and Observe Approach (cont...)

- If after a voltage perturbation the power drawn from the PV array decreases, this means that the operating point has been moved away from the MPP.
- Therefore the sign of the subsequent voltage perturbation is reversed. The switching converter is used to drive the perturbation of the operating voltage of the PV generator.
- Two basic P&O configurations can be adopted for controlling the switching converter and realizing the PV source voltage perturbation as presented in Fig.12.
- The first one involves a direct perturbation of the duty ratio of the power converter.

Now if after a voltage perturbation the power drawn from the PV array decreases, this means that the operating point has been moved from moved away from the MPP. Therefore, the sign of the subsequent voltage perturbation is reversed. The switching converter is used to drive the perturbation of the operating voltage of the PV generator. Students are can refer to this flowchart of the perturb and observe on trans-conductance method. It is well available and well documented in literatures.

So, two basic PO configurations can be adopted for controlling switching converter and realizing the PV source of the perturb as present in figure 12 next and first one involves direct perturbation of the duty ratio to of the power converter.

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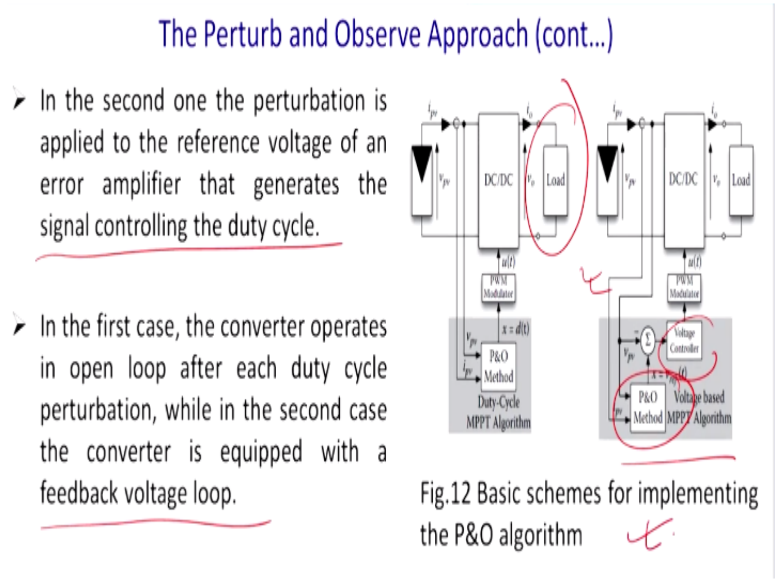

The Perturb and Observe Approach (cont...)

- In the second one the perturbation is applied to the reference voltage of an error amplifier that generates the signal controlling the duty cycle.
- In the first case, the converter operates in open loop after each duty cycle perturbation, while in the second case the converter is equipped with a feedback voltage loop.

Fig.12 Basic schemes for implementing the P&O algorithm

So this is basically basic scheme perturb and observe, this is the what we do actually we sense the voltage and current and this is the perturb and observe method and you feed the PWM and also not only that some controller require also the voltage control. Not only that the duty cycle is coming out by the maximum power we required to have, voltage control, both required to incorporate and ultimately this one is most preferred, because you required to charge the battery as 12 volt.

So, you are required to track the MPPT as well as you required to charge the battery is a 12 volt and for this reason the second method is preferred with PO. So, in the second one, the perturbation is applied to the reference voltage of an error signal that generates the signal controlling the duty cycle. In the first case, converter operates in the open loop, that is the problem, so you don't have any information whether this you required to volt leave this voltage at the desired level and by tracking the MPPT or then you are maintaining that.

So, the converter operates at open loop after each duty cycle perturbation while the while in the second case the converter is equipped with a feedback voltage loop and thus this method id preferred. Thank you for your attention. I shall continue with the discussion with the modeling of the different entities of the DC to DC converters, thereafter we have design this actually wind turbine, that we have design the solar cells and solar panel and these are the different entities of the DC Microgrid. Thank you for attention, so thank you.