Solar Energy Engineering and Technology
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Lecture No. 12
Fundamentals of Photovoltaic Conversion

Dear students, today we learn solar PV modules, arrays and PV system. So, before we start today's discussion, let us summarize what we have discussed in the last class.

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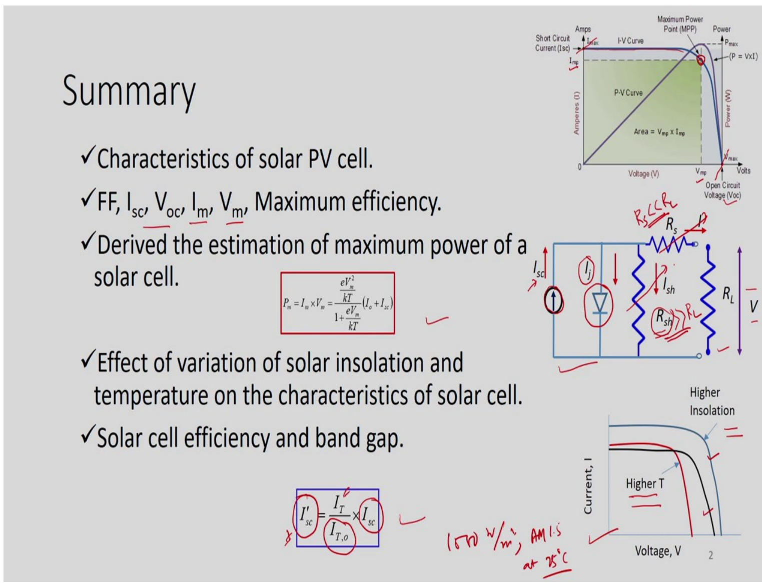

So, in the last class, we have learned how to develop I-V characteristics curve of a solar cell. So, here as you can see, this current is varying with voltage, and it reaches zero value here, and power increases linearly and reaches a maximum value, and then it reaches a zero value here. This intersection of this line in the x-axis is known as V_{oc} and intersection of these lines in the y-axis is known as I_{sc} or short circuit current. So, every curve will have a maximum power point.

Also, we have studied the performance parameter of a PV cell which includes field factor, which is a function of I_{sc}, V_{oc}, I_m, V_m. So, I_m is nothing but maximum current and V_m is nothing but maximum voltage at this this point. We also define how this field factor can be estimated. In order to analyze the performance of a solar cell, we have to take help of this equivalent circuit diagram, so which comprises of a current source which provides

I_{sc} is the amount of current and I_j is the current flows through this p-n junction, and I_{sh} is the amount of current flows through shunt resistance, and I is the amount of current which flows through the load resistance having voltage drop of V.

So, normally what happens, this R_{sh} is shunt resistance is very, very high compared to R_L and this internal series resistance R_{sh} is very, very low compared to R_L. Hence, under this consideration, this can be omitted, and we can modify this equivalent circuit diagram and we can derive the expression for maximum power. So that has been done in the last class.

And also, we have studied the effect of variation of solar radiation and temperature on the characteristics of solar cell. As you can see this I-V characteristics plot, here red line shows the at higher temperature, and this is at, this curve is at higher insolation. So, as temperature increases, this our shape of the I-V characteristic curve will change, and we will get lesser amount of current, efficiency finally we will get very less. If we can operate at standard test conditions, maybe at 25 ^oC, then we will get maximum conversion efficiency. Otherwise, if temperature increases, ambient temperature increases, then accordingly cell temperature will increase and then we will get lesser conversion efficiency.

Also, what we have studied if we know I_{sc} value for standard test condition, means at 1000 W/m^2 and AM1.5, and at ambient condition, at say 25 ^oC, then we can calculate I_{sc} value of other insolation. So, if we know this, then this can be calculated. And also, we have studied solar cell efficiency and bandgap, how they are related. So, with this background, let us move to the today's discussion.

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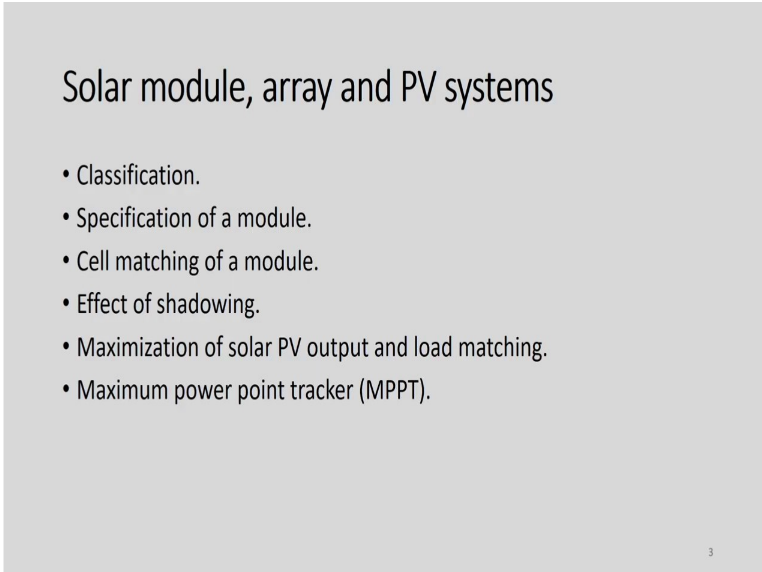

So, solar module classifications we will discuss today, then specification of a module, then cell matching of a module, then effect of shadowing, maximization of solar PV output and load matching and finally, maximum power point tracker for the PV system will be discussed. So, what is PV module?

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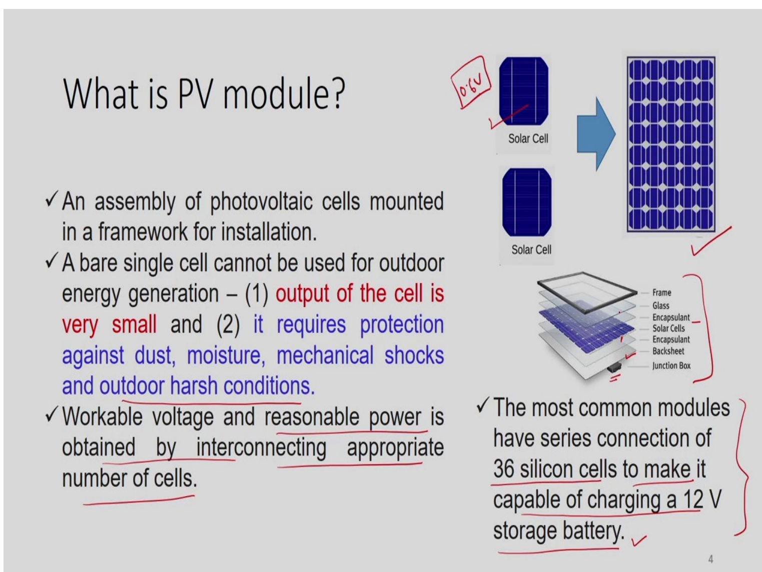

PV module is an assembly of photovoltaic cells mounted in a framework for installation. As you can see, this is a single solar cell, this single solar cell or you can say bare single cell cannot be used for outdoor applications; because its output is very less. As we can say, it will give about 0.6 V. So, single cell will provide about 0.6 V, so this cannot be used for many of the practical applications, if we are proposing for outdoor applications.

And also, it requires protection against dust, moisture, mechanical shock and outdoor harsh conditions. So, if we combine many cells, then we can convert to a module. So, that means this workable voltage and reasonable power is obtained by interconnecting appropriate number of cells. These cells have to be connected in series sometimes and then we have to connect in parallel, that has to be decided.

Mostly in common modules, have series connection of 36 silicon cells, to make it capable of charging a 12 V storage battery. So, thats why, most of the cases, single modules are 36 cells are there and which can be capable of charging a battery of capacity 12 V. Of course, it will have more numbers of cells in the international market.

So, if we see very precisely this module, what are different layers composed of these modules? Of course, we need a junction box at the end, and this is the back seat, and then on the top of it, we will have encapsulant, and then solar cells are placed, and again, at the top of the solar cells, we will have encapsulant then glass, then frame. You see, different layers are composed of a module.

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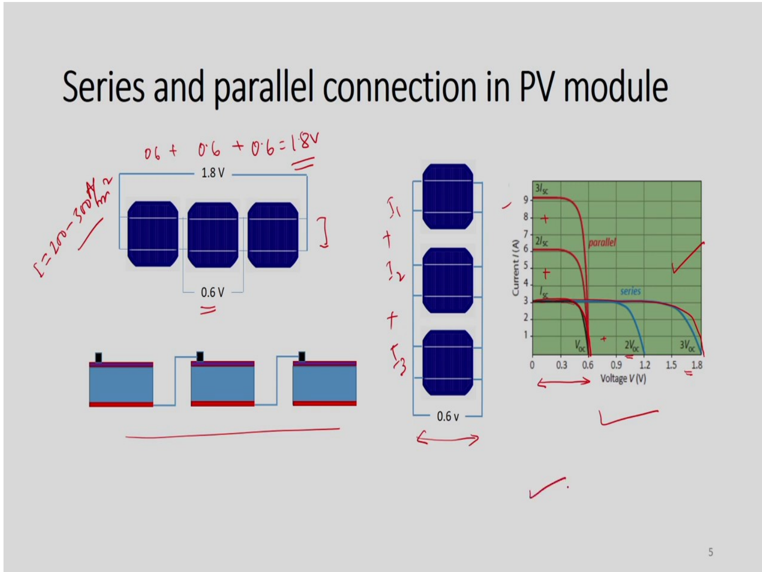

Now, let us see how these modules are connected in series and parallel. So, if we talk about a single cell, so this single cell can provide a voltage of 0.6 V. And if we talk about current density I, so this, it varies from 200 to 300 A/m^2. So, if these cells are connected in series then what will happen, current will remain fixed, but voltage will vary. So, since three cells are connected in series, so if you say (0.6 + 0.6 + 0.6), so it will be 1.8 V. And if we connect these cells in parallel then what will happen, its voltage will be constant but current will add up.

So, here current means I_1 then we have I_2 then we have I_3, so this will be added. So, if I am interested to develop I-V characteristics for these two conditions, then we can develop. Say for single-cell, we can we can draw this I-V and if we have two cells then two volts will be there, so this connection is for series, and this is for parallel. Then for two cells, it will be two V_{oc} and then for three cells will be three V_{oc}, so it will be something like this.

And in case of parallel connections, as we can understand, this voltage will be fixed, so this is the one and then if we add second one parallelly and then third one, so this will be $3 \times I_{sc}$. So, configurations of this I-V characteristics when we are interested for series and parallel connections, then it will look like something like this. And this figure shows how these batteries are connected in series, in a real situation. So, this knowledge is very very important. In most of the cases, we have to know go through this kind of considerations.

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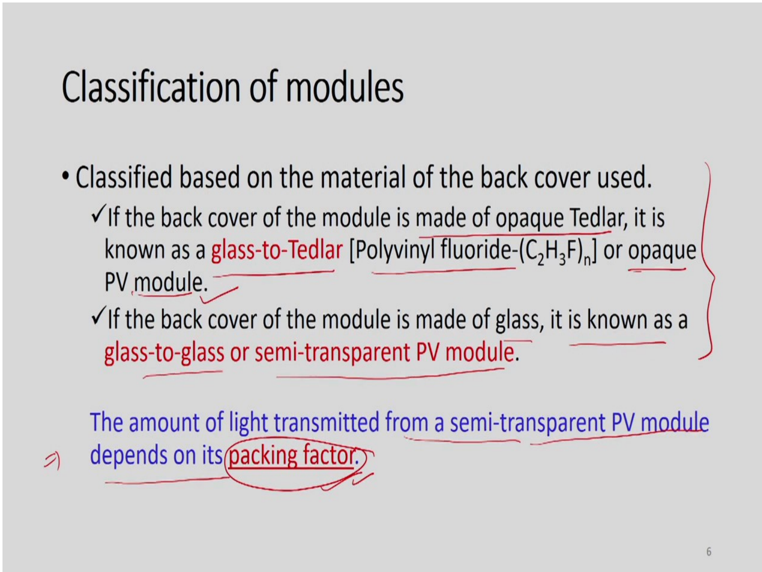

So, how does a module classify? So, classified based on the material used in the backside of the module. So, if the back cover of the module is made of opaque Tedlar, it is known as glass-to-Tedlar, and this Tedlar is nothing but polyvinyl fluoride or opaque PV module. This is known as glass-to-Tedlar or opaque PV module. And the second one, if the back cover the module is made of glass, it is known as glass-to-glass or semi-transparent PV module. So, primarily, these two categories are prominently available.

And the amount of light transmitted from a semi-transparent PV module depends on its packing factor. We will define what is packing factor. It will tell about the density of the cells in a given PV module. So, we will define this factor. Also, we will study the efficiency of a module. Since, we have the experience of calculating the efficiency of the cell, so how does this efficiency will be different for modules that will be studied in the coming slides.

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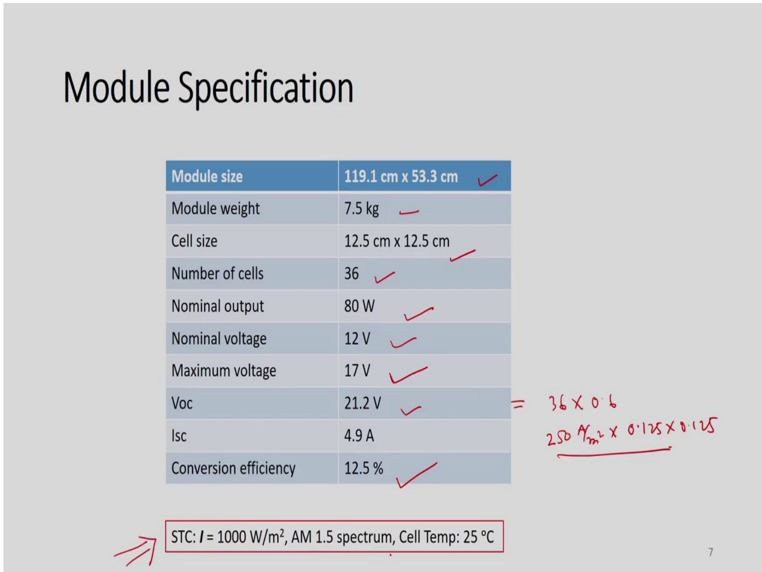

So, this is a standard specification of a module. So, here module size is about 119.1 cm × 53.3 cm is the size, and of course, there are multiple options of fabrication of modules and these are internationally accepted. But, normally these modules are widely available and practically used. So, module weight is about 7.5 kg, then cell size is 12.5 cm × 12.5 cm, and the number of cells as I say is 36, nominal output is 80 W, and nominal voltage is 12 V, then maximum voltage is 17 V, and V_{oc} is about 21.2 V and I_{sc} is 4.9 A.

So, this can be very easily calculated, how this will be? So, 36 multiplied by 0.6 will be something like this. And here if we consider about 250 average A/m^2 multiplied by we will have the area, it is about 0.125 × 0.125. So, that way we can calculate I_{sc} values and conversion efficiency is normally 12.5 %. And these values are found under standard test condition, where intensity of solar radiation is 1000 W/m^2 and spectrum of 1.5 and cell temperature of 25 ºC.

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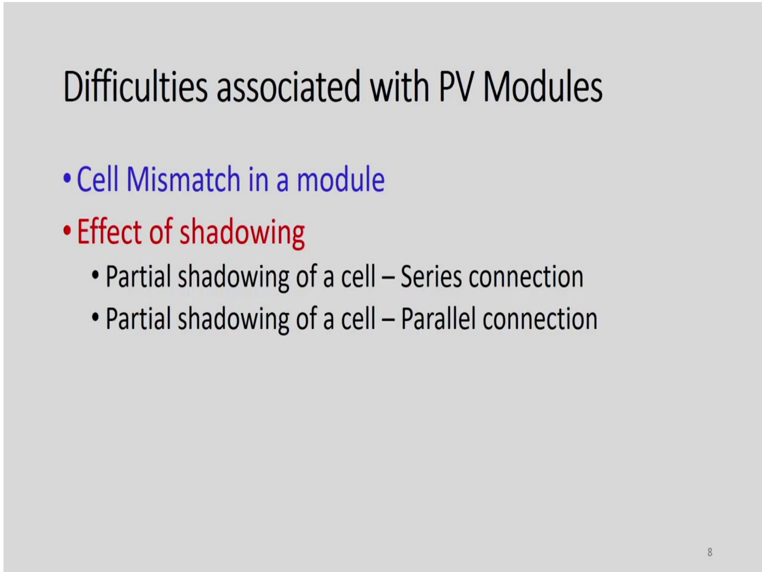

So, now let us study the difficulties associated with PV modules. So, problems may arises if cells are not matched and if these cells of the modules are shadowed. So, these two phenomenons will be studied. Under the effect of shadowing, we will study two cases, first case will be for partial shadowing of a cell with series connection and second case is partial shadowing of the cell with parallel connections. So first, let us study, cell mismatch in a module.

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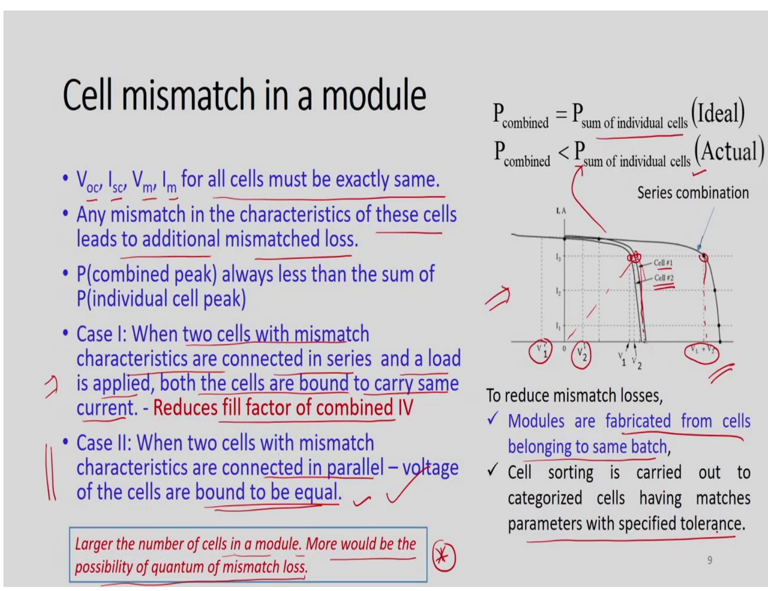

So what is cell mismatch? So, if two cells or maybe three cells, we consider, if their characteristics are not the same, then they are different. So, if they are connected in series, then then their behaviour will be different. So, what happens when we are connecting cells in modules in series or in parallel? What happens, these characteristics of the cells has to be identical. So, what does it mean? This characteristic means V_{oc}, I_{sc}, V_m, I_m or maybe field factor for all the cells must be exactly same. So, any mismatch in the characteristics of these cells leads to the additional mismatch loss.

So, what happens if we consider two cells? This is for cell one, and this curve is for cell two. If these two cells are connected in series, what happens, we can generate a combined I-V characteristics. So, this is the combined I-V characteristics, and combined voltage will be V_1 plus V_2. Normally, what happens in ideal case, if we consider this peak power here and here, if we draw this kind of voltage, this will come something like this.

So, these two values in case of ideal condition, this P combined here has to be equal to sum of the individual cells, maximum power of the individual cells. So, this maximum power of this combined I-V characteristics should be same as sum of the individual cell's maximum power. But this is not the case in case of actual situation, because they have a mismatch. So, if we compare two different cells of mismatch characteristics and we combine it, then what happens? We will have this situation. P combined is is less than power of sum of the individual cells. So, this is what I am talking about for case one.

When two cells with mismatch characteristics are connected in series, and a load is applied, both the cells are bound to carry same current. So, if they are different, then what will happen? One cell will produce power, and other cells will dissipate power. So, for example, if we short circuit the circuit, what will happen? They will generate two voltage V_1' and V_2'; these are, magnitude is the same but in opposite directions. So, what does it mean? So, one cell will produce power, and others will dissipate power. And as a result of which, we will have reduced field factor of combined I-V, so that will reduce the combined power.

In the second case, when two cells with mismatch characteristics are connected in parallel, the voltage of cells are bound to be equal. So, for parallel case as we have discussed in the last slides, so that is obvious. So, when we are connecting two cells of mismatch characteristics in parallel, then voltage of the cells are bound to be same. So, similar analogy or similar description can be given here for this case as well.

So, as I said, there are many modules, so what we have considered is a 36 cells composed of a module. So, there might be some cases, number of cells are very, very high. So, larger number of cells in a module, more would be the possibility of quantum mismatch losses; so that we should keep in mind.

So, how to reduce the mismatch losses? So, one option may be modules are fabricated from cells belonging to same batch. So, when it is manufactured so, we have to collect the cells from the same batch. In the second case, cell sorting is carried out to categorize cells having match parameters with specified tolerances, not exactly identical, but no it should be same.

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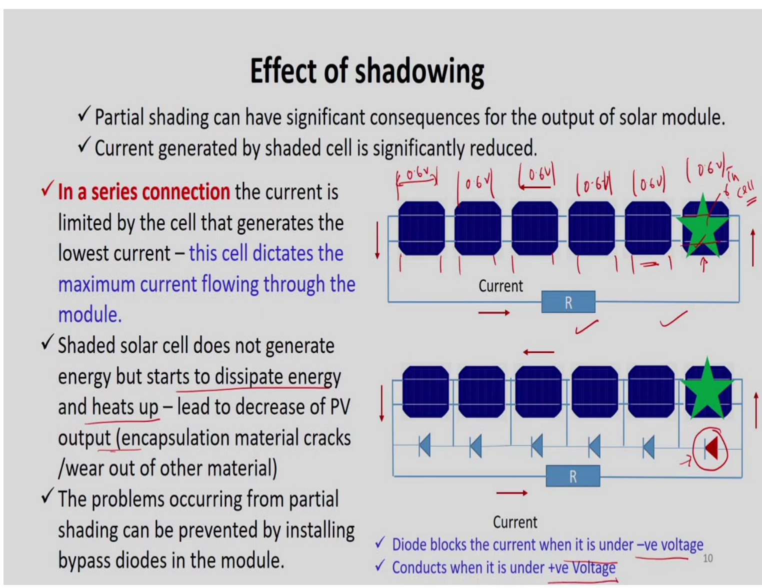

Now, let us discuss something about effect of shadowing. So, why this is important? Because, this partial shading can have significant consequences for the output of solar module. So, if maybe know some plant leafs are fallen on a single cell, then what will happen? So, this is the case, we have considered here. So, here we have considered 6 cells and one of the cells are affected by this shadowing of this plant leaf. Then what happens, let us discuss these issues.

The current generated by shadowed cell is significantly reduced, so what happens if it is shadowed by some external things? So, what happens, this current generated by these cells is significantly reduced, that affect the entire system. So, if you consider a case for series connection, the current is limited by the cell that generates the lowest current. So, as you can understand, so it will produce some kind of current ok current. So, what happens when it is shadowed, current generation will be very, very less in case of this 6^{th} cell. So, that affect the entire system.

So, this cell dictates the maximum current flowing through the modules. So, amount of current flows through these cells will dictate the maximum current flowing through the modules. This shadowed solar cell does not generate energy, but starts to dissipate energy and heat up, which leads to decrease of PV output. Sometimes wear out and burning off the cells, and other components are also observed. So, what happens, I will explain in the next slides, how this happens and I will draw this I-V characteristics.

So, for the time being, we must know, so here it's a 0.6 V and here is the 0.6 V, is the 0.6 V ok, again 0.6 V here that much of voltage will be there and here also 0.6 V. So, current will be lower here. So, once we connect a load here, what will happen? Here, current generation will continue, but here no current will be generated, so it will act like a reverse bias system. So, the bias voltage on these cells will be very, very high. So, because of this region, this problems arises, heating up and dissipation of energy.

So, this kind of problems can be solved by installing some kind of diodes. So, these diodes are called bypass diodes. So, how does this bypass diode works? This diodes blocks the current when it is under negative voltage, but conducts current when it is under positive voltage. Let us now, draw the I-V characteristics of this case.

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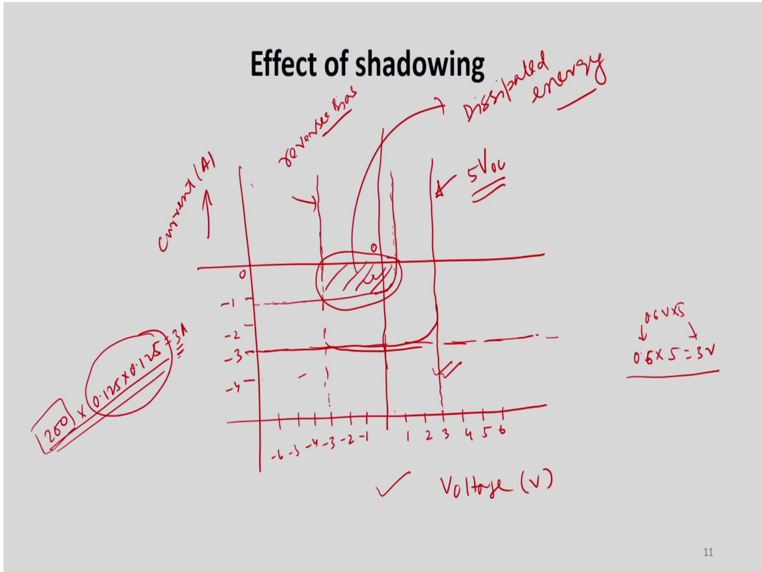

So, if we draw this I-V characteristics, so maybe I can take this plot, and maybe I can draw here, so maybe zero here, and we will have this. And so, maybe I can write 1, 2, 3, 4, 5, 6, ok; 1, 2, 3, 4, 5, 6 maybe 1, 2, we have 3, 4, 5, 6, this is -1, -2, -3, -4, -5, ok -6. This is current; this is the voltage. Now, if we have to draw this current, maybe we can here is zero and maybe here is -1, it is -2, this may be -3 and -4, something like that. So, what we can draw here, is we have, already we have understand; so this is the voltage, and then we will have, this voltage is 3 because we have 0.5 into, sorry (0.6 × 5) is 3 V, so this is in voltage. So, this maybe I can draw here.

So, this may, and this current is current, maybe I can draw is 3 here, so this will be something like this. And so here, we can understand how this has been calculated, because cell area is 0.25 × 0.125, 0.125 × 0.125 and then we have maybe 200 W/m^2, A/m^2; so, it will be here about 3 A. So, this current will be in ampere. So, this will be our curve for 5 5 cells or 5 V_{oc} ok and for 1, so this will be 0.6 right, this will be 0.6. I will explain, and current will be somewhere here. And we will have this reverse bias system, so this will be minus; so maybe I will use dotted line here, this will come something like this, dotted line and it will go something like this.

So, as I said, when this reverse bias, so this is for reverse bias reverse bias. So, now this part is the dissipation ok, so dissipated energy is this one dissipated energy. So, what I have drawn here, for this is 5 V. So, this is an I-V characteristics curve; for this scenario, what we have discussed in the last slides, so there are 5 cells which are producing energy. So, for 5 cells, so what will be the voltage? Because, every cell are having 0.6 V or V_{oc}, and then we have 5, so it will be 3 V. So, this is the 3 V line. And then, current is 3 because if we multiply this, if we take the area of a cell is 0.125 × 0.125 and then, if we take current density is 200, then it will be 3 A. So, close to 3 A. So, we can we can have this plot.

And for the shadowed cell, already we know the voltage is 0.5, then amount of current generation is very, very less. So, its close to here. And as I said, in order to pass the current through this shadowed cell, then that will act as a reverse bias. So, reverse bias voltage will be applied on that shadowed cell, and its magnitude will be same as what we got by connecting 3 cells in series, but in the opposite direction. So, that is the that much of voltage. And, the amount of power dissipation is shown here.

So, this figure gives an idea, how this shadowing actually know is reducing the energy generation. So that much of dissipation will be there. And as you can understand, that minimum current, what is there in the circuit is the maximum amount of current to be drawn in that circuit. So, if you go back to the slides, this can be reduced by connecting these diodes. There are rules how to connect those diodes and how many diodes can be connected in a single string.

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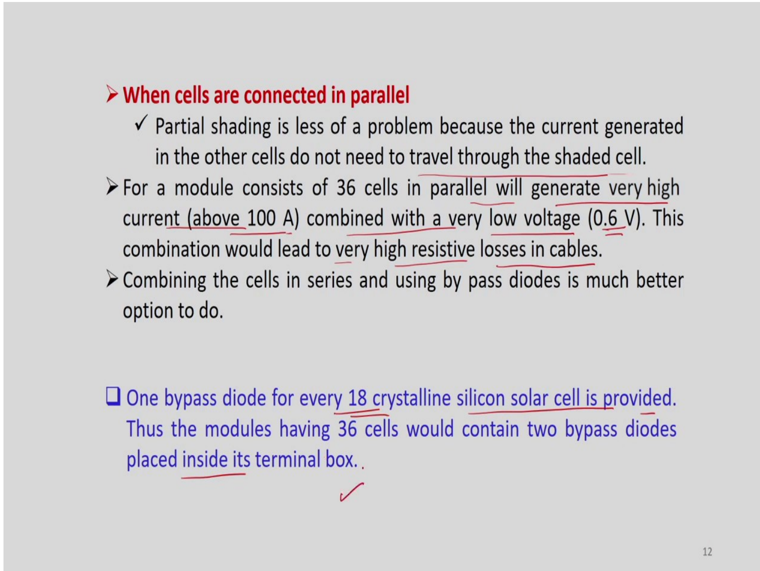

Now, come to the situation, when the cells are connected in parallel. This partial shading is less of a problem because the current generated in the other cells do not need to travel through the shadowed cell. This is one important aspect. And for a module consists of 36 cells in parallel, will generate a very high current above 100 A, and combined with a very low voltage is about 0.6 V.

This combination would lead to very high resistive losses in the cable. So, this kind of configurations are normally not preferred because of these reasons. And, for your understanding, so one bypass diode for every 18 crystalline silicon cells is provided. So, if we have 36 cells, then we need two bypass diodes, which are normally installed in the terminal box of the PV module.

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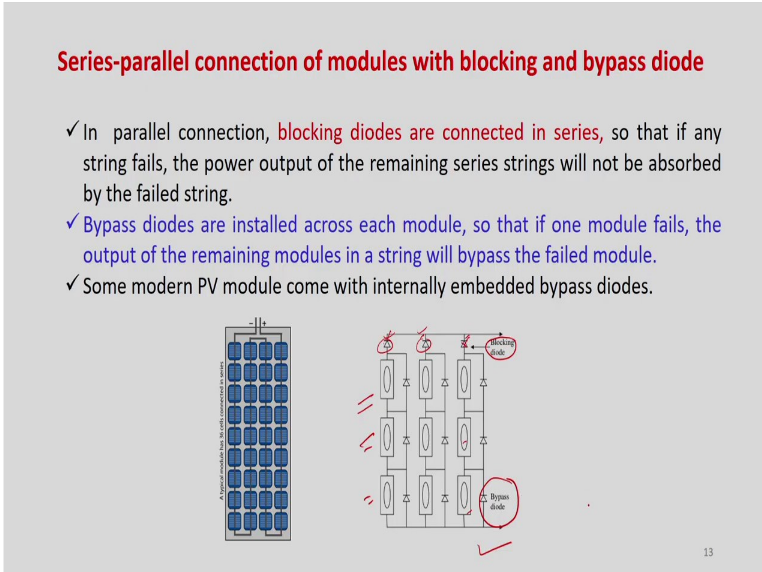

Now, let us also learn what happens when we connect many modules in these configurations. Now, these are modules, not cells; these are modules. So, these modules sometimes need to be connected in series and sometimes need to be connected in parallel. So, in parallel connections, blocking diodes, these are the blocking diodes, these are blocking diodes in all strings normally installed, so that if any string fails, so any of the string fails, the power output of the remaining, so any of the string fails then power output of maybe these two strings will not be absorbed by the failed string. So, if this is failed, then the other two will will be working; this is something like that.

So, this bypass diode, if we talk about now, bypass diode are installed across each module, these are the modules, so that if one module any of the modules fails, the output of the remaining module in a string will bypass the failed module. Nowadays, in the advanced modules, these kinds of diodes are embedded in the system itself.

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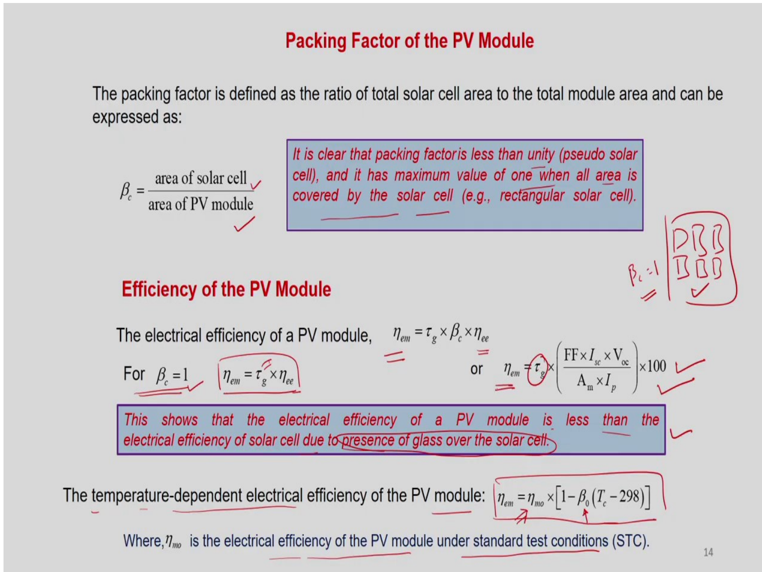

So now, let us learn the packing factor of a module. As I said before, packing factor plays a key role in maximizing the efficiency of a PV module. So, how does packing factor define? Is defined as the ratio of total area of the solar cell to the area of the module. So, it is clear that packing factor is less than unity, and it has a maximum value of one when all the area covered by the cell. So, if we take this module and then cells, then all the area of the modules is covered by the cells, its packing factor will be one.

And also, we can define the module efficiency. So, electrical efficiency of the module can be defined something like this, $\eta_{em} = \tau_g \times \beta_c \times \eta_{ee}$. So, β for, if packing factor is 1, then our expression will be something like this, this τ_g is transmissivity of the glass and η_{em}, this is module efficiency, electrical efficiency of the module can be something like this.

And also, we can derive the temperature-dependent electrical efficiency of the PV module by using this expression. So, this η_{mo} is the electrical efficiency of the PV module under standard test condition. So that is 1000 W/m^2 of insolation and spectrum of AM1.5 and an ambient temperature of 25 ^oC and this is the temperature coefficient, β_o.

And this expression shows that the electrical efficiency of the PV module is less than the electrical efficiency of solar cell due to the presence of glass cover. So, this is the reason why we cannot take the efficiency of the cell as efficiency of the module. So, we need to consider this transmissivity of the glass. Since, you understand now, what are different layers of a PV modules.

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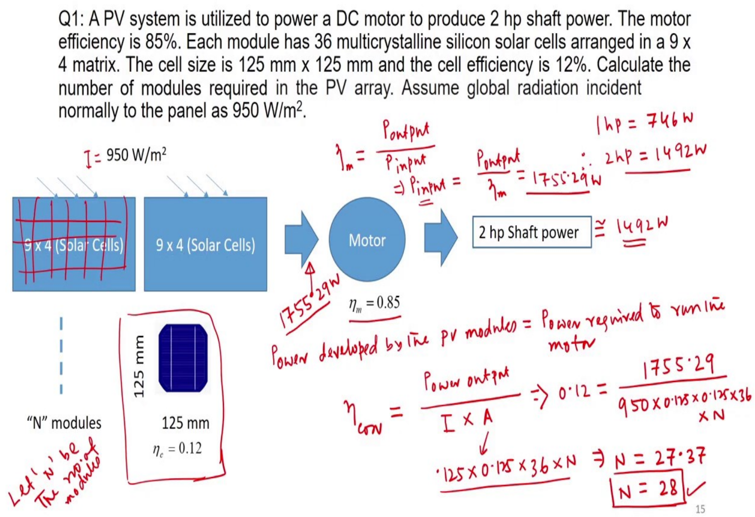

Let us take a practical example. How these solar modules can be employed for practical utility? The problem goes something like; a PV system is utilized to power a DC motor to produce 2 hp shaft power. The motor efficiency is given as 85%, which is shown here, and each module has 36 multi-crystalline silicon solar cells arranged in a 9 × 4 matrix. So, here you can see 9 columns, so here you can get 9 columns, and then we have 4 rows, so thats how 9 × 4 is equal to 36. The cell size is 125 mm × 125 mm, which is shown here.

So, for a single cell, size is 125 × 125 mm, and the cell efficiency is 12%. Now, we need to calculate the number of modules required in the PV array. Assuming global radiation incident normally to the panel as 950 W/m^2. So, this is nothing but I which is equal to 950 W/m^2.

So, in this problem, we need to find out number of modules required to run the motor. So, what are the parameters given? Shaft power output is 2 hp and then conversion efficiency of the motor is given as 85 %, and cell efficiency is 12 % and then how the cells are located, means how many cells constitute the module that is given to us and then the amount of solar radiation received by the modules is given to us.

Now, let us solve this problem. So, as we know, 1 hp = 746 W; hence for 2 hp, it will be 746 × 2, which comes to be 1492 W. So, this is equivalent to 1492 W. As we know the motor efficiency, by utilizing these two parameters, we can calculate what the input power required to run the motor.

So, if we write the expression for efficiency of motor, so η_m we represent, this is power output, then we will have power input. So, here we need to find the power input, so this power input is equal to power output divided by η_m. So, if we substitute the value of power output is equal to 1492 and η_m is 0.85 then this power input which is required to run the motor will be 1755.29, this will be in W, so here this power required to run the motor is 1755.29 W.

Now, our next step is to calculate the number of modules. So, let n be the number of modules required to provide the energy needed to run the motor. So here, what happens this much of energy is required from the solar modules. So, what we can write here, this power developed by the PV module or, say, modules is equal to power required to run the motor. So, let us use the expression, $\eta_{conversion}$ is equal to power output power output from the PV module or PV modules, and then we will have amount of solar radiation which is falling on the modules is I ×A.

So, this conversion efficiency is 0.12, and we will have I is 950, and this area this area for a single module is 0.125 × 0.125. So, this is the area of a single cell, and there are 36 cells, and that is arranged 9 × 4 matrix, so it will be 36. And then we do not know the number of modules required, let n be the number of modules required.

So if we substitute here, this value, so this I can write here again 0.125 × 0.125 then we have 36. And of course, we need to multiply with n, so here is the power output or the amount of energy required to run the motor which is equal to 1755.29. So, if we do the calculation, then n is found to be 27.37, which is equal to 28 numbers.

So, this problem is very, very practical. So, what we have investigated, so in order to generate 2 hp shaft power, we need about 28 number of PV modules of size something like that. So, if the cell size is 125 × 125 mm and its conversion efficiency is 12 %, and it constitutes 36 cells, then we require 28 numbers of PV modules to generate 2 hp shaft power.

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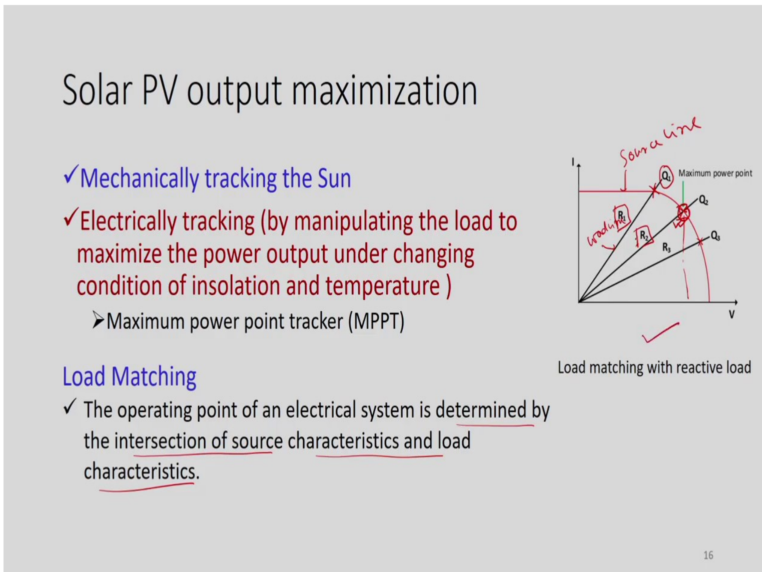

Now, let us learn about, how we can maximize the PV output? What are different ways of maximizing the PV output? So primarily, there are two ways; one is mechanically tracking the sun. So, we can track the position of the sun by operating the PV system, so that maximum exposure of solar radiation can be obtained. Or in the second case, we can do by electrically, that is called electrical tracking, by manipulating the load to maximize the power output under changing condition of insolation and temperature.

Also, we learn what is maximum power point tracker? And, how we can do this load matching? So, if we see the operation of a PV system is something like this. So, if we consider, so this is source line this is source line source line, and this is your load line load line. So, we need to find out the intersection point of source line and load line.

So, what happens, say one resistive load is connected here, so this shows the load matching with reactive load, so maybe R_1 is the reactive load for a particular set of operation. So, if we extend this R_1 and we get the intersection point here, so operating point is Q_1. If we increase the resistive load to R_2, its operating point is Q_2. And then further, if we increase R_3, then its operating point is Q_3.

So, now what happens? Our primary intention is to operate the system at this maximum power point. So, what we have observed, so if we can connect this load at this condition, then what will happen? We can maximize the power output from the PV system. So, that way, we can do the load matching; different load we can connect, and you can see which load is giving the best performance. So, this operating point of electrical system is determined by the intersection of the source characteristics and load characteristics. So, this has been shown here, and our target is to operate the system at maximum power point.

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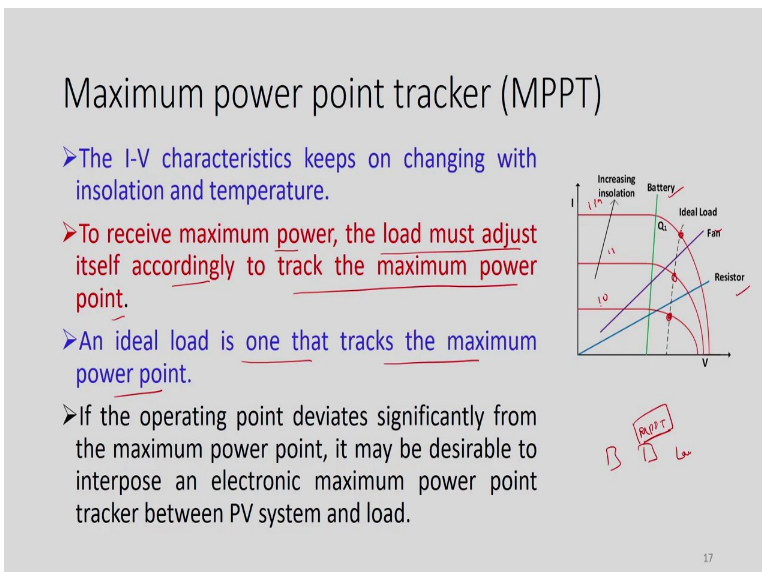

So, now let us study maximum power point tracker, which is very, very important to control electrically, to control the maximum power electrically. So, as you can understand, this I-V characteristics will change which weather condition. May be, so this may be say at morning, say maybe at 10 o'clock, this may be at say 11 o'clock, this may be of 1 o'clock, 1 pm. So, different curve can generated at different times. Also, these are dependent on temperature, what we have discussed in the very beginning of this class.

This I-V characteristics keep on changing with insolation and temperature. So, to receive the maximum power, the load must adjust itself accordingly to track the maximum power point. So, this is very, very important; load has to be matched. An ideal load is one that tracks the maximum power point. So, at every I-V characteristics, there is a maximum point. So, at that particular time, what will be the P_m, what is the I_m, V_m so we can get what is P_m. So, always our target is to operate at this P_m.

So, if the operating point deviates significantly from the maximum power point, it may be desirable to interpose an electronic maximum power point tracker between PV system and load. So, we have PV system, and then we have loaded, so in between, we need to install this MPPT, to control and to get maximum power.

So, in this figure, you can see the different loads, these are increasing insolation, and then this is for battery; this is for fan, resistor but know, we need to operate at this maximum power point.

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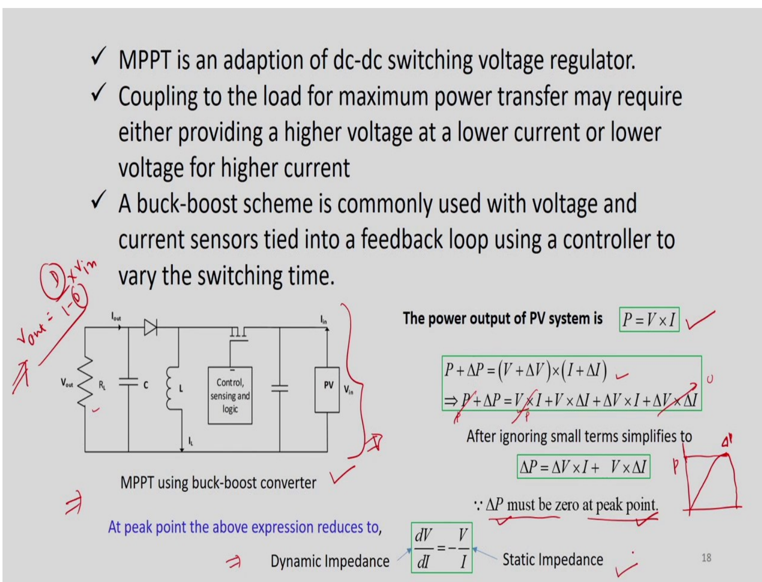

So, this MPPT is adoption of the dc-dc switching voltage regulator. So, coupling to the load for maximum power transfer may require either providing a higher voltage at lower current or lower voltage at higher current. Normally, a buck-boost scheme is commonly used with voltage and current sensors tied into a feedback loop using a controller to vary the switching time. So, duty cycle is applied.

So, if I am interested V output, $V_{out} = \frac{D}{1-D} \times V_{in}$, D is nothing but the duty cycle of a MOSFET. So, this is the buck-boost converter that is used in MPPT; you can see the different components here. So finally, what we are interested about this V_{output}. So, details of these configurations can be seen in some other electronics books, so how this can be fabricated for real-time operation.

So, if we consider this power output of a PV system, which is nothing but P = V × I. And if we consider an incremental increase in power, so (P + ΔP) = (V + ΔV) × (I + ΔI). So if we do the simplifications and we ignore the very small terms like this is very small, so this may be cancelled, and this V × I is nothing but P, this is P, so this is gone. So finally, we will have ΔP = (ΔV × I)+ (V × ΔI).

So, this ΔP must be zero at peak point so as you can understand, if I recall this curve, so this will be linearly goes and this will be something like this. So, at this point, this gradient will be zero, or ΔP = 0; because if you consider P is here, so there is no change in power here. Thats why, ΔP must be zero at the peak point. If ΔP is zero, then from that, what we can calculate is dV/dI = - (V/I). So, this dV/dI is known as dynamic impedance of the source, and this –V/I is static impedance. So, this knowledge is applied for controlling this operation of MPPT.

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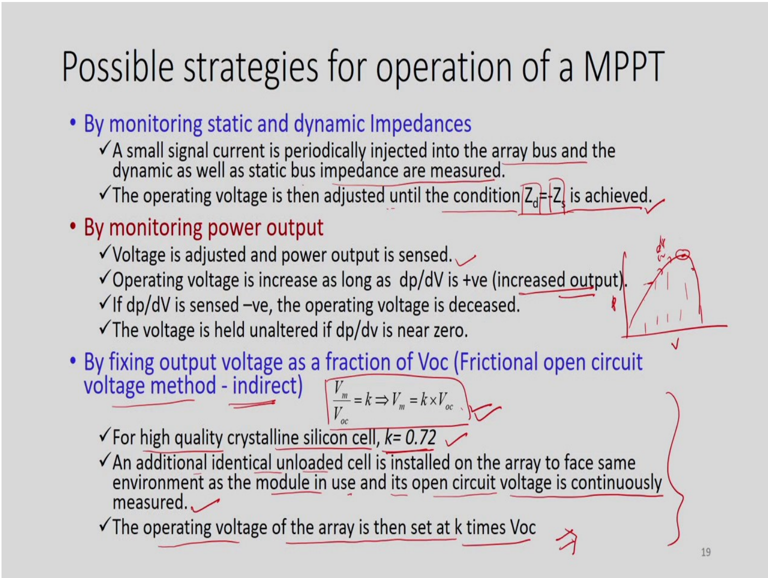

So now, what are the different strategies adopted for operation of an MPPT? So, first one is by monitoring static and dynamic impedances, and second one is by monitoring power output, and third one is by fixing output voltage as a function of open-circuit voltage. This is also known as frictional open-circuit voltage method, and this falls under indirect method.

So, in the first case, what happens a small signal current is periodically injected into the array bus, and the dynamic as well static bus impedance are measured. The operating voltage is then adjusted until the condition dynamic impedance, and static impedance are equal, but in the opposite direction is achieved.

And in the second case, voltage is adjusted, and power output is changed. So, we need to change the voltage as you can see, this kind of configurations. So, here is the voltage, so we can change the voltage we can change the voltage, and this power output can be changed. So, this is power, so operating voltage is increased as long as dP/dV is positive obvious. So, this is a positive gradient, so dP/dV is positive here, and this will be zero, and this will be negative. So, that means that is increased power when dP/dV is positive. And if dP/dV is negative, then operating voltage will decrease. So, this voltage held unaltered if dP/dV is near zero.

So, in the third category, by fixing voltage as a function of V_{oc}, what we can do, that V_m is nothing but the voltage at maximum power to the open-circuit voltage is constant for a particular semiconductor material. So, this expression $V_m = k \times V_{oc}$. So, for high-quality crystalline silicon cells, this k is about 0.72. So, for doing this, we do not have to close the circuit for calculation of V_m every time.

So for that, what you need to do, an additional identical unloaded cell is installed on the array to face same environment as the module in use, and its open-circuit voltage is continuously measured. And this operating voltage of the array is then set at k times V_{oc}, so this k time V_{oc}. So, this is one of the simplest methods of calculating this V_m. So, out of these three methods, researcher can adopt any of the methods for calculation of V_m for MPPT operation.

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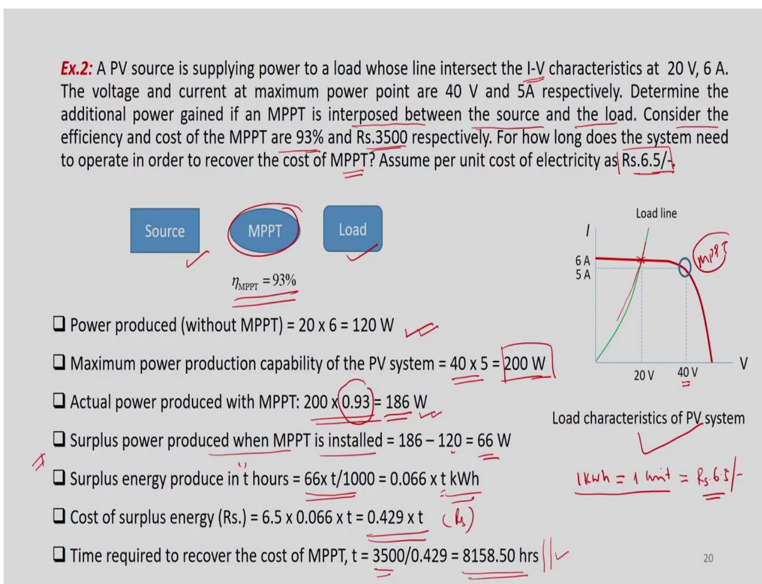

Now, let us solve one more problem. So, this problem goes something like this. A PV source is supplying power to a load whose line intersects the I-V characteristics; this is something like that. This is the load line and this is the source line, and this is the point of interaction or intersection. So, coordinates are given here, maximum power point, this coordinate is 40 V and 5 A and here at intersection point 20 V and 6 A.

So, determine the additional power gain if an MPPT is interposed between the source and the load. Consider the efficiency and cost of the MPPT are 93% and rupees 3500 respectively. And also, we need to calculate how long does the system need to operate in order to recover the cost of MPPT?

So, electricity cost per unit is rupees 6.5, need to be considered. So, configurations are something like source we have, load we have, and then in between, we have MPPT having efficiency 93 %. Load characteristics are given here; all the values are given. Now, this power produced without MPPT; if we are not imposing any MPPT here, so this is MPPT. So, if no MPPT is there, so this is the point.

So, what happens, this 20 V multiplied by 6 A will be 120 W, and then this maximum power production capability of PV system is how much? 40 × 5, so 40 V and 5 A, so it will be 200 W. And then actual power produced with MPPT will be something like this; because efficiency is 0.93, so it will be 186 W. So, if I am interested to know the surplus power produced when MPPT is installed, then this much is the actual power produced, and then power produced without MPPT is known, already calculated, and we can use this value here, so (186 – 120) will be 66 W.

Now, this surplus power is 66 W and then surplus energy produced in t hours. So, if we multiply it by t and then divide by 1000, it will become kWh. So, t will be in hour and 1000 we have divided, so it becomes kWh. Already we know, 1 kWh is nothing but 1 unit. So, here one unit cost is rupees how much is given? 6.5 rupees.

So, now we can use this information here. So, cost of the surplus energy is 6.5 × 0.066 × t, so this will be something like this, this will be in rupees. And this time required to recover the cost of MPPT will be, because cost is known to us. Then 3500 divided by 0.429 will give you this much of hours. So, this many of hours are required to recover the cost of the MPPT what we have invested. So, this is a quite an interesting problem. So, we can see how economically you can make, so how long we need to operate to get the payback period.

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Now, if these modules, what we have discussed so far, are connected for generation of large amount of power, then it is called PV arrays. A photovoltaic array is a collection of series or parallel or both series and parallel connection or connected photovoltaic modules. So, these are the modules which are connected, and this is for a large power generation unit.

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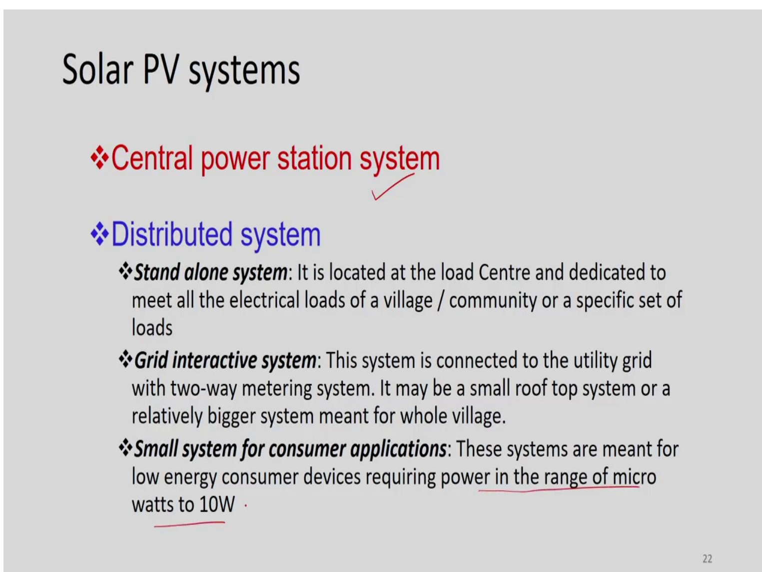

So, how these PV systems are classified? Primarily, there are two major classifications, first one is central power station system, and second one is distributed system. The central power system is a large power stations like our coal based power generation unit. So, at day time, huge amount of power will be generated, and then this will be given to the grid. And second one is distributed system.

So, under these distributed systems, there are many categories like stand alone system, grid-interactive system and small system for consumer applications. So, stand alone systems, maybe if you are interested to give power to a small village or locality, so, that can be given. So, that will fall under stand alone system. Or maybe for irrigation purpose, if we have to give some kind of energy from solar, that is nothing but stand alone system.

And for grid-interactive system, what you can do, suppose in my building, if I want to install some kind of solar PV and the energy generated by the solar PV can be given to the local grid when more amount of energy is generated, and we can take the energy at night from the grid when our energy is requirement is there. So, that is controlled by this two-way metering system or net metering system. So, that is called grid-interactive system. And small system for consumer applications like maybe in watches, maybe calculators and its power range from μW to 10 W. So, under that category, we can generate that much power.

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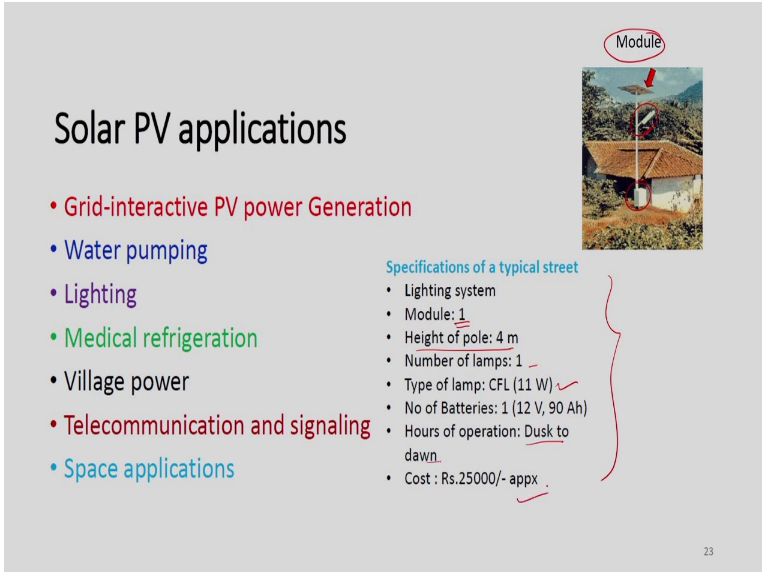

So, there are many applications what you can see, like grid-interactive PV power generation, power water pumping, lighting, medical refrigeration, village power then telecommunications and signalling, space applications. There are multiple applications of those solar PV systems. So, what I am showing here, its a application of a module for lighting. So, that is a battery bank here, and one charge controller will be there, and one module and one tube or say lamp, normally CFL lamps are used. So, this is the specifications normally used for this kind of street light system.

So, module is one, and its pole is about 4 m tall, and number of lamp is one and type of lamp is CFL, and its rating is about 11 W and number of batteries is one, and its rating is 12 V and 90 Ah and hour operation, of course, dusk to dawn and cost is about 25,000 in Indian market.

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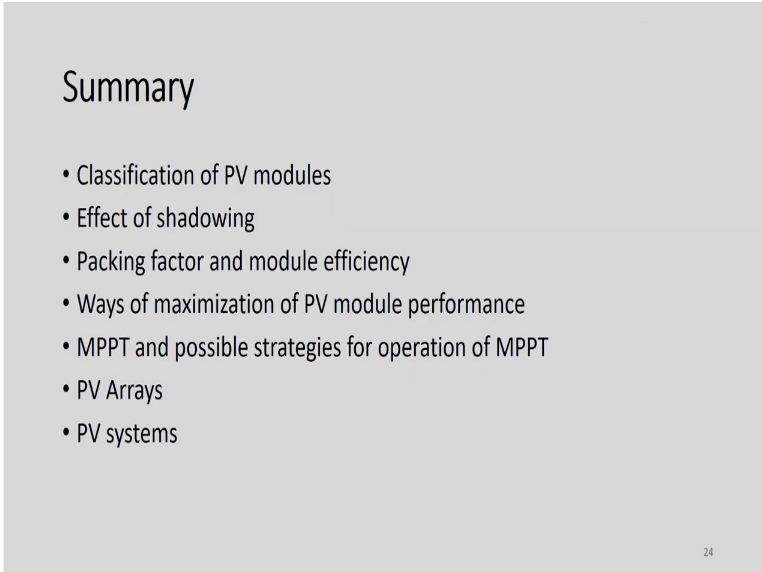

So, let us summarize what we have discussed today. So primarily, we have discussed the classifications of PV modules. Then effect of shadowing, then packing factor and module efficiency, how this module efficiency is different than cell efficiency, and we have discussed the different ways of maximization of PV module performance. Then, MPPT and possible strategies for operation of MPPT, PV arrays, and PV system.

So, I hope you have enjoyed the lecture, so thank you very much.