Solar Energy Engineering and Technology
Professor Doctor Pankaj Kalita
Centre for Energy
Indian Institute of Technology, Guwahati
Lecture 16
Grid Connected PV System

Dear students, today we will be discussing about design of grid connected PV system. So in design of grid connected PV system what are the different steps?

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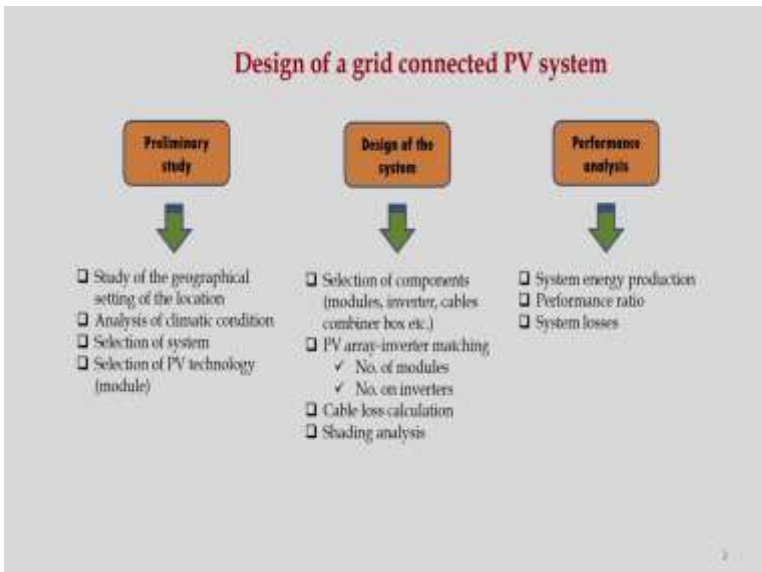

The first step is preliminary study. Second step is design of the system and third step is performance analysis, okay. So, in preliminary study what are the work components includes? Study of geographical setting of the location, okay. We must know the geographical condition of that particular locations where we are going to install the solar PV system and then analysis of climatic condition. So, we must analyze the climatic condition. What are the different radiation levels, sunshine hours and all those radiation parameters. And then selection of the systems, so what kind of systems is appropriate, maybe stand alone, maybe grid connected system and what capacity? Then selection of PV technology, the kind of modules and others.

So, under design of the systems, primarily it includes selection of components like modules, inverters, cables, combiner box and others. And this PV array-inverter matching is very, very crucial for design of this grid connected PV system. So, to match those output of the PV module and input of the inverter, okay, so other parameters like current, voltage, power. And also, we need to find out the appropriate number of modules, appropriate numbers of inverters required for a particular capacity.

Of course, we need to learn cable loss calculation then shading analysis. And under performance analysis we need to do the system energy production, the amount of energy will be produced by the PV system, performance ratios then system losses. Of course this component will be discussed in the next class.

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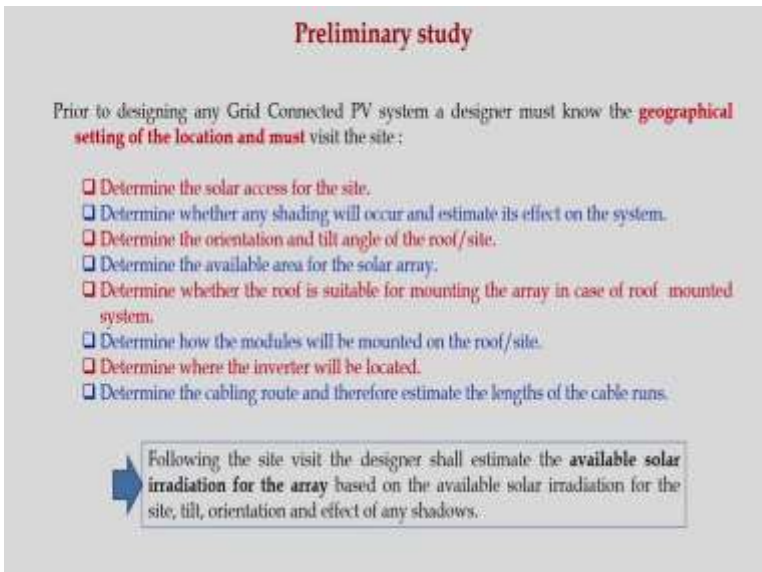

So prior to designing any grid connected PV system, a designer must know the geographical setting of the location and must visit the site to determine the solar access for a site, to determine whether any shading will occur and estimate its effect on the system, to determine the orientation and tilt angle of the roof or a particular site, to determine the available area for the solar array, to determine whether a roof is suitable for mounting the array in case of roof mounted system, to determine how the module will be mounted on the roof or the site and determine where the inverter will be located and to determine the cable route and therefore estimate the length of the cable runs, okay. So how long we need to maintain the cable length?

After this is done then what we need to do as a designer? So, this designer will estimate the available solar irradiation for the array based on the available solar irradiation for the site. And tilt is known for the particular location then orientation and effect of any shadows, okay. So, by analyzing this information, so amount of solar radiations to be received by the solar plant will be estimated.

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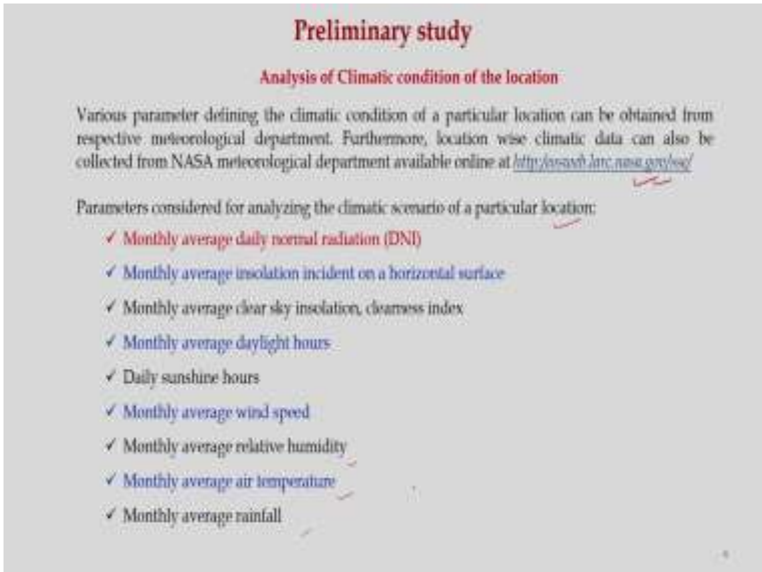

In the next phase, analysis of climatic condition of the location is very important. Normally, in order to get those meteorological data the government meteorological departments provide those data. Otherwise if it is difficult to get those data from the government departments, we can rely on some open sources. So, this location wise climatic data can also be collected from NASA meteorological department available online. So, this website we can access and we can download the required data.

The following parameters are considered for analyzing climatic scenario of a particular location. Number 1 may be monthly average daily normal radiation, monthly average insulation incident on a horizontal surface, monthly average clear sky insulation or clearness index, monthly average daily hours, daily sunshine hours, monthly average wind speed, monthly average relative humidity, monthly average air temperature, monthly average rainfall. These information’s are required. Already we have discussed many more techniques how to investigate many of the parameters mentioned in this list.

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So now come to the design of the system, selection of the components, okay. So, system design should follow appropriate standard. This standard may be BIS standard, may be IEC Standard, may be IP Standard, IS, EN, SS there are many standards. But country-wise these standards may vary, okay. So components with applicable BIS or equivalent IEC Standard or MNRE specifications what is used in India are something like for solar PV modules, IEC, IEC stands for International Electrotechnical Commission, okay, so they have standards, and 61215 or Indian Standard 14286, this standard is used. For inverter IEC 62109, this 1 or 2, these configurations are used and for cables, this BS stands for British Standards and EN stands for European Standards, 50618, this kind of cables standards are used.

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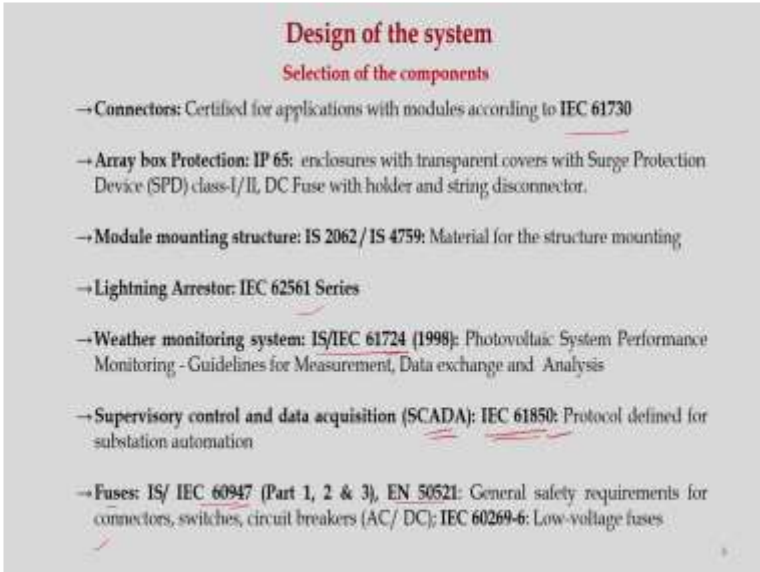

For connectors also there are specific standards. This IEC 61730 and error box protection it is IP 65, then module mounting structure IS Indian Standard 2062 or may be 4759, a lightning arrestor which is very, very important component of a grid connected PV system, its standard is about IEC 62561 series, and weather monitoring stations are also attached in a grid connected system, so it has got one standard. Then SCADA systems also has got standard that is IEC 61850, and fuses, as you can see there are standards, okay, IS Indian Standard or EN that is European Standards, okay. So, these standards are used normally for a grid connected PV system.

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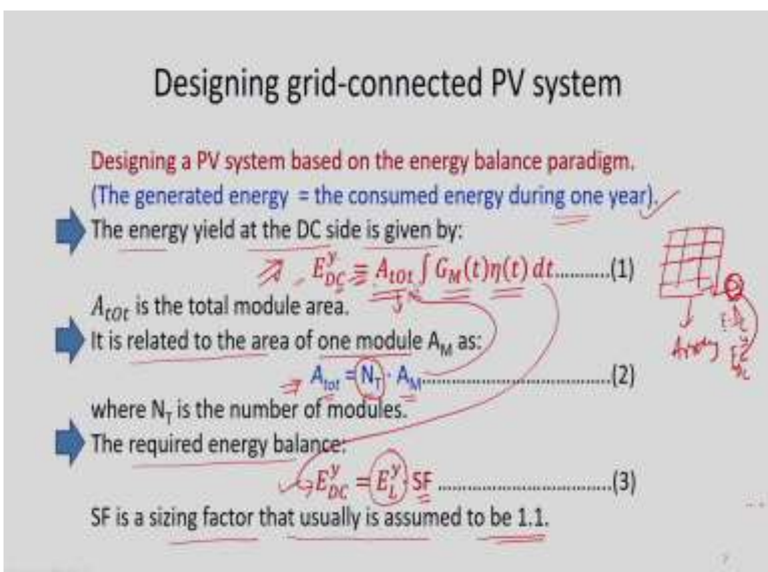

Now, come to the designing of grid connected PV system. We apply the principle of energy balance paradigm. So, here what happens, the energy which is generated by the PV arrays has to be equal to the consumed energy during one year. So, this paradigm is normally applied for designing a grid connected PV system.

So, let us learn how this can be calculated. So, the energy yield at the DC side is given by E is the energy, yearly energy, y stands for yearly and DC stands for DC, okay, so this is something like if we have these PV modules, there are many modules, there are many modules, okay so this becomes array, this becomes array so output of this array, this is something like DC, okay. DC is DC energy, E_{DC} okay or you can write E_{DC} okay. Since it is yearly we will write y, okay, this something like that. This energy we are talking about E_{DC}^{y}, okay. This is something like A_{tot}, this total area of the modules, $\int G_M$ is the intensity of solar radiation and η is the conversion efficiency, right. So, this will give yearly energy yield in the DC side. So this is the energy yield.

So, this A_{tot} is related to the area of one module, right. So, $A_{tot} = N_T . A_M$ What is N_T; N_T is the number of modules in that particular array. Once we know this information then we can use this A_{tot} and that can be applied here and we can calculate E_{DC}^{y}, okay or the yearly energy yield in the DC side, right. So, the required energy balance, what we can do, E_{DC}^{y} is equal to E_{L}^{y}, this part is something called load, okay, load side, multiplied by SF. This SF is nothing but sizing factor that usually assumed to be 1.1, right.

So, we equate this E_{DC}^{y} is equal to E_{L}^{y}, that is load side energy and this is your sizing factor, okay. So, once we equate this and if we substitute this expression, this expression here, okay and also use this equation 2 here, okay then we can simplify this equation 3 as something like this, okay.

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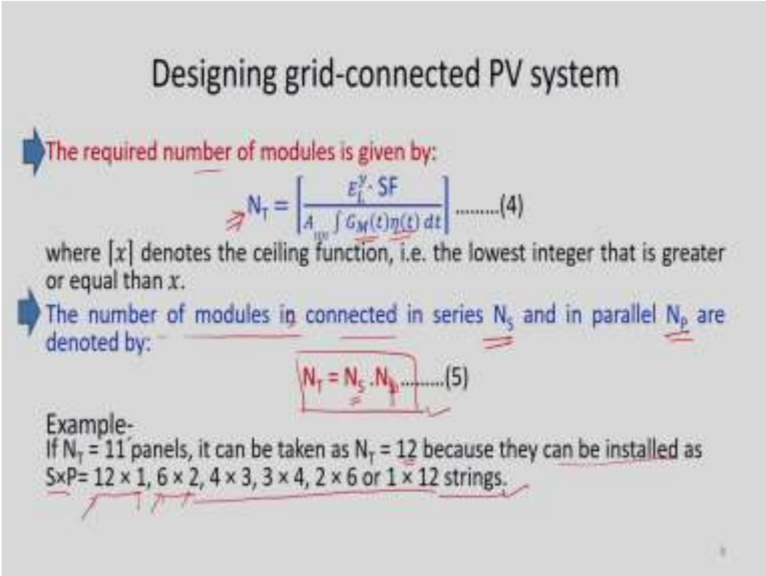

So, we can calculate the number of modules required, that is N_T. $N_T = \left[\frac{E_L^y \times SF}{A_{tot} \int G_M(t)\eta(t)dt} \right]$ means this is radiation, this is normally global radiation integration for the entire year and this is the conversion efficiency, right. Now, we need to know how are you going to connect those modules because we need to connect parallely and series, okay. So, how this configuration will look like? How many modules will be there in series? How many modules will be there in parallels, okay? So as a whole, if we say the number of modules is connected in series N_S and in parallel N_P are denoted by N_P, sorry this should be N_P, this is N_S, okay. So, $N_T = N_S \times N_P$.

Okay, so now we are not saying the number of modules connected in parallel and number of modules connected in series, okay. We learn how this can be done. And for example if N_T is 11 panels or 11 modules, it can be taken as N_T is 12, because this is a odd number, because they can be installed as S into P so this may be 12×1, okay or may be 6×2, 12 in series and 1 in parallel, 6 in series, 2 in parallel. So this kind of configurations may be adopted, okay. So best combination has to be find out, what will be the best which give you the maximum power output, okay. So, we will solve problems to understand this knowledge for betterment of the design of the PV grid connected system.

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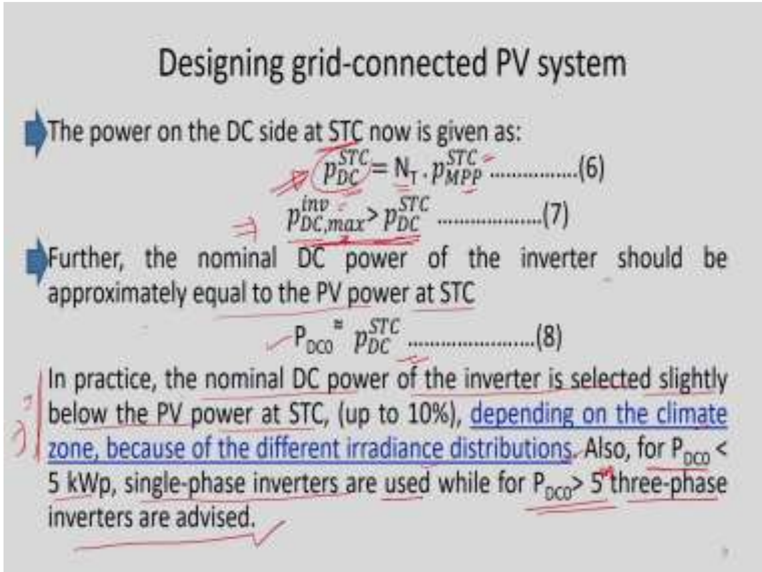

So, the power on the DC side at standard test condition is given by something like this, okay. So under test condition it will be something like this, okay, which is equal to $N_T \times p_{MPP}^{STC}$ okay.

So, what is the condition? $p_{DC,\max}^{inv} \rangle p_{DC,}^{STC}$, okay. So, once we know this value we must know this value has to be less than this $p_{DC,\max}^{inv}$,okay. So, there are some ratings of inverter. So, we must know the ratings of the inverter. So that will dictate us how to match this energy, okay. So, we will discuss in the coming slides.

Further the nominal DC power of the inverter should be approximately equal to the PV power at STC, okay. This is also one condition. So, p_{DC} at nominal power is equivalent to $p_{DC,}^{STC}$. This is also one condition has to be met, right. So, in practice the nominal DC power of the inverter is selected slightly below the PV power at STC, okay. So, depending upon the climatic zone because of the different irradiance distribution. So, this is very, very important.

Also, for p_{DC} at nominal condition has, if it is less than 5 kW peak then single phase inverters are used while if it is more than 5 kW, Watt peak, so this is kW peak, 3 phase inverters are advised, okay. So, this kind of know, design methodology we have to adopt for designing a system.

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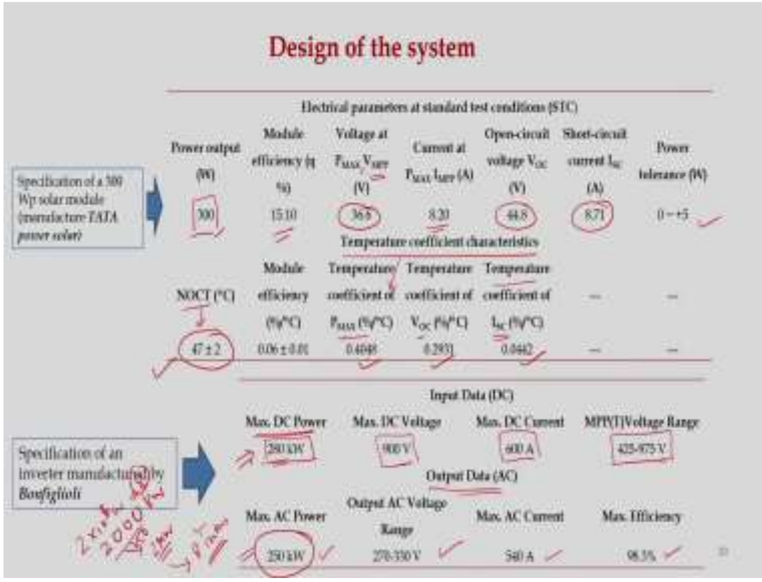

So, let us have a look about the specification of modules and inverter, okay. So, if we talk about the specification of a module we can see, for example we can consider a module having know output power or Watt peak is 300, okay and efficiency is 15.10 and voltage at p_{MAX} that is in V_{MPP} in voltage is 36.6 and current at p_{MAX} is 8.20 and than open circuit voltage V_{OC} is 44.8. Short circuit current is 8.71, okay and power tolerances are given, and also NOCT, Nominal Operating Cell Temperature is 47 ± 2, okay. This is also important. And these components are very, very important because this performance of PV modules detoriates with respect to temperature and insulation, okay.

So, if temperature increases, this performance decreases, okay and solar radiation if increases then performance increases but no, if it increases further from the standard test condition then temperature rise will be there and that causes lot of problems in the PV modules.

So, this temperature coefficient of p_{MAX} is something like this, 0.4048, temperature coefficient of open circuit voltage is something like this and temperature coefficient for current, short circuit current is something like this, okay. Let us also learn the specification of a, an inverter, okay. So, in case of inverter as you can see, maybe we can consider this inverter manufactured by Bonfiglioli.

So, here DC power input is 280 kW and maximum DC voltage is 900 Volt. DC current is 600 ampere and this MPPT voltage range is 425 to 975 Volt, okay. So, these information's are required while designing or matching these PV array and inverter, okay. And output voltage also required, maximum AC power is 250 for this configuration and then voltage is 270 to 300 Volt, then AC current is 540 ampere then maximum efficiency is 98.3 percent.

So, for example if we design for a capacity of 2 MW, okay and single inverter will give 250 kW then how many inverters will be required? It will be 8 inverters, right? 8 inverters okay, so that way we can do lot of design calculations, okay. So, what I am saying 2 MW is 10^6, okay. kW means again 3, okay, maybe 2111 kW, okay. If we divide it by 250 it will be 8, okay, it will be 8. So, that is how we need 8 inverters for a 2 MW capacity grid connected PV system, okay.

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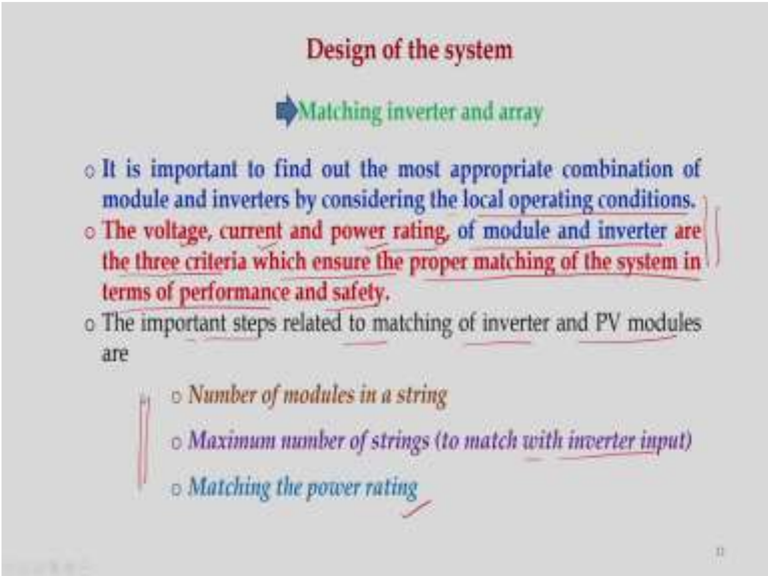

So, now come to the matching of inverter and array, okay. So how we are doing it, okay? So, it is important to find out the most appropriate combination of module and inverter by considering the local operating conditions, okay. The voltage, current and power rating of module and inverter are the three criteria which ensure the proper matching of the system in terms of performance and safety. This is very, very important. What we are doing actually? Voltage, current and power ratings has to be matched, okay.

The important steps related to matching of inverter and PV modules are something like, number of modules in a string, how many modules should be connected in series? When it is a string, there is a series connection, and then maximum number of strings to match with inverter input, right? And matching of the power rating, okay. So, these three components are very, very essential for designing.

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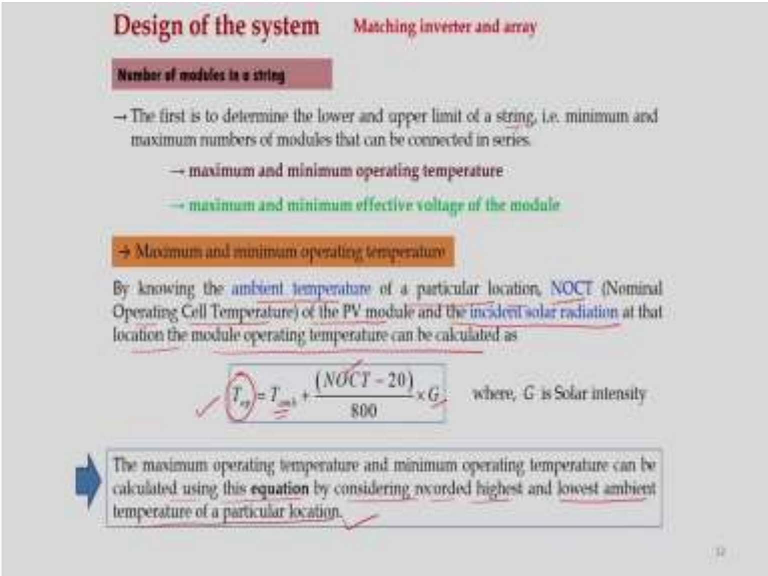

Now, what we will do? We will do the number of modules in a string that we will try to calculate now. The first is to determine the lower and upper limit of a string, that is the minimum and maximum number of modules that can be connected in series, that we need to find out. So, in order to find out these, we must calculate the maximum and minimum operating temperature. So, how we will get the minimum and maximum operating temperature? By observing the particular place temperature fluctuation, okay.

So, may be winter is, minimum is 5, and in summer maximum is 38. So, if we know this temperature variation then from that we can calculate what will be the minimum and maximum operating temperature of a PV cell, okay. Then we need to calculate maximum and minimum effective voltage of the module. So, what will be the effective voltage of the module? That needs to be calculated once we are done with the maximum and minimum operating temperature.

So, how to calculate minimum and maximum operating temperatures? So, as I said, by knowing the ambient temperature of a particular location, NOCT, Nominal Operating Cell Temperature of the PV module and the incident solar radiation at that location, the module operating temperature can be calculated as this, okay. So, we want to calculate this T_{op} and we must know T_{amb} and then

NOCT is required, okay. So, this is a standard formula you can use, and G is solar intensity, right.

So, the maximum operating temperature and minimum operating temperature can be calculated using this equation by considering recorded highest and lowest ambient temperature of a particular location. So, if we know this temperature fluctuation, from that we can calculate what is the minimum operating temperature and maximum operating temperature, right.

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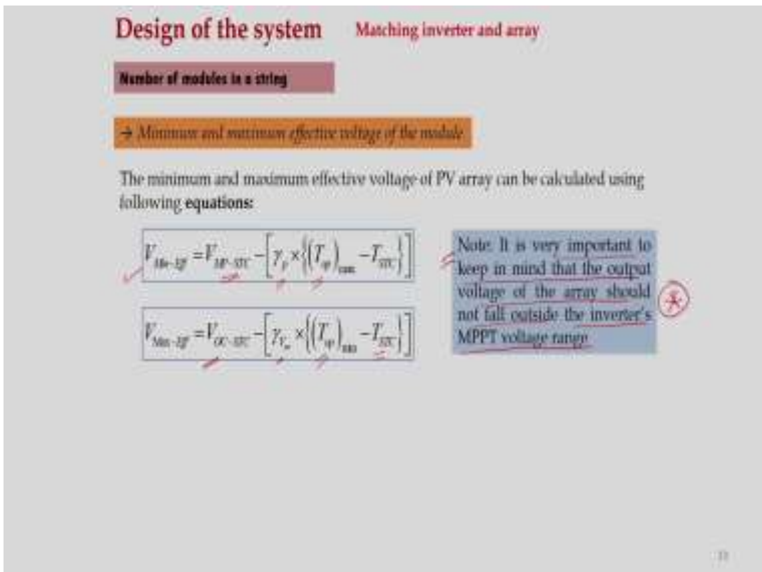

Let us move on to the next slides. So here, we need to calculate number of modules in a string. So minimum and maximum, effective voltage of the module, how to calculate it? So, we can use this equation. So $V_{Min-Eff}$ is equal to V_{MP-STC} okay, this is maximum point under standard test condition in the module side and γ_P is temperature coefficient for this voltage and $(T_{op})_{max}$ because already we know what is the operating maximum temperature, okay and STC condition is 25, and for calculation of $V_{Max-Eff}$ then we need to know what is open circuit voltage, okay, under standard test condition and we have to use this temperature coefficient for open circuit voltage and we know this T_{op} temperature by knowing the climatic condition of a particular location and T_{STC} is known to us, okay.

So, we can note that it is very important to keep in mind that the output voltage of the array should not fall outside the inverter's MPPT voltage range, okay. So, this is very, very important, okay. This is one of the important design observation.

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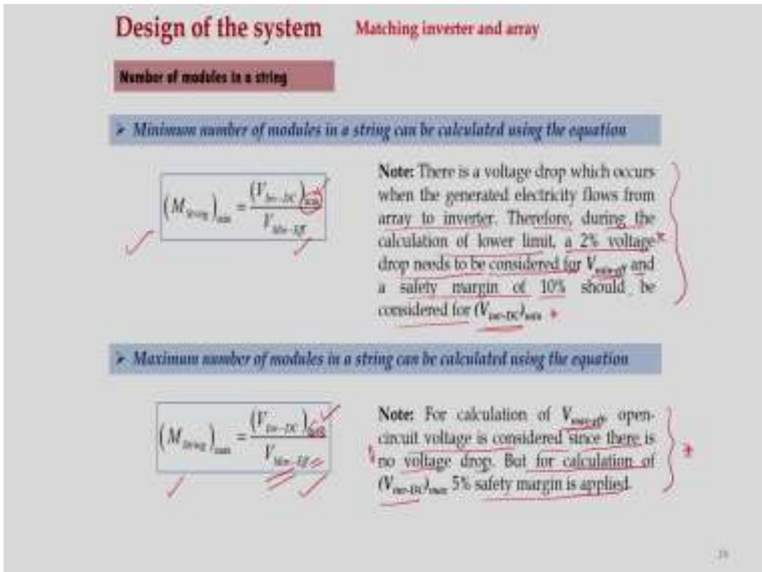

So now, let us know how to calculate this M string that is minimum number of modules in a string, okay. So, by using this equation we can calculate the minimum number of modules in a string, okay or minimum number of modules which can be connected in series, right. So, for this we need this inverter input voltage and then minimum effective voltage, okay which already we have discussed, okay.

So please note that there is a voltage drop which occurs when the generated electricity flows from array to the inverter, okay. So, voltage drop will be there, okay. Therefore, during the calculation of the lower limit, a 2 percent voltage drop needs to be considered, okay for $V_{Min-Eff}$ and a safety margin of 10 percent should be considered for V_{Inv-DC}. So, when we are doing very precise calculation we need to remember these two condition, okay. So how we are going to use those values for calculation of minimum number of modules in a string, right?

So, we are also interested to know the maximum number of modules in a string, okay. So, in order to find out the maximum number of modules in a string, we need to rely on this $(V_{Inv-DC})_{Max}$, so here it was minimum and it was maximum because MPPT variation will be there, okay, minimum to maximum, that voltage you need to use. And this V max effective, what we already we have discussed, that can be used to calculate this maximum number of modules in a string, okay.

Please note that for calculation of $V_{Max-Eff}$, this value, the open circuit voltage is considered since there is no voltage drop, okay. So, this is important. But for calculation of inverter voltage that is maximum voltage, is 5 percent safety margin is applied, right. So, this information need to be keep in mind while designing the grid connected PV system specially for minimum number of modules in a string and maximum number of modules in a string, okay.

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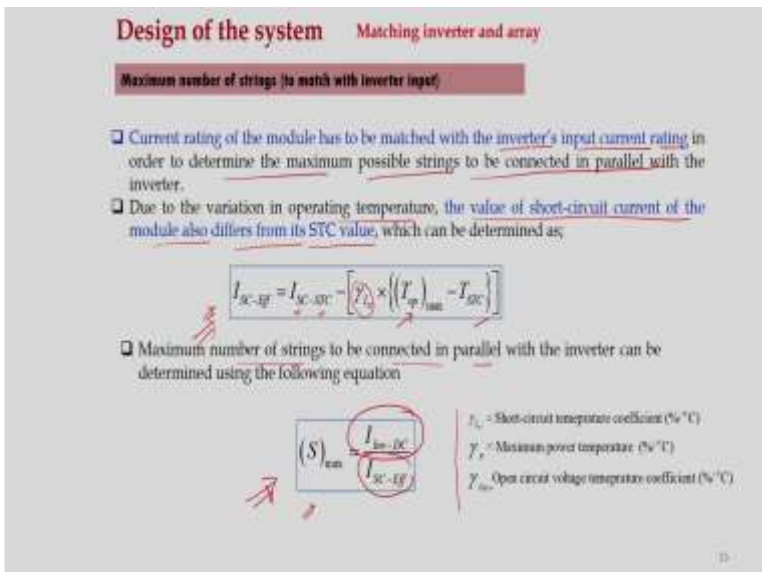

So now, let us use this current rating, okay. This current rating of modules has to be matched with the inverter input current rating, okay in order to determine the maximum possible strings to be connected in parallel. So, so far what we have discussed, the number of modules to be connected in series, okay, minimum number of modules to be connected in series and maximum number of modules to be connected in series.

Now, we must know the number of modules to be connected in parallel. So, once we have decided with this know, series connection or strings then know, we have to connect it in parallel. So, this is the procedure how we can do it. Due to the variation in operating temperature the value of short circuit current of the module also differ from its STC value that is obvious, okay.

So, if we need to account those variations, then we need to use this equation. I_{SC-Eff} is something like I_{SC} that is short circuit current under standard test condition minus this temperature coefficient for this short circuit current multiplied by $(T_{op})_{max} - T_{STC}$, okay. So, T_{STC} normally is 25 °C, okay. So, these are the values, what these parameters stands for, $\gamma_{I_{SC}}$ short circuit temperature coefficient, γ_p maximum power temperature coefficient and then γ_{VOC} is open circuit voltage temperature coefficient, okay.

Now, also we must know the maximum number of strings to be connected in parallel, okay. So, this is the equation we can use for calculation of maximum number of strings to be connected in parallel. Once we know this I_{Inv-DC} and then I_{SC-Eff} which one already we have calculated here, so if we substitute these two values then what we will get, that is a maximum number of strings to be connected in parallel, okay.

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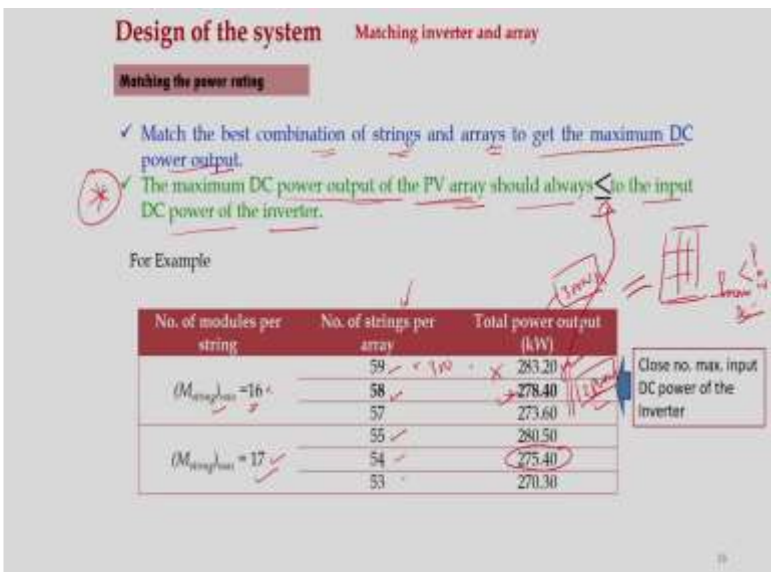

Now, now what we need to do, match the best combination of strings and arrays to get the maximum DC output, right. The maximum DC power output of the PV array should be always less than or equal to the input DC power of the inverter. This condition is very, very important, okay. The maximum DC power output of the PV array, okay, so we have these PV arrays, okay. So, we have calculated maximum, maximum power output okay or I will write P_{max}, okay and that will be DC is always less than the input power of the inverter, okay. So, in our case, it is input power of the inverter is 280, okay. So, this is input power of inverter inv, okay. So, this is something like that.

Now, for example, so if in a calculation if we know the minimum number of string and maximum number of string, okay and number of arrays based on our calculations, okay, so maybe 59 we got, okay but this is fixed. Because see, rating if we consider without derating of the module, say 300 Watt peak, module we have considered, right. Then here if we multiply by 16×59, say number of string per array is 59 and number of modules is 16, right. So, if you multiply $16\times59\times300$ so what we get is something like this value.

So, as already we know, this maximum input power is 280 kW, input power of the inverter is 280 kW so it should not be more than that, okay. So, it is more than that so it is not feasible, right? So, if we take 58 number of strings per array so it will be 270, it is a feasible case because it is less than 280, what is discussed here in the second bulleted point, right?

So, if we consider the maximum number of strings, that is 17 and if we take different strings or number of strings, say 55, 54 we can see which one is best fitted, okay, so this one is found to be best fitted, okay. So, we can decide based on the economics and other conditions which one will be the best fit for the particular plant, okay.

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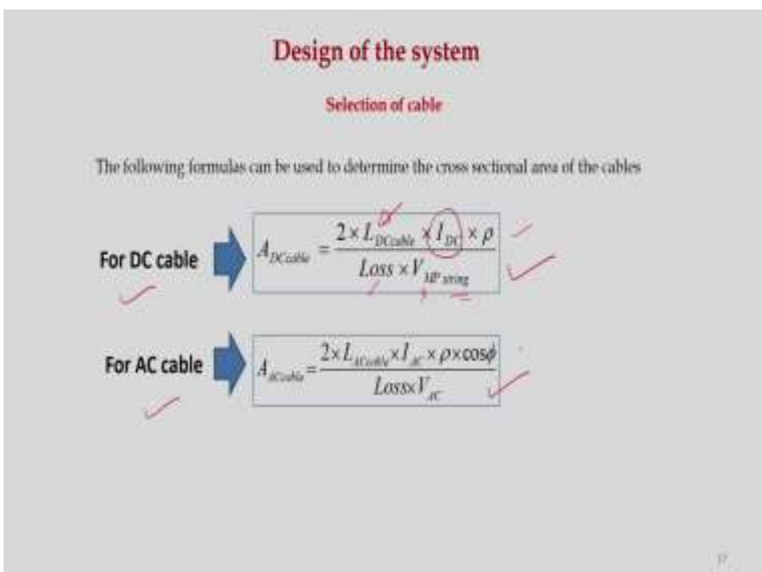

Now, we need to pay attention about the cables, right because this cable also consumes huge amount of power and cost, okay. So, to determine the cross-sectional area of DC cables we can use this equation, ρ is the resistivity, I is the know, current flowing through this circuit and this is cable length and losses will be there. And we already know $V_{MP\ string}$, okay and for AC cable these equations are used, okay. Of course power factors are need to be multiplied.

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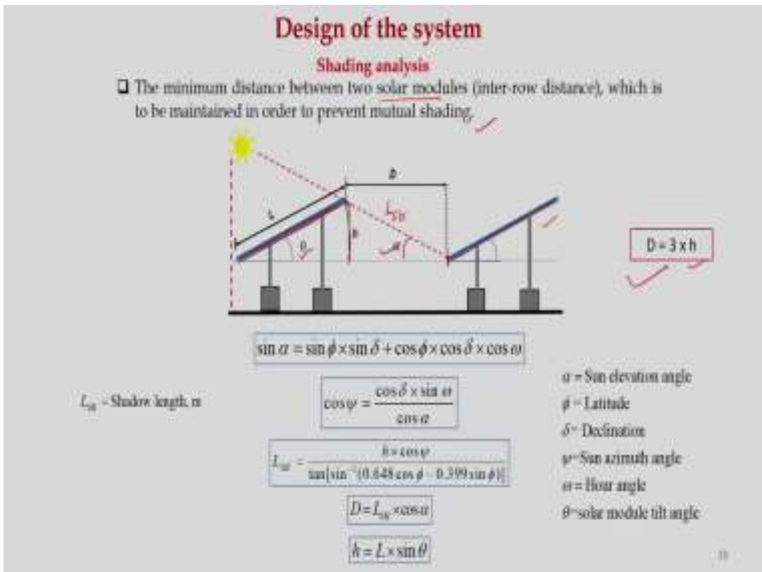

Now we need to see the shading effect. When we are installing PV modules, we must know how are you going to install these modules. If shadow is occurring then know, instantly we are losing lot of generated power, okay. That means if one module is shadowing others, then know, shadowed modules are not generating power. So, this effect of shadow is very, very important and we need to analyze it very critically.

So, the minimum distance between two solar modules which is maintained in order to prevent mutual settings are need to be studied, okay. So, if we consider this module and this module, okay what will be the appropriate distance between this top of this module and this position, so we need to specify so that shadow caused by this module should not hamper the functioning of this PV module, okay.

So, we can do lot of calculations and we can come up with a solution and it tells us that know, this D has to be $3 \times h$, so h is nothing but this height and this is know, solar module tilting called as θ here, okay and alpha is the sun elevation angle, okay, and if you consider this L_{SH}, so this $L_{SH} \cos\alpha$ is also the, and this equation can also be used for investigating the distance between these two modules, okay. So, tip of this and then bottom of these modules is D, right.

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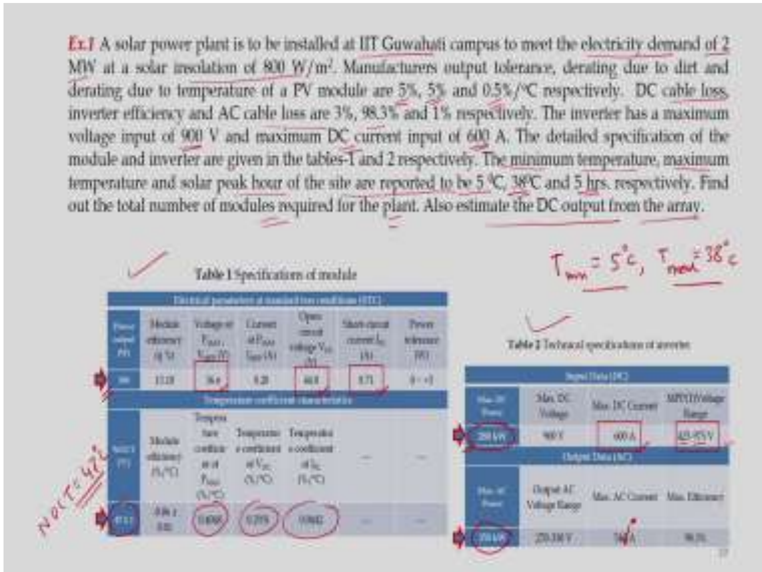

So, let us now take an example, okay so that you understand how these kinds of problems can be solved, okay. So, the example goes something like this. A solar plant is to be installed at, say IIT Guwahati campus to meet the electricity demand of 2 MW at a solar installation of 800 W/m^2, okay. This may be considered as global radiation. The manufacturer's output tolerance derating due to dirt and due to temperature of PV module are 5 percent, 5 percent and 0.5 percent per degree increase in temperature, okay.

So, DC cable losses are given. AC cable losses are also given, okay. The inverter has a maximum voltage input is 900 Volt, maximum DC current is 600 ampere. So detailed specifications are given here, specifications of the module and specification of the inverter, okay. And also it is given that the minimum temperature and maximum temperature and solar peak hours of the site are 5 degree, 38 degree and 5 hours. So, find out the total number of modules required for the plant and also we need to estimate the DC output of the area, okay. So, we need to solve this problem now, okay.

So, what I can say, this is T_{min}, T_{min} is given as 5 °C and T_{max} is given as 38 °C, okay. So, this power rating is 300-Watt peak, okay and voltage at p_{MAX} is 36.6 so these values are going to be used. And open circuit voltage is 48.8, short circuit current is 8.71 and these values are also required, okay, these values are also required, and NOCT is 47.

So, in our case NOCT we will use 47 °C, okay and here in inverter as I said this is maximum power, DC power, that is input to the inverter is 280 kW and this is the output 250 kW, right and we will have DC maximum current is 600 and MPPT voltage range is 427 to 975 volt. These informations are required for solving this problem.

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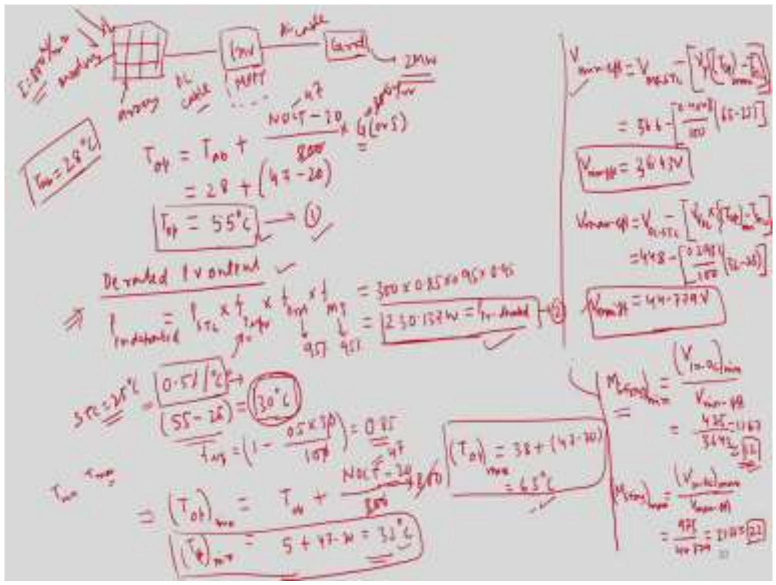

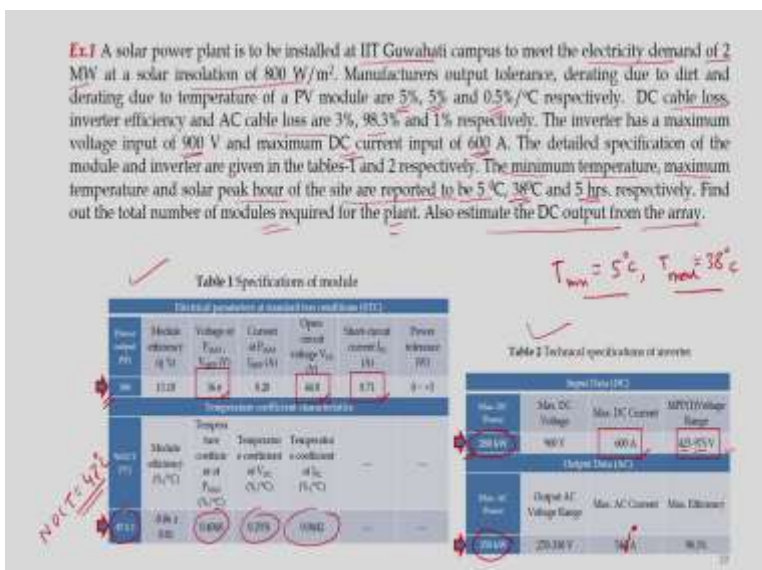

So, let us first calculate, or first let me draw this diagram, okay. This may be different know, this is an array, array and these are modules, modules, solar radiation is falling here, okay and then we will have inverter, we will have inverter here okay, MPPTs are attached, MPPTs are attached to it. And we will have this is DC cable, DC cable and this is AC cable. Even datas are given for DC and AC cable and losses so maybe we will not consider for this problem. It is a grid, okay.

So, we need to produce 2 MW of power, right. Now, this I is given as 800 W/m^2, and since we have already discussed the expression for operating temperature $T_{op} = T_{amb} + \frac{NOCT - 20}{800} \times G$ or I, okay, G or I, okay, solar insulation. So, this value is given as 800 W/m^2. So, if we substitute 800 here, NOCT is 47 here, and T_{amb} is given as may be, 28 °C, okay. This is T_{amb}.

So, if we substitute this, $28 + NOCT$ is 47 minus 20, because these are same, both will goes off, so this will be, T_{op} will be 55 °C, okay. And also, we must know this may be 1. The derated PV output okay, so now we will calculate derated PV output, derated PV output; derated PV output so how to calculate it? So, PV derated, so derated will be how much? It will be P_{STC} multiplied by this f may be temperature, derated due to temperature, f derated due to dirt and f derated due to, we have manufacturing tolerances.

So, as we know this operating temperature is 55 °, okay and in our problem it is given that this rise in temperature, okay, 0.5 percent per degree rise in temperature is a deration, derated factor, okay. So, we know STC is at 25 °C and then this operating temperature is 55 so 55 minus 25, it will be 30 degree C, okay. So, if we can operate at 25 °C then there is no decrease in performance of the PV modules. Since it is more than 25 then this rise in temperature, as need to be considered as we understand that know, every degree rise in temperature, there is a decrease about 0.5 percent, okay.

So, what we can do in order to calculate this f, temperature, so this will be $\frac{(1 - 0.5) \times 30}{100}\%$, okay. So, what we will get here is 15, okay, it will be 0.85, right, 0.85 and for dirt it says it is 5 percent. So, it will be 95 percent, okay and it is 5 percent again. Derated factor is 5 percent so it will be 95 percent, okay.

So, if we substitute here and T_{STC} is 300-Watt peak already we have discussed and this is 0.85 and then we have 0.95, and then we have 0.95 then what we will get is a PV derated. So, this is calculated to be 230.137 Watt. So, this is nothing but PV derated, okay, PV derated. So, this value is required. So, this may be 2, you can write.

Now, in the next page what we can say, or what we can calculate because already we know, T_{min} and T_{max}, okay so what will be the $(T_{op})_{Min}$, okay. $(T_{op})_{Min}$ we can calculate, T_{amb}, okay so $T_{op} = T_{amb} + \frac{NOCT-20}{800} \times 800$, okay. This will goes off; this NOCT is 47, okay. So, 47 minus 20 and this is minimum is 5, okay. So, 5 plus 47 minus 20, okay, 47 minus 20 so this will be 32 degree, okay.

Similarly, we can calculate what is $(T_{op})_{Max}$. $(T_{op})_{Max}$ will be, we have 38 °C which is given plus, because this will goes off, 47 minus 20 so it will be 65 °C, okay, this is C. So, these values are known to us now. These values are known and $(T_{op})_{Min}$ is known to us now, okay. Now, next step, what we can do? We can calculate what is $V_{Min-Eff}$, okay.

So, we will calculate $V_{Min-Eff}$. So, already we know $V_{Min-Eff}$, okay which is already been defined. So, we will use this equation $V_{Min-Eff} = V_{MP-STC} - \lfloor \gamma_p \times \{(T_{OP})_{\max} - T_{STC} \rfloor$ okay. So, this will be something like this. So, we can substitute this value, V_{MP-STC} is nothing but you can go back to the last slides so this is something like 36.6. So, this value is required to calculate $V_{Min-Eff}$

So, this is 36.6 minus, gamma is given as, so γ_p also we can calculate or we can take it, this is 0.4048, so 0.4048 here, 0.4048 divided by 100 so this, so this is, this is under this, okay this is under this, okay. So, $(T_{op})_{Max}$ is how much, 65 okay, 65 minus T_{STC} is always 25, okay. So, if we substitute this value then what we will get, a value of 36.43 Volt, okay. This is $V_{Min-Eff}$, okay.

So, once we are done with this then next step is to calculate $V_{Max-Eff}$, okay. So, what was the formula? V_{OC-STC} okay, open circuit voltage under standard test condition of the module, and then $\gamma_{V_{OC}}$ temperature coefficient, so I will write here, $(T_{OP})_{\min} - T_{STC}$, okay, right. So, this value, open circuit voltage we have to take it from here, so this value 44.8 and this value we need to take, okay, so this 44.8 we need to substitute (44.8-0.2931)/100 and this minimum is 32 minus 25, okay.

So, if we do the calculation, this $V_{Max-Eff}$ is found to be 44.779 Volt, okay. So, $V_{Max-Eff}$, right. This is known now, okay so next step what we need to do is the minimum number of modules to be connected in series and maximum number of modules to be connected in series. So how to do that? So we can use the equations what we have discussed, so this M_{string} that is minimum, okay which is nothing but V_{inv-DC} that is minimum, okay and then we have V min effective, okay.

So, I have to go back to this specification part. So here this is the V_{inv} voltage that is minimum that is 425, okay. This 425 need to be used here, so 425 and then we have $V_{Min-Eff}$, already we have done it, that is 36.43 which is equal to 11.67 so that is equivalent to 12, because there has to be whole number, okay. And maximum number of string, that is max, how do we define it?

Already we have the equation. V in DC that has to be maximum, okay, maximum voltage divided by, we have V_{max}, already we know effective, okay. So, this value is how much, we will go back and see. This is 975 volt, okay. So, this is 975 and $V_{Max-Eff}$ is 44.779 and which will give you a value of 21.77 so which is equivalent to 22, okay. It is 22.

So, what I have done here, so first we have calculated operating temperature. Then we have calculated derated power output of the PV array, okay and then since we know these values of the derated factor, so we have used it while calculating this derated PV output and then our attempt was to calculate $(T_{op})_{Min}$ temperature and operating maximum temperature, okay.

So, this is found to be 32 and 65, and then we have calculated $V_{Min-Eff}$ and $V_{Max-Eff}$ and we have calculated number of modules to be connected in series, minimum number of modules to be connected in series and maximum number of modules to be connected in series, okay. We just found to be 12 and 22.

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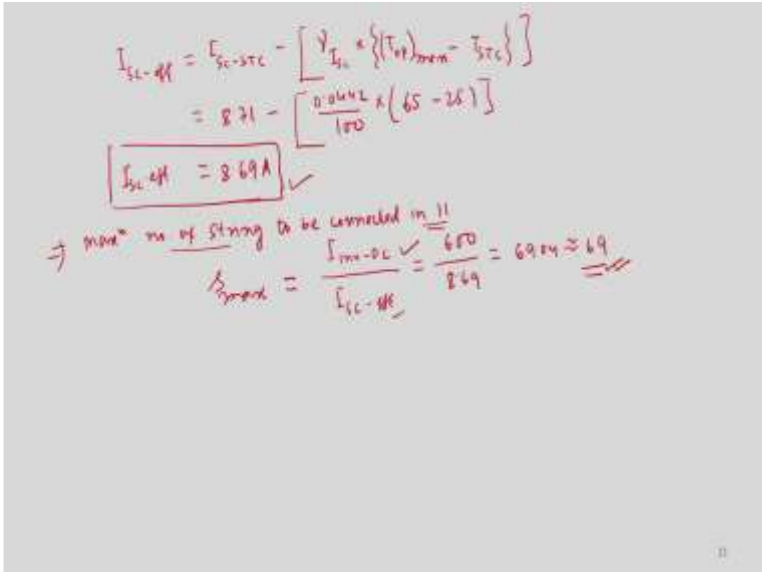

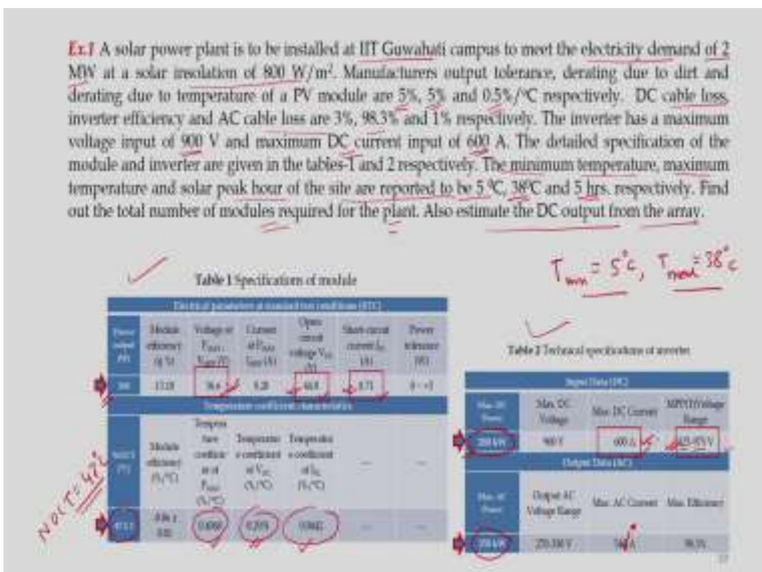

So, our next calculation will be the calculation of I_{SC-Eff}. Because we need to now know the number of strings to be connected in parallel, okay. So, we know the expression $I_{SC-Eff} = I_{SC-STC} - \lfloor \gamma_p \times \{(T_{OP})_{\max} - T_{STC} \rfloor$, okay. So, what is the value of I_{SC-STC}? We will go back again this value is 8.71, okay. And also temperature coefficient is 0.0442 percent per degree C, okay. So this is 8.71 from the specification table and same from the specification table and we have 100 and then we will have 65 minus 25, okay and this is found to be 8.69 ampere, okay. So I_{SC-Eff} is something like this.

Now, we need to calculate the maximum number of strings. So maximum, now we will calculate maximum number of string to be connected, to be connected in parallel, okay. So for that we have the equation $S_{\max} = \frac{I_{inv-DC}}{I_{SC-Eff}}$ which is calculated just now, okay. So, this value we need to use here and this is already given in the specification table. So, what is this I_{SC-DC} value, I_{inv-DC} value? It is nothing but 600 ampere, okay. So, if we substitute 600 here then I_{SC-Eff} is 8.69 then it will be about 69.04. Or it is equivalent to 69, right.

So now what we have calculated is the maximum number of strings to be connected in parallel is 69, okay. Now we have to match it. So, we know now the minimum number of modules to be connected in series, maximum number of modules to be connected in parallel and also the maximum number of these strings to be connected in parallel, okay.

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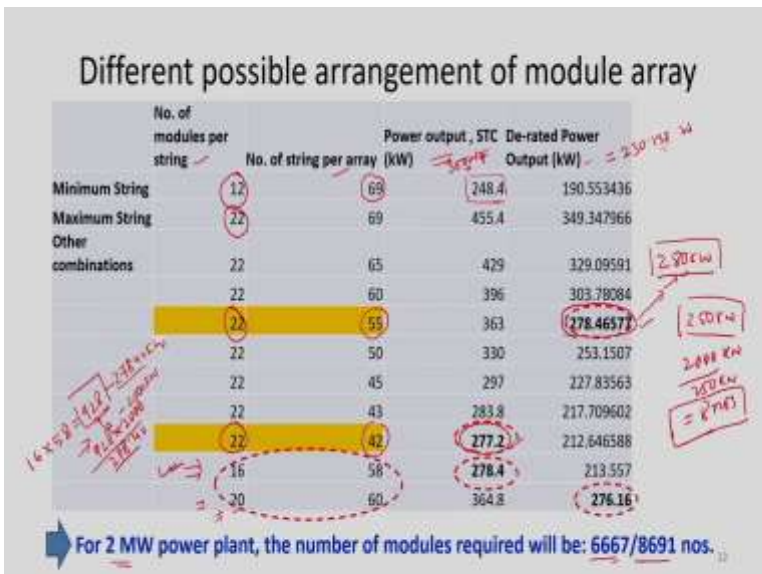

	No. of modules per string	No. of string per array	Power output, STC (kW)	De-rated Power Output (kW)
Minimum String	12	69	248.4	190.553436
Maximum String	22	69	455.4	349.347966
Other combinations	22	65	429	329.09591
	22	60	396	303.78084
	22	55	363	278.46577
	22	50	330	253.1507
	22	45	297	227.83563
	22	43	283.8	217.709602
	22	42	277.2	212.646588
	16	58	278.4	213.557
	20	60	364.8	276.16

And let us now see the different possible arrangement of module array. Already I have prepared this table where possible arrangement of number of modules per string and number of strings per array at two different power outputs, one is extended test condition and other one is at derated power output. So, when derated factors like manufacturing tolerances, temperature and dirt are considered, what will be the derated power output which is about 230.137 Watt and for standard test condition it is 300-Watt peak, okay.

As calculated before, the minimum and maximum number of modules per string are found to be 12 and 22. So, for the case of 12 modules per string and as you know the maximum number of strings per array is 69 so if we multiply 12 with 69 and then 300 Watt peak then what we will get is 248.4 kW, okay. And same calculations if we make then $12 \times 69 \times 230.137$, then what we will get is 190.55 kW, right.

So, we can have one more combinations like $22 \times 69 \times 300$ then what we will have? It is about 455.4 kW. And if we consider derated parameters then output will be about 349.35 kW, okay. And we will have more number of combinations and we can select the best one. But we must keep in mind that what is the input power for the inverter, okay. So, inverter power requirement is 280 kW. So, we need to provide energy just near to 280 kW, okay.

So, that way we need to find out the best combination. So, we can have something like 22 number of modules per string and number of string per array 55, then what we will get if we consider derated power which is equal to about 278.46577 okay which is very, very close to 280 kW power which is the input to the inverter, okay. Or we can think of another class if we do not consider derated power, something like 22 number of modules per string and 42 number of strings per array. So, under the condition what we will have, we will get power output close to 277.20, okay which is also close to 280 kW, right? So, we can consider this or may be this, or we can think of some other alternatives, okay.

So, the other alternative combinations are something like 16 number of modules per string and 58 number of strings per array which gives power output under standard test condition is 278.4 kW, and if we consider one more category or combination that is 20 number of modules per string and 60 number of strings per array then what we will get, 276.16 when we consider the rated parameters, okay.

So, there are multiple combinations so we need to find out the best combinations for maximum output power. And if we consider these two cases for a 2 MW power plant the number of modules required will be about 6667, for the first case, this case and for the second case we will have 8691 numbers of modules. So, how we will get it? Say for example, in this case, this case so 16 multiplied by 58 which is equal to 928 okay, so that many number of modules are required, okay for this combination and this gives about 278.4 kW, right.

So, for 278.4 kW generation power output we need about 928 number of modules, okay. So, for 2000 kW the number of modules required can be easily calculated, okay. So, this will be something like $\frac{928\times2000}{278.4}$, okay so which is found to be about 6667. In the second case similarly, we can find out the number of modules required is 8691 numbers.

Now, for these 2 MW power plants the number of inverter required can also be calculated. As you know this rating is 250 kW, okay so 2000 kW divided by 250 so it will be, this will be kW, 8 numbers so minimum 8 numbers of inverters are required for a plant having capacity 2 MW, okay. So, this is how we can design a solar grid connected PV system, okay. There are many components, what I left, may be this can be considered in the next class when we analyze the performance of a grid connected PV system, okay.

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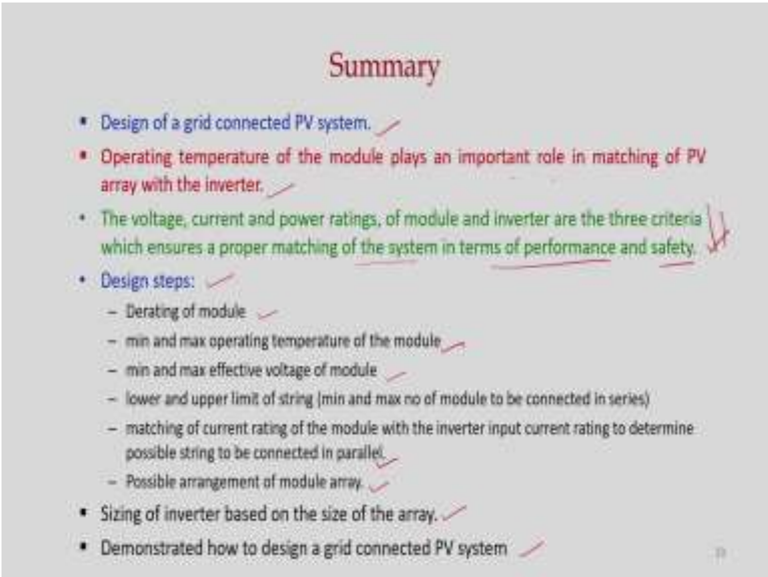

So, we can summarize what we have discussed in this class. We understand the design of a grid connected PV system then the operating temperature of the module plays an important role in matching PV arrays with inverters, that also we understood. The voltage, current and power ratings of modules and inverters are the three criteria which ensures a proper matching of the system in terms of performance and safety, okay. That we have clearly understood. And the kind of design methodology that we have adopted here, first we tried to calculate this derated module, or derating of modules, how derating of module takes place, what are different factors?

Then minimum and maximum operating temperatures of the modules, then minimum and maximum effective voltage of module, then lower and upper limit of strings okay, then matching of current rating of modules with inverter input current ratings to determine the possible string to be connected in parallel. And finally, the possible arrangement of module array we have studied. And sizing of inverter based on the size of the array, that we can understood now. And also we have demonstrated how a, how to design a grid connected PV system, okay. So thank you very much for watching this video. Thank you.