Solar Energy Engineering and Technology
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Module 5
Standalone Photovoltaic System
Lecture 14
Design of Standalone PV System

Dear students, today we will be discussing about Design Principle of a Standalone PV system.

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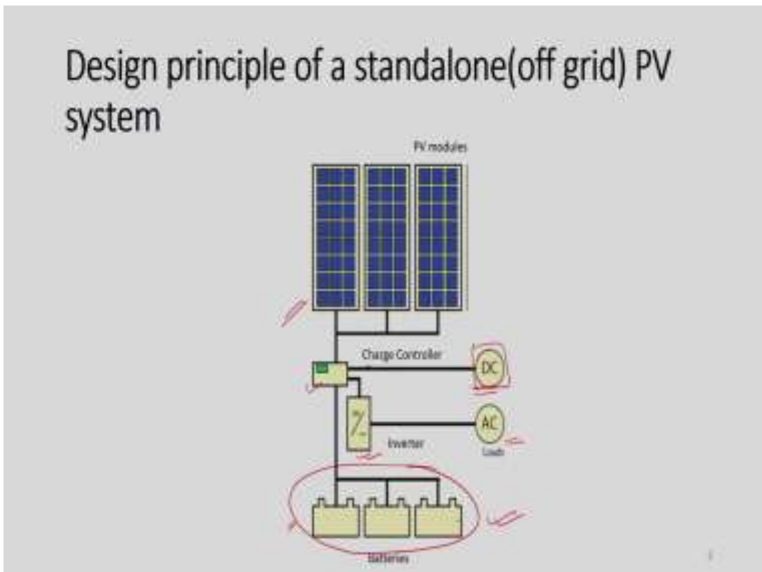

In the last class, we are discussing about a different component of a standalone PV system, okay so what are different components involved in a standalone PV system? It is a PV modules, many modules will be there and then we will have charge controller and then if you have DC load, then we must provide this DC power and inverter is required if we have AC load okay and we must required some kind of storage system okay. So, the sizing of the storage system and PV modules are interconnected okay, so this major component of this standalone PV system is a storage system okay.

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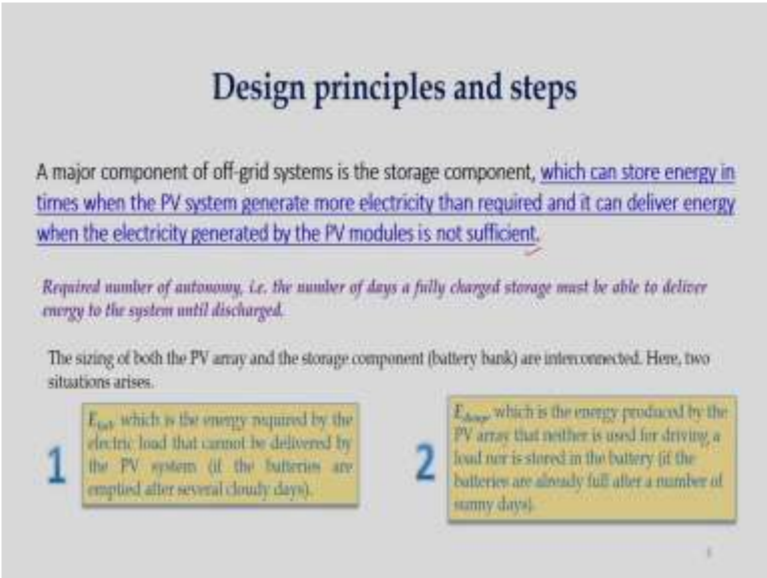

So, let us learn something about storage system. So this storage system is something like battery in case of off-grid system or standalone system, which can store energy in times when PV system generates more electricity than required and it can deliver energy when electricity generated by the PV modules is not sufficient. So we must know how many days we need to store that much of generated energy. So, for that we must know the required number of autonomy, which means the number of days a fully charged battery or storage system must be able to deliver energy to the system until discharged okay.

So, as I said this PV arrays which is composed of many modules and the storage components are interconnected. So we must know two important terminologies, one is called E_{fail}, so which is nothing but is the energy required by the electric load that cannot be delivered by the PV system.

So, if this happens if the batteries are emptied after several cloudy days and the second terminology is E_{dump} which is the energy produced by the PV array that neither is used for driving a load nor is stored in the battery. That means if the batteries are already full after number of sunny days, these two situations we need to know understand very critically.

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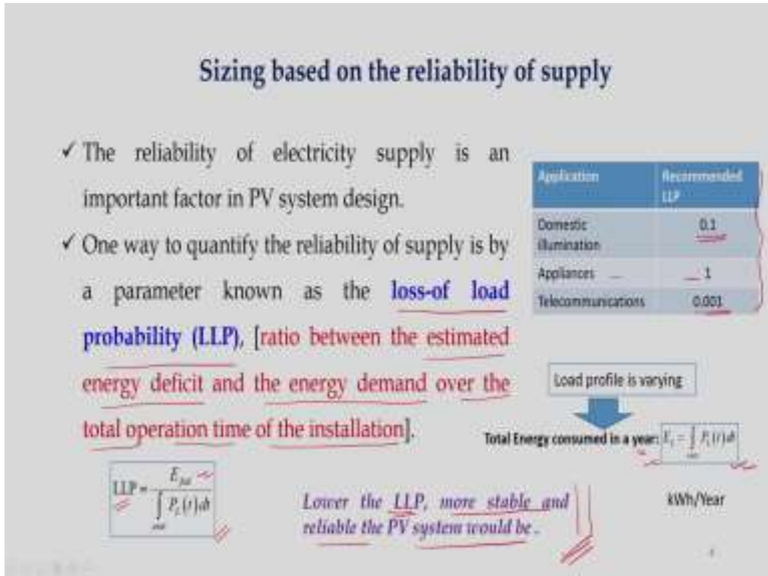

Now, let us see what is reliability of supply so we can design the system based on this reliability of supply. The reliability of electricity supply is an important factor in PV system design, the one way of quantify the reliability of supply is by a parameter known as loss of load probability which is nothing but LLP and it is defines as the ratio between the estimated energy deficit and the energy demand over the total operation time of the installation. So, in order to find out this LLP that is loss of load probability we must know the load profile.

So, for a particular day how much energy is consuming by a particular household, that must be known to us while calculating this load profile. Normally this has been calculated based on annual basis. So how much energy is consumed annually that must be known to us, so total energy consumed in a year that can be calculated by using this expression, once we know this as already we know E fail, so this ratio of these two will give LLP.

This value of this LLP for domestic illumination is about 0.1 which is recommended by international societies and other appliances is 1 but in telecommunication it is 0.001, these values we should keep in mind while designing the system with reliability of supply okay. So, what we understand the lower this LLP more stable and reliable the PV system would be, so this is very very important observations of this reliability of supply.

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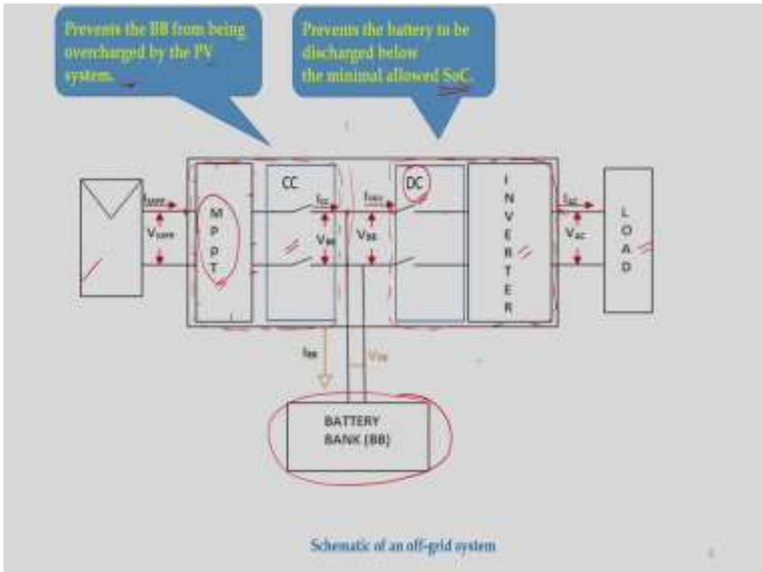

Now, let us see the components of a off-grid system, this schematic shows all the components, we have PV modules and then MPPT, then CC means charge controller, then DC means discharge controller, then inverter then we have loads right and then as we know we need a very important component called battery bank.

So, as we have learned in the last class like this charge controller is very, very important because it prevents the battery bank from being over charged by the PV system and what is the function of this DC? This DC is discharge controller, so here it prevents the battery to be discharged below the minimum allowed SOC.

So, charge controller and discharge controller, so this is the discharge controller not discharge current this is a discharge controller. So, you can see this I_{MPP} so maximum power point and V_{MPP} so not always this MPPTs are installed in this entire system, so that is why sometimes it is given as dotted lines, the solid line I have given because it is presumed that MPPT is interconnected.

So this MPPT and this charge controller are attached together and here discharge controller and this inverter are attached together. So, while designing we will make some kind of analysis, so maybe here, maybe here we will take some points and then we will try to energy balance it and then we will see the number of modules required and number of batteries required. In a nutshell, what we have learned in this slides the different components involved in a standalone PV system and how this CCs and DC are important in this system.

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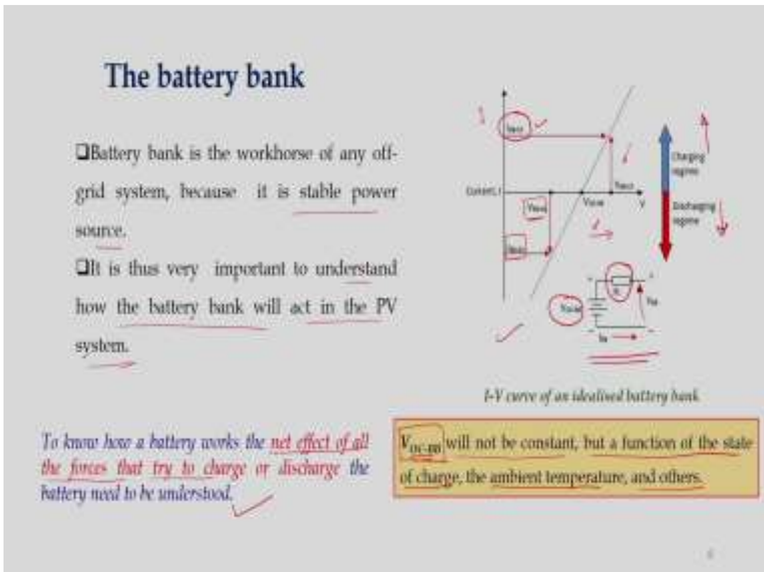

Now, let us pay attention about this battery bank because as we said battery bank is very, very important component of a standalone PV system, this battery bank is the workhorse of any off-grid system because it is stable power source. It is thus very important to understand how the battery bank will act in the PV system right .

So here, what you can see here this plot is nothing but IV curve of an ideal as battery bank. So this I is here in the vertical axis and V is here in the horizontal axis and what is $I_{BB\text{-}CH}$? That is battery bank charging current and $V_{BB\text{-}CH}$ is battery bank charging voltage and here is a battery bank discharge voltage and battery bank discharge current. So, this parts what you see is charging and this lower part is for discharging regime.

So, what we can see here this is a simple circuit diagram this is the supplied voltage and internal resistance will be there in the batteries and this is the output voltage. Normally, this $V_{OC\text{-}BB}$ will not be constant but a function of the state of the charge and ambient temperature and other factors. So but for our analysis we will presume that this V_{OC-BB} is constant. So, to know how a battery works the net effect of all the forces that try to charge or discharge the battery need to be understood.

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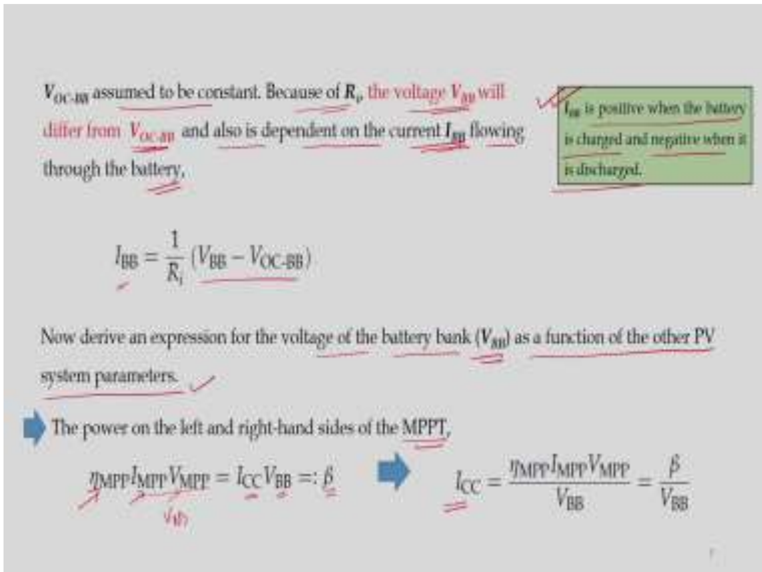

So, now as we said this V_{OC-BB} assumed to be constant for our analysis because of this R_i the voltage BB that is a battery bank voltage will differ from this open circuit battery bank voltage and also is dependent on the current I_{BB} the amount of current that is a battery bank current flowing through the batteries.

So, this I_{BB} can be related to it V_{BB} ,V_{OC} and R_i because as you know V is equal to iR so BB minus VOC is equal to I BB into Ri so I_{BB} can be calculated $I_{BB} = \frac{1}{R_i}(V_{BB} - V_{OC-BB})$.

So, now let us derive an expression for the voltage of the battery bank V_{BB} as a function of PV system parameter. So, if we need to do it as I said before in the schematic diagram of the PV system then power on the left and the right side of the MPPT should be equal.

So, if we consider the efficiency of MPPT is η_{MPP}, maximum power point and I_{MPP} is the maximum current at power point and V is V_{MPP} is the maximum voltage at that point and then I_{CC} is the charging current and V_{BB} is the battery voltage, so maybe we can define a parameter called β and then from that we can calculate what is I_{CC}.

So it is nothing but this expression divided by V_{BB}. So, since this expression is something called β, so we can write $\frac{\beta}{V_{BB}}$ we must also know this I_{BB} is positive when battery is charged and negative when battery is discharged. So, this information is also required for us.

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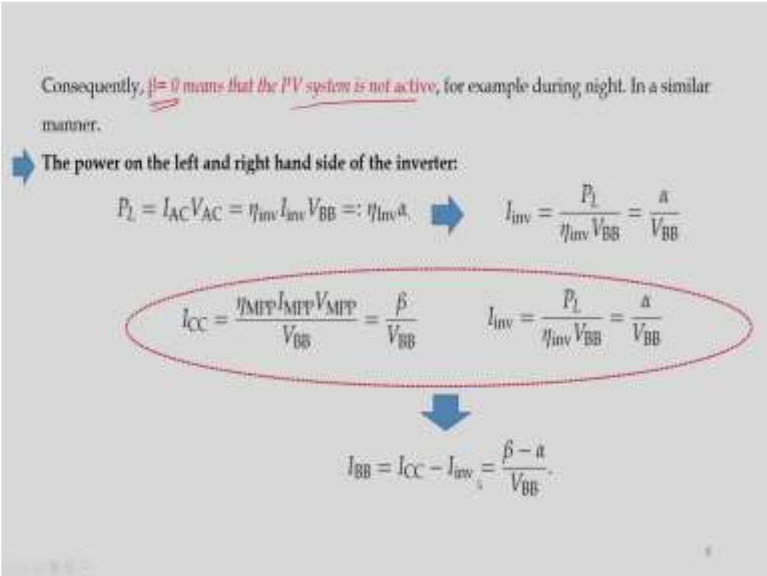

So, now let us learn more in depth, if β is 0 means that PV system is not active, maybe at night PV system is not active because no solar energy is there, no solar radiation is falling on the PV system. So what happens then if β is 0 then you can see the expressions what will happen, so β is 0 means no current will flow through this circuit.

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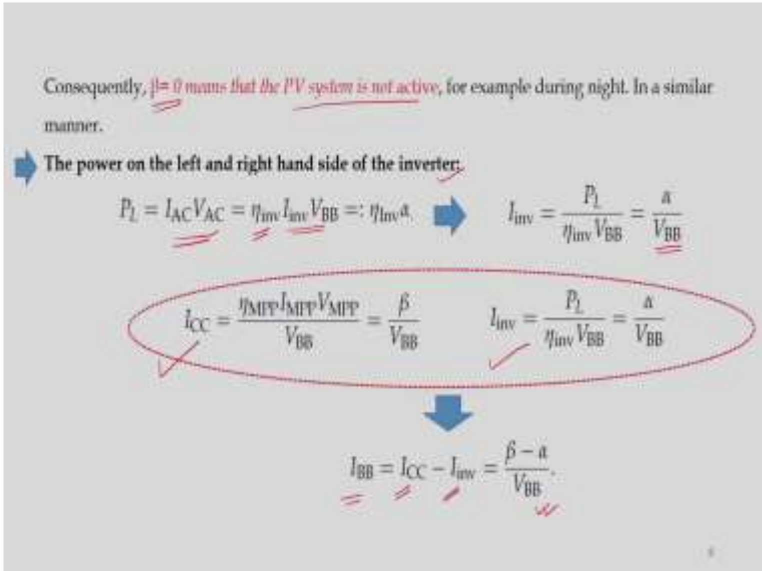

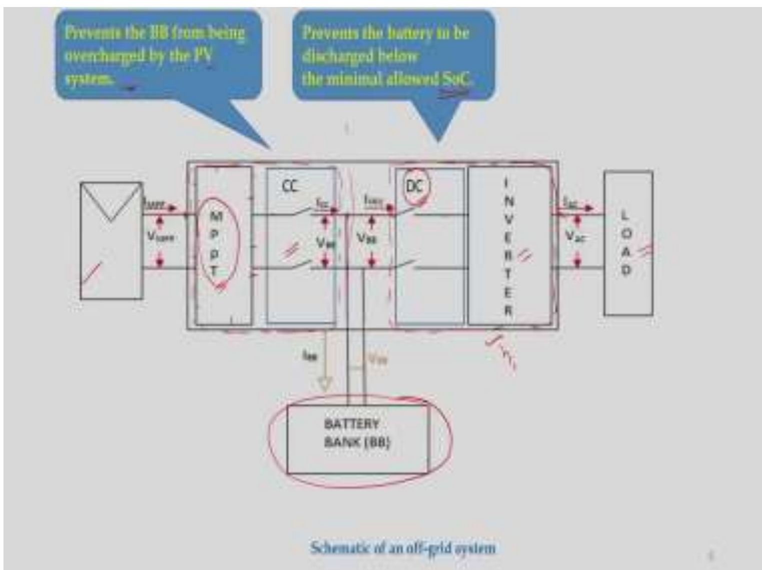

So, the power on the left and right hand side of the inverter, so if you go back to the slides you can see, so this is the inverter, so this side is how much is the $I_{AC} \times V_{AC}$ and this side you need to consider the efficiency of the inverter, then see how it look likes.

So I_{AC} V_{AC} this is the AC current and AC voltage and inverter efficiency is known to us, then $I_{inv} \times V_{BB}$, so if we define this parameter as α then what we can have

$I_{inv} = \frac{P_L}{\eta_{inv} \times V_{BB}}$, so this is nothing but $\frac{\alpha}{V_{BB}}$. Now, we have two expression I_{CC} and I_{inv}, so what we can do now from here we can calculate what is I_{BB}, since $I_{BB} = I_{CC} - I_{inv}$,this charging current minus this inverter current and this is nothing but $\frac{\beta - \alpha}{V_{BB}}$.

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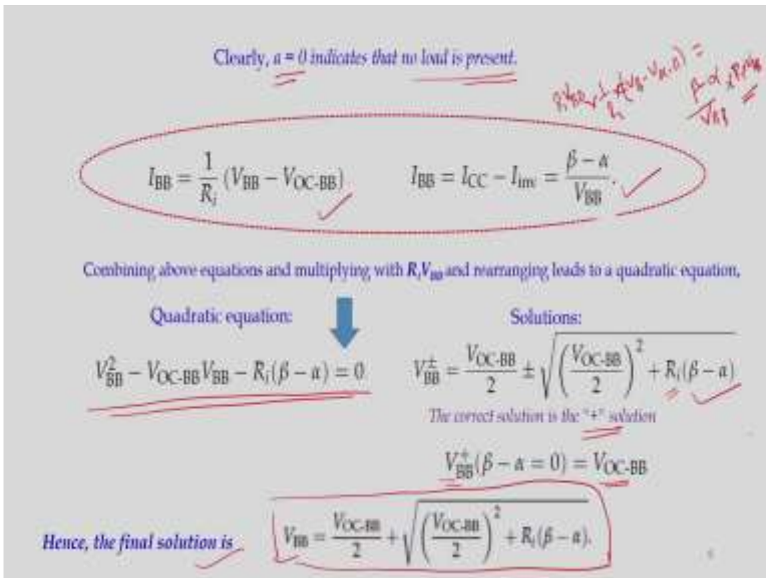

So, if we have this information then what we can do next it is clearly understood that if alpha is 0 indicates that no load is present, no load is connected there then what we will have I V is something like this and also we have this expression of I V, then we can combine this expression and let us develop an quadratic equation.

So, by combining this these two are same so I can write $\frac{1}{R_i}(V_{BB} - V_{OC-BB}) = \frac{\beta - \alpha}{V_{BB}}$. So and if we multiply this expression with Ri and V_{BB} then how will look like? R_i multiplied by V_{BB} and if we simplify it then we will get this kind of quadratic equation.

So, we will have two solutions, so this $V_{BB}^{\pm}$ will be something like this, this is the solution, so this correct solution is the positive solutions. If we see precisely, so if $\beta - \alpha = 0$, then if we use this here then what will happen $V_{BB} = \frac{V_{OC-BB}}{2} + \frac{V_{OC-BB}}{2}$, so it will be V_{OC-BB}, so this will be something like this. So this final solution will be this is the true solution V_{BB} is something like this. So now, let us pay attention to this solution and see what we can bring out of it.

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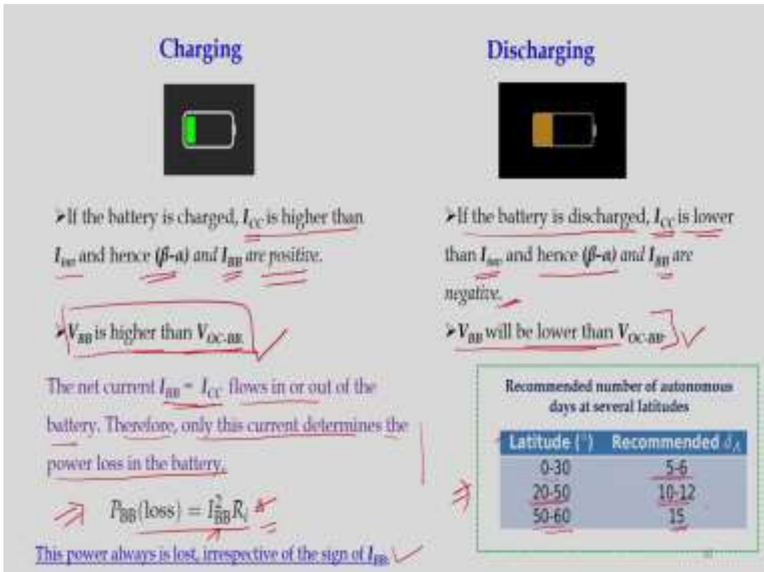

So, there are two conditions, already we know charging and discharging. So in case of charging if the battery is charged then I_{CC} is higher than I_{inv}, that we must know. So, this I_{CC} is higher than I_{inv} and hence, $\beta - \alpha$ and I_{BB}, this current flowing through this battery bank are positive. So, V_{BB} is higher than V_{OC}, so we can see why V_{BB} is higher than V_{OC} by analyzing the solution of the quadratic equation.

So, in case of discharging if the battery is discharge that is I_{CC} is lower than I_{inv} then $\beta - \alpha$ and I_{BB} are negative. So this V_{BB} will be lower than V_{OC}. So, this is the condition at which BB is lower than V_{OC}. So, the net current I_{BB} and I_{CC} flows in or out of the battery. Therefore, only this current determines the power loss in the battery.

So, how we can write this power loss? P_{BB} is something like $P_{BB} = I_{BB}^2 \times R_i$, since R_i is the internal resistance of this battery and I_{BB} is the current flowing through this battery bank. So, this power is always lost irrespective of the sign of I_{BB}. So this is very, very important, so the amount of power lost due to this resistance. So we will come back this autonomy, so as I said number of days autonomy to be maintained for a standalone system are specified by latitude.

So, if latitude varies from 0 to 30 then we need to consider the autonomy about 5 to 6 days and 20 to 50 if latitude varies, then this autonomy will change from 10 to 12 and for latitude having 50 to 60, then it is recommended that this autonomy should be 15 days. So, again it depends the kind of locations this kind of systems are installed, so that will dictates the requirement of this autonomy.

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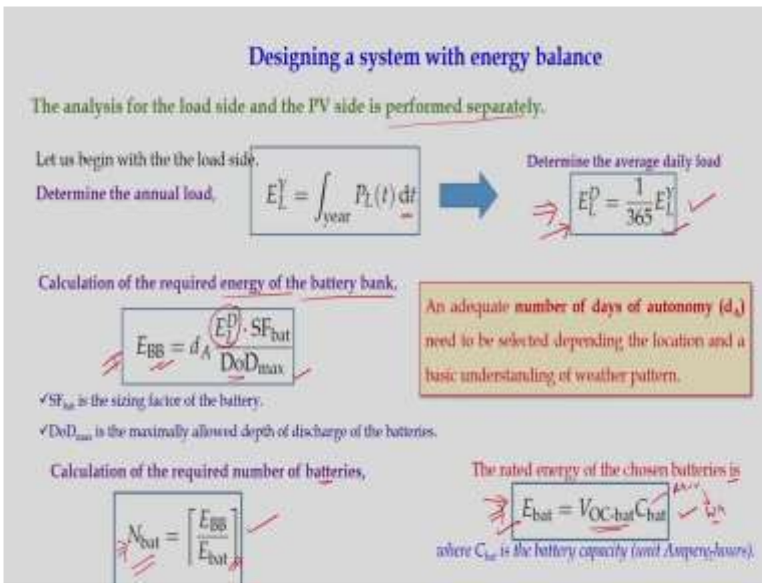

Now, let us design a standalone PV system with energy balance. So, the analysis for load side and the PV side is performed separately, so first let us consider the load side, then we will go for the supply side or generation side. So, if we start with the load side then first we are interested to know the annual load.

So, load profile is very, very important, at the beginning of this class I said, so we must know the load profile of a particular maybe, particular household or maybe some industries because if we talk about a particular day, so that may not be same for all the other days, maybe if we consider in winter things should be different, so we need heaters but in summer we do not need heaters but we need air conditioning systems.

So, we need to understand the annual load of that particular industry or maybe household or maybe any systems. So this E_Y^L is something like $E_Y^L = \int P_L(t)dt$. So if I am interested about average daily, then we will divide this E_Y^L by 103, sorry 365 so E_Y^L, this will give you the daily load.

So then, what we are interested about the calculation of the required energy of the battery bank, once it is done then from that we must know the amount of energy to be delivered by the battery, this much of load we know that this much of load is there, daily load is something like that, so for that we must design the number of batteries required of that particular capacity.

So, for that we must know what is energy required from the battery bank. So, it is something like $E_{BB} = d_A \frac{E_D^L.SF_{bat}}{DoD_{\max}}$ what is d A? d A is the number of the autonomy or say the number of days we need to store energy and this SF is sizing factor of the battery, normally its value is 1.1 or 1.2 and this DoD is depth of discharge, there is a maximum depth of discharge you need to consider and this can be evaluated by using what already we have discussed.

Now, what we are interested about the required number of batteries, once you know this E_{BB} that is energy to be delivered by the battery bank and we know E_{bat}, then we can calculate what is N_{bat} or number of batteries required. So, how to calculate E_{bat}? So, the rated energy of the chosen batteries are something like this, so E bat is something like $E_{batt} = V_{OC-bat} \times C_{bat}$, this capacity of the battery then what we will get that is E_{bat}.

So, this is the energy of the battery, so this will be in watt hour because C is in ampere hour, if you multiply by voltage it will be watt hour. So, once you know this then if we substitute here and what we will get the number of batteries required for performing the required task.

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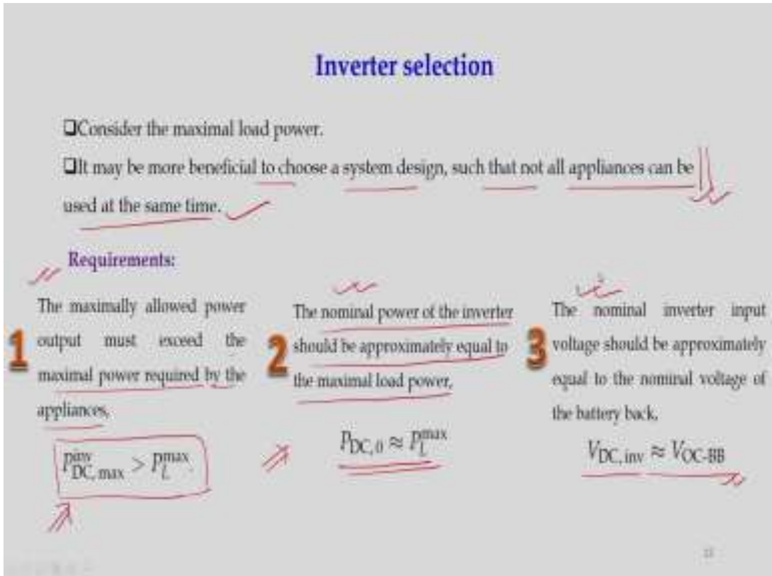

Now, very important factor is selection of inverter. So, while selecting the inverter we must be very, very particular, this inverter should meet some of the requirements. So, number one is the maximally allowed power output must exceed the maximal power required by the appliance.

So, this will be something like this. So P_L^{max} has to be less than inverter what is, DC inverter power max, this is one requirement and second requirement is this nominal power of the inverter should be approximately equal to the maximal load power, this is the second requirement. And third requirement is the nominal inverter input voltage should be approximately equal to the nominal voltage of the battery bank, this V_{DC} of inverter has to be equal to V_{OC} of battery bank.

So, it may be more beneficial to choose a system design such that not all the appliances can be used at the same time. So, this is one of the observations but while selecting an inverter we must see these parameters, so this has to qualify this parameters then only you can select the inverter.

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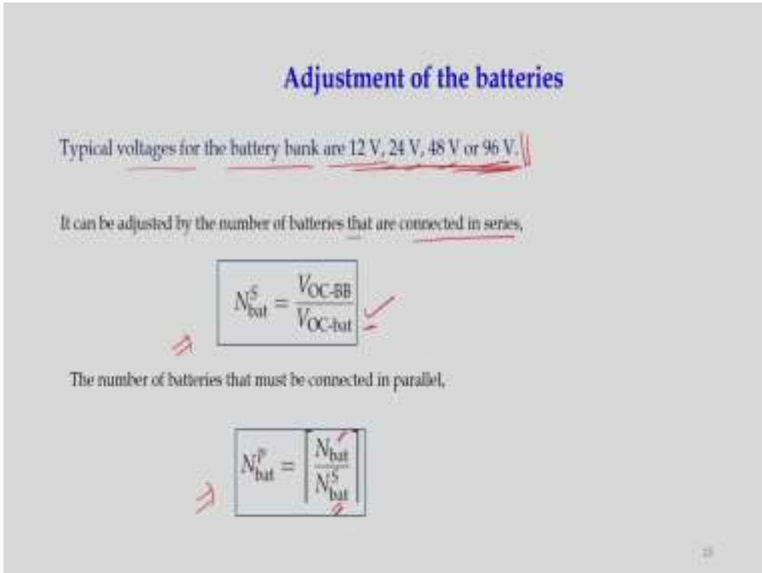

Now, we must know the number of batteries to be connected in series and number of batteries are to be connected in parallel. If we consider a typical voltage for battery bank maybe 12 volt, 24 volt, 48 volt and 96 volt these are specified in case of lead acid batteries.

So it can be adjusted by number of batteries that are connected in series. So, if we have to connect batteries series then we need to follow this strategy like if we know open circuit voltage of battery bank and then the V_{OC} of batteries, then we can calculate what is the number of batteries to be connected in series. And in case of parallel connection then we must know this number of batteries and then number of batteries are connected in series, then from that we can connect or we can calculate the number of batteries are to be connected in parallel.

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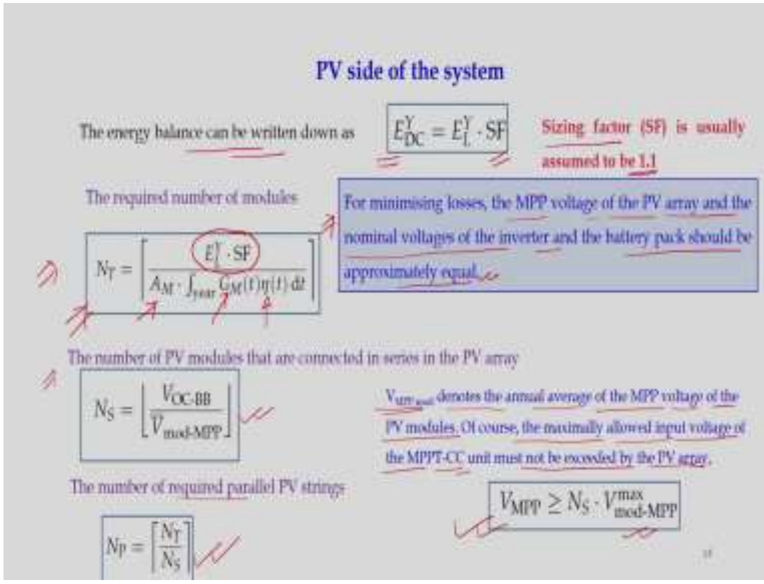

Now, let us come back to this new energy balance in the other side. So, far what we have discussed is the load side, now we will come to the generation side or PV side. So, here what happens $E_{DC}^{Y} = E_{L}^{Y}.SF$, again this SF is nothing but sizing factor as usual is about 1.1.

So, we can calculate the number of modules required straight away if we know these values and we know this area of the module and then the amount of solar radiation falling, then efficiency of the module, then we can calculate what is the number of modules required. Of course, for minimizing losses this MPP maximum power point voltage of PV array and the nominal voltage of the inverter and the battery pack should be approximately equal, this we should keep in mind.

Again, if we are interested to know the number of PV modules to be connected in series then we need to follow this rule like $\frac{V_{OC-BB}}{\overline{V}_{\text{mod}-MPP}}$. So this is something like $V_{MPP-\text{mod}}$ denotes the annual average of the maximum power point voltage of the PV module. So, of course, the maximally allowed input voltage of the MPPT charge controller unit must not be exceeded by this PV array, so this condition has to met. Then, we can calculate the number of PV modules to be connected in parallel, so this equation we can use for calculation of number of modules to be connected in parallel.

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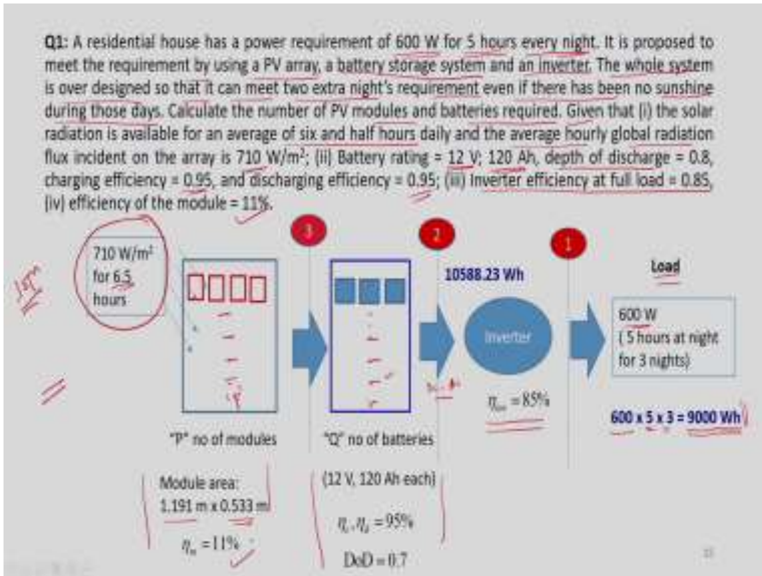

So, let us take an example to understand how we can design a standalone PV system. So, this example goes something like this. A residential house has a power requirement of 600 watt for 5 hours every night and it is proposed to meet the requirement by using a PV array, a battery storage system and an inverter. The whole system is over designed so that it can meet two extra nights requirement even if there has been no sun shine during those days.

So we have to design for three nights, calculate the number of PV modules and batteries required and some of the information are given like solar radiation is available for an average of six and a half hours, so 6.5 hours daily and the average hourly global radiation flux incident on the array is 710 watt per meter square and as far as battery ratings are concerned it is given as 12 volt, 120 ampere hour, depth of discharge is 0.8, charging efficiency is 0.95, discharge efficiency is again 0.95 and inverter efficiency is given as 0.85 and of course, module efficiency is required which is given as 11 percent.

So, we can make the problem something like this, this is solution and we are making this block diagram so that much of energy is falling on this PV modules, there are many modules, so dot indicates there are many modules, so we need to know the number of modules.

We are representing P as the number of modules, we need to find out the number of P's. So, here is the batteries, so from here to here we will have batteries, so number of batteries we need to find out and then we need to convert this DC current to AC by using this inverter, inverter has got efficiency of 85 percent and then load is given 600 watt, so 5 hours per day for 3 nights. So, if we calculate this $600 \times 5\, hours \times 3\, days$ so it will be 9000 Wh is the load.

So, these specifications are given and also module area is given as 1.191 meter multiplied by 0.533 meter and efficiency is 11 percent. Now, we are dividing this into three categories, 1, 2 and 3 so that we can do it more clearly.

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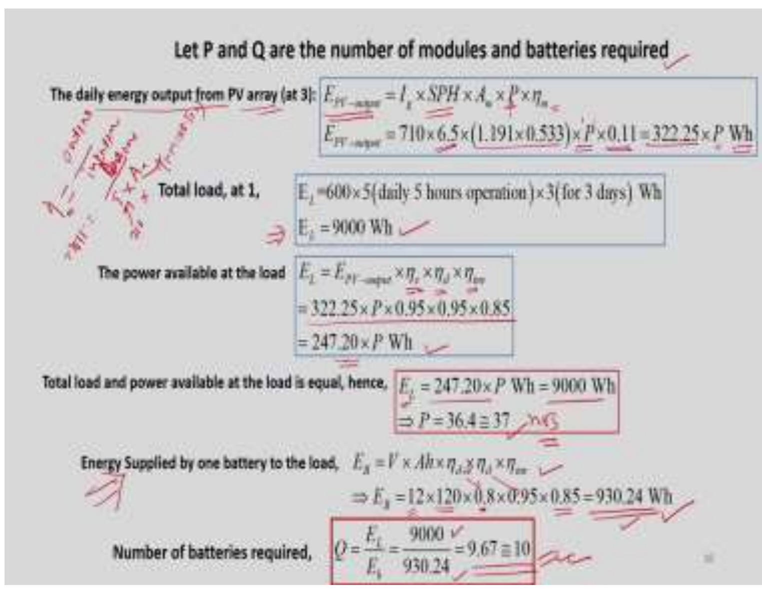

So, let us consider P and Q are the number of modules and batteries required to run the system. So, now what we will do? We will start with this supply part, like daily energy output from PV array at 3, if we go back here.

So, we are representing this is here, so the amount of energy which is generated by this PV module we need to know, so how much amount of energy generated here at this point. So of course, this is a DC power. So how we can define it? We know efficiency, this efficiency is output power by input power, this is input power, so input power is nothing but i into area and output power we need to calculate maybe I will write P_{out} and η_{module} is given as 11 percent.

So we will write 0.11 and this is given as 710 and area so what we have done here this area is nothing but module area is given as 1.191/0.533. So, that is how this E or I can write this E_{out}, $E_{PV\text{-}output}$ what I have representing here $E_{PV-output} = I_g \times SPH \times A_m \times P \times \eta_m$ why it is P?

Because P numbers of modules are present to produce that much of power. So, this E_{output} or $E_{PV\text{- }output}$ is something like 710 multiplied by 6.5 because we are measuring in watt hour, so we need to multiply how many hours solar radiation will be there. So, 6.5 multiplied by this area of a single module and this is the P is the number of modules and we know the efficiency of the module.

Once we do this calculation, then what we will get is about 322.25 P, and also we know the total load at 1, so what is 1 here? This is the 1 and we know the load here, already we have done the calculation, so 600 watt/day and for 5 hours and for three days, so it will be 9000 Wh.

So, this information is known to us, this can be calculated and E_L is load E_L this is the energy required is 9000 Wh and this power available at the load if we come from this side, from the left side, so if we come from this side, so if I am interested to calculate this P.

So, how much power will be available here? Because we know this charge, discharge efficiency and inverter efficiency, so that means 5 percent inefficiency will be there and 15 percent inefficiencies will be there. So, if we use those efficiencies and if we try to calculate this power available at the load, then we can calculate it. So, this is nothing but η_C is charging efficiency, η_D is discharging efficiency multiplied by inverter efficiency, so if we multiply all then what we will have is 247.20 P Wh, that much of energy is available.

Now, the total load and power available at the load is equal, because that much of power we have to generate and that has to be equal to the amount of energy required on a daily basis or for meeting all those three days. So, see this for our problem it is for three days, so E_L is equal to this, so from that if you do the simple calculation then P is found to be about 37.

So, number of modules required to get that much of energy or to provide the energy of the load is about 37 numbers. Then, this energy supplied by one battery to the load we can calculate something like this, so this is already we know 12 into ampere hour is 120 volt is 12 volt and discharge efficiency is 0.8, then we have DoD this is actually DoD, DoD is 0.8 and this is discharge efficiency is 0.95 and inverter efficiency is 0.85, so it is about 930.24 Wh.

So, from this we can calculate the number of batteries, so this is for a single battery, so if I am interested to know number of batteries required of course, we need to divide this by 930.24. So, that way if we calculate so it will be about 10, so number of batteries required for this problem is 10 numbers, so 9.67 so we cannot divide the batteries, so it will be 10 numbers. So, that way we can solve the problems and we can calculate really the number of batteries required and number of modules required to meet the particular load.

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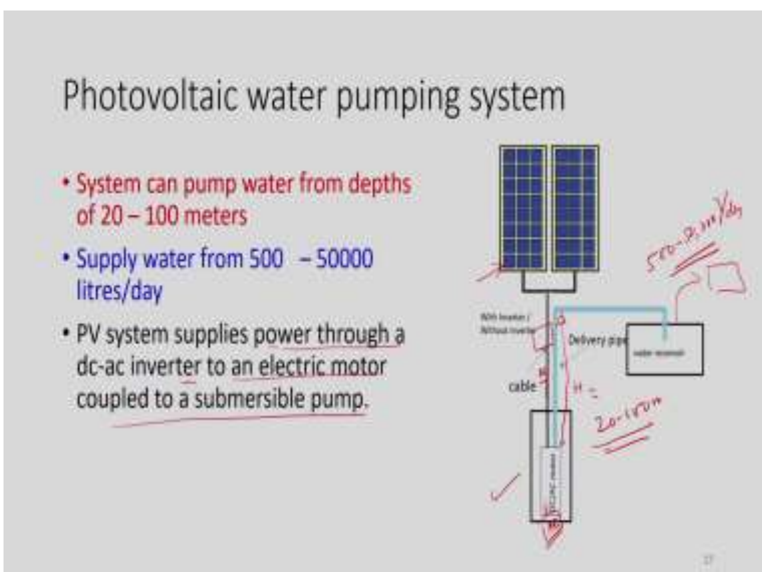

Now, let us learn about Photovoltaic water pumping system. So, this kind of pumping systems are very, very important for agricultural activities or irrigation. So, as we understand when you talk about standalone system, so there are many components PV then we will have inverter, then we need cables, then maybe this kind of motor generator component which is submerged under water and we need to have a delivery pipe and then storage tank. So, whenever required this water can be utilized for irrigation purpose.

So, this kind of systems we can go up to depth of 20 to 100 meter, so this depth we can go from this head may be 20 to 100 meter and this kind of system can supply water from 500 to 50000 liter per day, so that much of water can be lifted. So, this PV system supplies water through a DC-AC inverter to an electric motor and coupled to the submergible pump. Sometimes so DC cables are there if no inverter is connected, if inverter is there then so this will be AC cables and this will run on alternating current, otherwise if inverter is not there means these are DC operated system.

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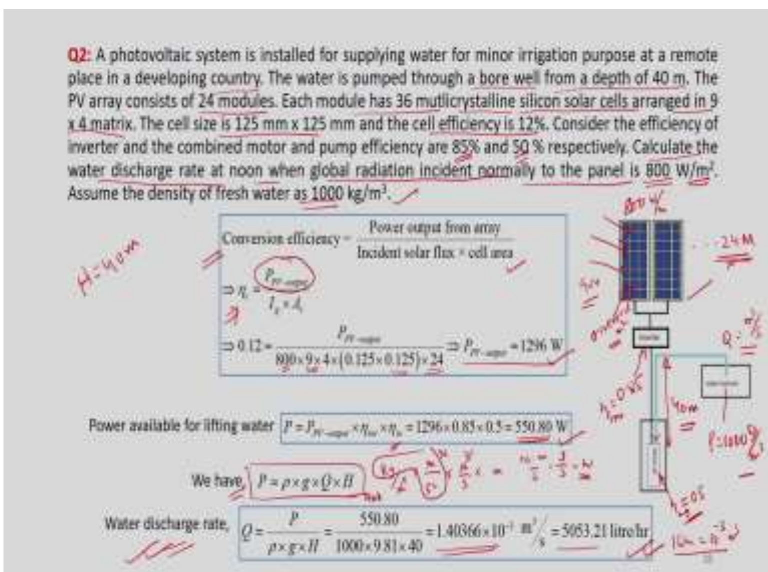

So, let us take a small exercise to understand this properly. So, this problem goes something like this. A photovoltaic system is installed for supplying water for minor irrigation purpose at a remote place in a developing country. The water is pumped through a bore well from a depth of 40 meter, so head is given as 40 meter, 40 meter head.

The PV array consists of 24 modules and each module has 36 multi crystalline silicon solar cells and arranged in 9 by 4 matrix and cell size is also given as 125 mm by 125 mm and the cell efficiency is 12 percent. So, inverter efficiency and this motor and pump efficiency which is submerged under water is given as 85 percent and 50 percent respectively.

Now, we need to calculate the water discharge rate at noon when global radiation incident normally to the panel is 800 W/m^2 and we know the density of water is 1000 kg/m^3, same can be used even though some variation is there sometimes, so we can use 1000 W/m^2.

So, configuration will be something like this, so we need to know that discharge, the amount of water, so which will be in cubic meter per second we need to calculate. So, PV module there are this kind of 24 modules, 24 modules are connected and this size, if we talk about this size is 0.125 by 0.125 mm square so that much and solar radiation falling onto this PV system is 800 W/m^2, 800 W/m^2.

So, here density ρ is 1000, 1000 kg/m^3 and this head is given as 40 meter and this inverter efficiency is 85 percent or 0.85 I can write inv inverter, okay? And this motor generator or this component having efficiency or I can write motor generator because motor will be connected to leave the water, so this is about 50 percent.

Now, as we know this conversion efficiency is something like power output from the array to the incident solar flux multiplied by cell area. So, this is known to us, so we will calculate this PV output, so efficiency of conversion is given as 0.12 and I_g already I said 800 W/m^2 and these cells are arranged by a matrix of 9 by 4 and 4 columns, 9 rows and then cell area is given as 0.125 multiplied by 0.125 and we have 24 that kind of modules.

So from that we can calculate what is PV output, it will be 1296 watt. So, this power available for lifting water is PV output, so power available for lifting water will be here, so how much it is? PV output multiplied by inverter efficiency and then this motor generator efficiency.

So if you multiply this then what we will have this is the power available for lifting water, also we know this P is this power required to lift water is $\rho \times g \times Q \times H$, so what is the density of water and its unit is kg/m^3, then acceleration due to gravity m/s^2 and Q is in m^3/s and then we have here is in meter. So, this cubic meter cubic meter has got cancelled kg m/s^2 this is something like Newton, so and then Newton $\times$meter so what we have Newton meter $\times$ second, Newton meter is joule, Newton meter is joule, joule per second is watt.

So, this will be in watt. So, once you know this then what you can do you can use power available for lifting water and this power which is required to lift is equal, so if we equate it and if we calculate this Q then we will get a value of something like this in m^3/s and that can be converted because we know $1\,litre = 10^{-3}\ m^3$.

So, that way if we do this then we will get 5053.21 liters per hour. So, that much of discharge can be generated by using this many modules, 24 modules. So, this is an example to understand how a water pumping system work, so of course, these are helpful in designing a standalone system where water requirement is an important for irrigation purpose.

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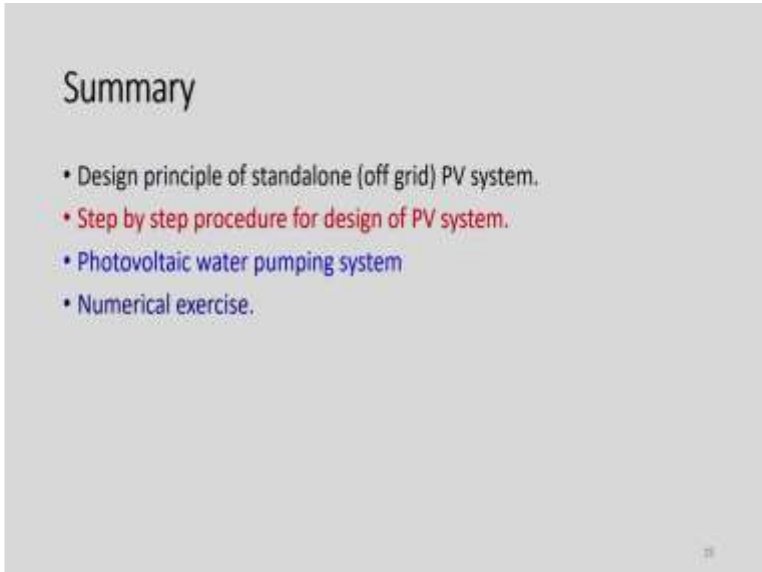

So, let us summarize what we have discussed today, we have discussed the design principle of a standalone PV system and also know the step by step procedure for designing the system and also we have learned how does a photovoltaic water pumping system works and also we have solve a numerical problems to strengthen the understanding of both the design, like how to design number of modules required and the number of batteries required to meet some kind of load and for design of a water pumping system. So thank you very much for watching this video.