# Energy Resources and Technology
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**Lecture - 18**
**Photovoltaic Power Generation (Contd.)**

… mechanism by which the charges are separated in a photovoltaic cell and how they flow through the external circuit and we started developing the equivalent circuit.

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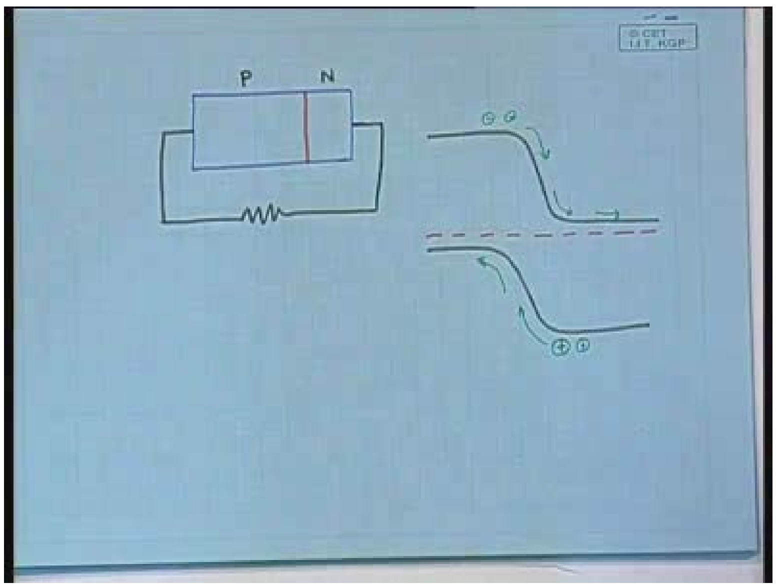


So, just to briefly recapitulate, we have a PN junction, which if I draw it as a diode can be seen something like this. Here is the PN junction and you have an external circuit connected. So, this is the P part, this is the N part and we have seen that because of the PN junction, there would be a, I deliberately drew the junction closer to the, to this side, because normally the P acts as the substrate and N on top of it, so that the thickness of the N layer is smaller than the thickness of the P layer, though it is not really like this. It is drawn in a very visually convenient manner, but it does not really look like that.

So, you have seen that, because of this there would be a band bending, like so, with the fermi level somewhere in between, that becomes the same for both sides and as a result, the electrons that are produced, they move down and move like this. The holes that are produced, they bubble up and move like that, as a result of which there would be a concentration of the holes in this side and concentration of electrons in this side. There would be a voltage difference produced.

Now, this essentially is a current source and therefore, the way it is to be seen is I mean when you, when you say that there is a concentration of charge here, the concentration of charge here and your mind normally thinks of it as a voltage source. No, it is not, it is still a current source. So, what happens is when this external circuit is not connected, then here is a positive charge, here is the negative charge. As a result, this PN junction is forward biased, so there is a current flowing through the diode. So, there is a charge separation and there is a charge recombination going on, since it cannot flow through the external circuit.

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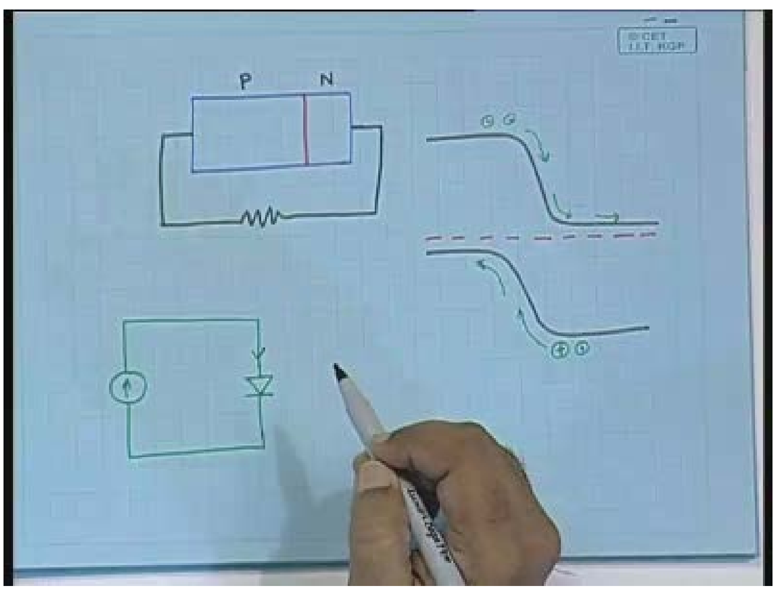


Now, if we have this balance, that means some amount of charge is separated creating the I ph, photocurrent and some of it goes through the diode without going through external circuit, then your equivalent circuit essentially becomes a, only becomes this. Now, if it only becomes this, this much, then the question is can we then obtain the open circuit voltage? Through the balance we can and that is what we obtained in the last class, clear. So, we obtained the open circuit voltage, what will be seen as the open circuit voltage that we saw from this kind of a simple representation, where the current through this is a simple diode current. So, that is where we were in the last class.

So, today to start with, let us just draw the full equivalent circuit and let us write the full equation including all the components.

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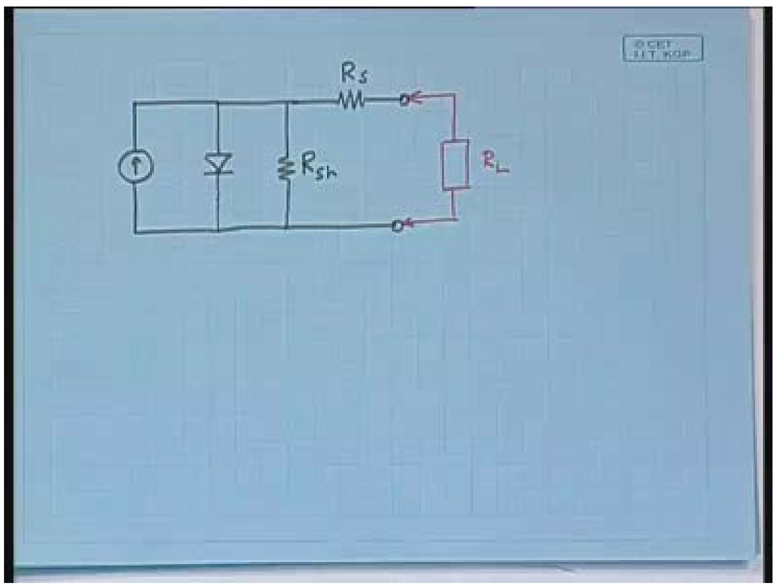


So, the equivalent circuit will have, first the photocurrent as a current source, then the diode that shunts a part of the current depending on the voltage. Then, there will be a shunt resistance which represents the recombination, recombination of the electron holes, electrons and holes, whose magnitude will depend on the recombination sites. If it is a perfect crystal, then the recombination sites are very small in number, mainly on the top. That means the top layer is of course, exposed, they have dangling bonds. So, that is where mainly the recombination would take place. But, if it is poly crystalline or if there is a deformity in the crystal structure, there are dangling bonds and they act as a recombination centers.

For idealized, ideal photovoltaic cell, this would be very high, close to infinity. But in actuality you will find, if you measure in physical things, you will get something like a large value, like 300 ohms or so, but nevertheless is there. So, this will use the shunt resistance and in addition to that there is a series resistance. This series resistance is owing to the resistance encountered by the flow of the charges, both electrons and holes as it moves through the bulk material as well as, as it moves from the semiconductor material to the metal collecting points. So, there would be some kind of an interface resistance and that resistance is also included here, clear and then you will have a load connected at this point.

Now, this load could be anything. Mostly, these photovoltaic panels, I will, I will be using the photovoltaic cell and the photovoltaic panel in most of the cases, a cell means a single cell and since a single cell produces a voltage something like 0.8 volts which is not useful for most purposes, so a large number of cells are connected in series, normally something like 30 to 36 are connected in series to produce a voltage like 24 volts. That is a panel. So, when I refer to it is a panel, it is a collection of such cells. When I refer to just cell, it is a single cell. But, even if it is a panel, normally we assume that the equivalents circuit is similar.

There are more detailed models of the solar panels where these represent individually the cells and they are connected in series and finally, you have, oh, that will be enormously complicated, not necessary, because it has been found that even if you consider a panel, its equivalent circuit for all practical purposes can be treated as the same. So, we can, at least at the level that we are teaching here in this course, we can assume that as the equivalent circuit both of the cell as well as the panel. So, here you have got, you have connected a load. That load could be a battery charging load, that could be some kind of a heating load, that could be a pump kind of load, I will come to those things a little later, but some kind of load.

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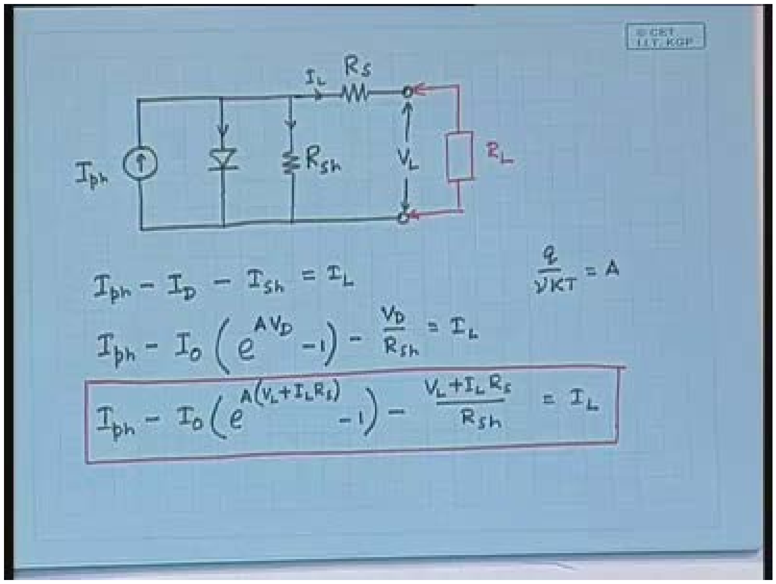


So, now if you write the equations, it would be I ph is here, minus I D, diode current minus I sh, shunt line current is equal to I L, right. So, let us break them up I ph minus I D is I naught e to the power, now let us make it shorter, the things that do not change like q by gamma KT, let us call it A. So, our representation the things that we have to write again and again they would be smaller. So, this is AV D minus 1, this is the diode current minus I sh. What is I sh? V D by R sh, is equal to I L, clear. Now, V D that is an internal thing, so we have to find out what it is. We …. to write I ph minus I naught e to the power A, now V D is V L that is something measurable, the load voltage. So, here is I L that is something going to the load, V L plus I L R S minus 1 minus V D is again …, is equal to I L. This is the complete equation of the photovoltaic panel that relates the voltage and the current; this is a complete equation.

Now, as I, as I told you, in some cases we often ignore a part of it to make things appear simpler, but nevertheless this is the complete equation. You would notice that the current I L appears here, here, here, the voltage V L appears here and here and they are hopelessly mixed up. So, the only way to obtain the value of the current for any given voltage is by solving by Newton-Raphson and that is what I asked you to do yesterday. Have you done? Has anyone, have any one of you done? No; yes?

Student: …

No, no, no, no; no, it will not have, wait a minute. The I L that is passing through this resistance R, after all it is coming through here, that idea is true for voltage sources. Here it is not quite so. This load what is it? Is it a resistance, is it a motor, is it a, is it a some, I said that it could be anything. That is why even though I have written, it does not appear here.

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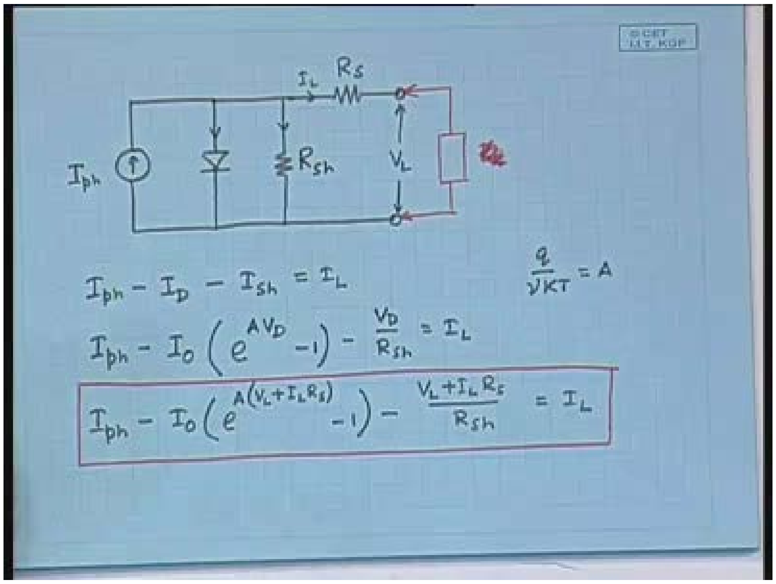


You could as well simply ignore, ignore this written and assume that some kind of load. There is no reason to assume that it is a specific load, specific resistance load. So, it does not really appear, it could be any load. Essentially, the relationship between the voltage and current depends on the character of the source. In case of the typical voltage source that you see in your, in your home socket, there the voltage is constant and depending on the resistance, you have current, voltage constant. Voltage and current are not proportional to each other. You vary the resistance, the current changes.

Here also, if you have simply a resistance connected, you vary the resistance the current changes. But, not only that, because of this complicated structure, there would be change;

that change will not be a linear relationship. In fact, this equation will give you a specific kind of relationship. Let us see the specific kind of relationship.

Student: Can you test it, R L?

You will get a, for fixed R L, you will get a fixed voltage and a fixed current.

Student: …

No, current and voltage ratio does not make any sense. Current and voltage ratio is the resistance; current and voltage ratio will be the resistance, all right. So, for any fixed voltage, …. resistance, the current voltage ratio will be the resistance; that is okay, but the, but the point is this particular equation would mean that that for any resistance if you have particular value of the voltage and the current, for another resistance you will have another volt, another volt, voltage and current. Yes.

Student: That will be dependent on R L.

Yes, it will be dependent on R L, it will be dependent. But because of this source characteristic, they will not be linearly related. If it is fixed, they will be linearly related. The idea that, idea was, the linear relationship was that there is a source fixed. You have got a resistance that is varying, so the current varies linearly with the resistance. But here, the source is not fixed. As a result, the relationship between V L and I L will have a specific property given by this equation. Let us see what this specific property is.

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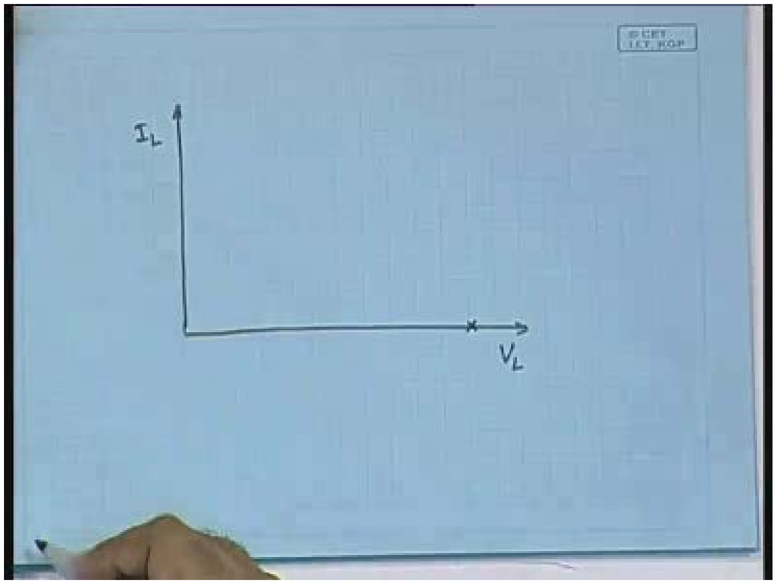


It will have a character. If you draw, you can yourself solve the Newton-Raphson equation and you will get it that is V L here and I L here. You have seen in the last class that if you substitute I L equal to zero, then you will get a specific value of open circuit voltage. So, open circuit voltage at I L zero has a specific value, right.

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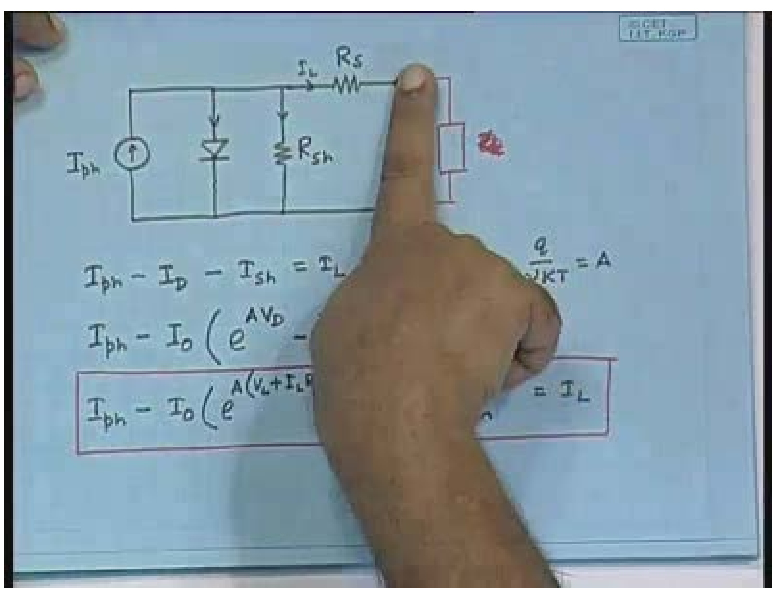

Now, if instead you completely short circuit this fellow, at this point you completely short circuit, then V L is zero. Then you will get a certain amount of current flowing that is a short circuit current.

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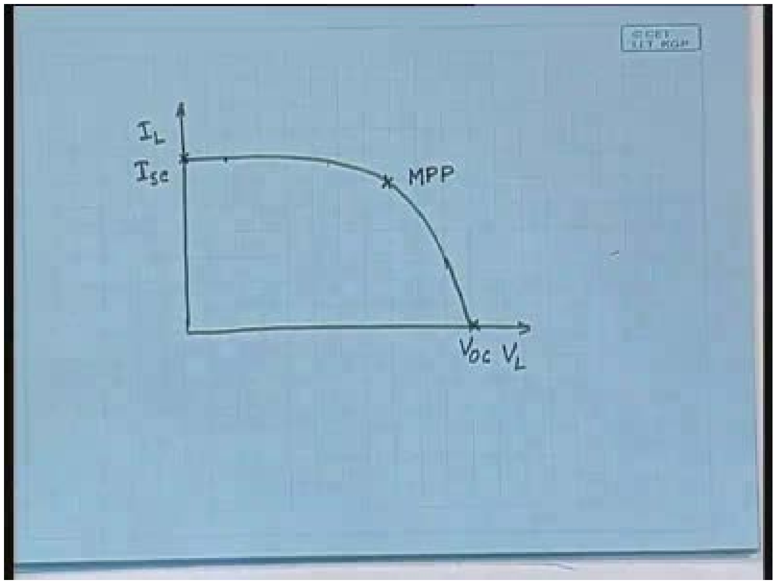


So, there will be a specific value of the short circuit current. In between, what the character will be? In between this character will be of this shape. This shape is essentially the characteristic of the photovoltaic panel. So, this point is V oc and this point is I sc, short circuit current and the open circuit voltage. This is the characteristic; this curve is a characteristic of the panel.

Now, there is one important parameter that specifies the characteristic of a particular panel. That is you would notice that, where will it be? This is the characteristic, all right. That means at any point of time, depending on the load, the relationship between the voltage and the current will be on this curve. Now, whether it will be here or here or here depends on what? The load; but, you see, if it is here, the power that is actually taken from the photovoltaic panel to the load is this product, this area. Now, at this point, it will be this area. It is easy to see that this area is different for different points on this characteristic curve. If it is here it will be small, if it is here it will be zero, because there is current, but no voltage. If it is here, it is again zero. So, depending on the load, the amount of power, there is a power generator all right, amount of solar radiation that is received will produce a …. separation all right, but it does not mean any load will be able to accept that.

If the, if it is working here the actual power transferred to the load is zero, if it is working here it is again zero. In between, there is a curve like this that must be a maximum; there must be a maximum point. So, they should be somewhere here. That is called the maximum power point which means for a photovoltaic panel, it is not just sufficient to make the charge separation. It means that, this particular characteristic means that you have to choose the load in such a way that it operates very close to the maximum power point. Else, even though the charge separation is there, it will not flow through the load. What will it flow through? The diode actually; so, there is a shunting diode it will actually flow through, it will not flow through the load. In order to make it flow through the load, you will have to choose the load very accurately, very properly, so that it operates close to the maximum power point.

Now, there is an important characteristic that signifies the character of a photovoltaic panel.

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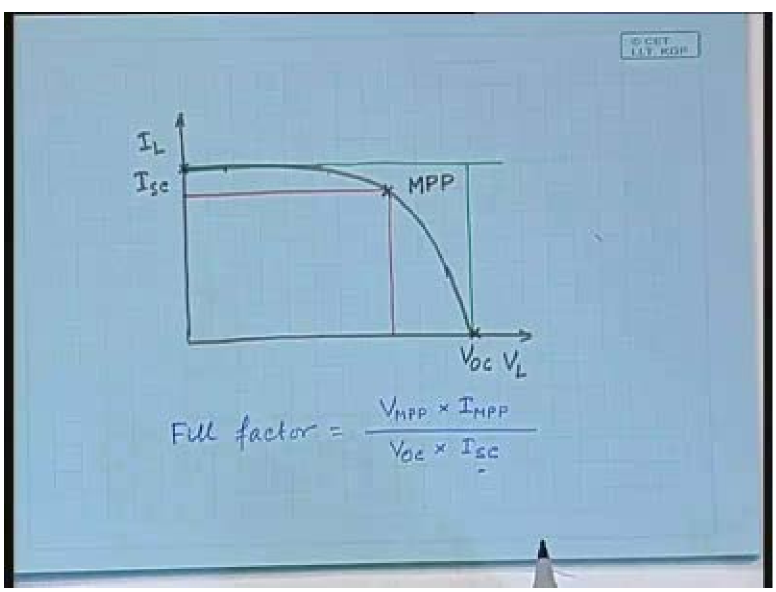

Suppose, you take a horizontal line through the short circuit current point and a vertical line through the open circuit voltage point, you get a rectangular. The rectangle has an area which means that if the short circuit current and the open circuit voltage were the things available, then the total power would have been this. But, actually the power that you can maximally extract is only this much, this area. So, this area divided by this area is called a fill factor. So, let me write, fill factor is voltage at the maximum power point times current at the maximum power point divided by voltage open circuit times the short circuit current. That is the fill factor.

Why this is so important? When you buy a photovoltaic panel, you will find a fill factor of that panel mentioned.

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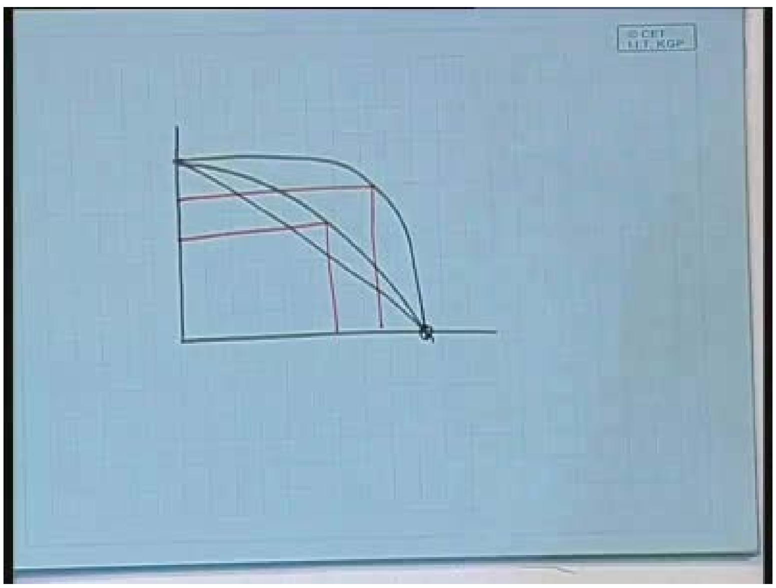

Why is it important because, the characteristic of a panel, if you have this point and that point specified, could be like this, could also be like this, could also be like this. In either case, the open circuit voltage and the short circuit currents are the same and therefore, it does not suffice simply to say that this produces this much open circuit voltage. You will find that in many cases, the photovoltaic panels are sold; if you just go to the market you can get photovoltaic panels and you will say that it produces 30 volts and energy engineer should say it makes nothing, tells me nothing because photovoltaic panels 30 volts is here. Because people have an idea that when I buy a battery it is 1.5 volt battery, so when they sell, they often sell by saying that it is a 30 volt photovoltaic panel; makes no sense, it is only this point at open circuit, it produces this.

Actually you need to know how nice is the characteristics or in other words, in all the three cases, you will notice that here this much is the, here is the maximum power point, in this case it is here. So, the fill factors are widely different, even though the open circuit point and the short circuit points are the same. Actually these, this characteristic depend on the value of the series resistance and the shunt resistance. As the series resistance increases and the shunt resistance falls, the characteristic go from this kind to this kind and that is why whenever an energy engineer or anybody exposed to energy engineering wants to buy a photovoltaic panel, he should immediately ask for the fill factor, not only the voltage, the open circuit voltage. Is that clear? So, we have come to the concept of the fill factor. Fill factor is a very important parameter of a photovoltaic panel.

Now, let us understand a few things. As you know, the photovoltaic panel will be exposed to the sunlight and the sunlight will vary continuously; you cannot help that that is beyond your hands. So, as the sunlight varies continuously, how will the V-I characteristic of the panel vary? Let us, let us try to think about that.

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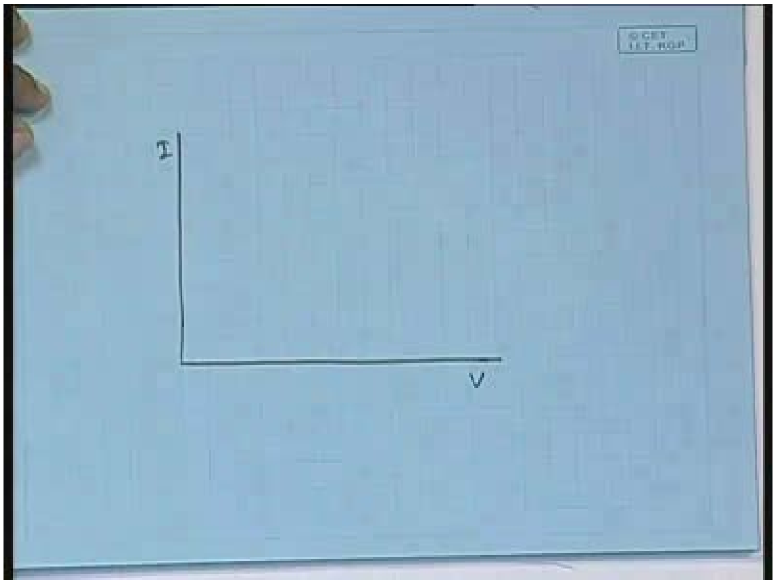


Here is the V, here is I, here was the essential equation.

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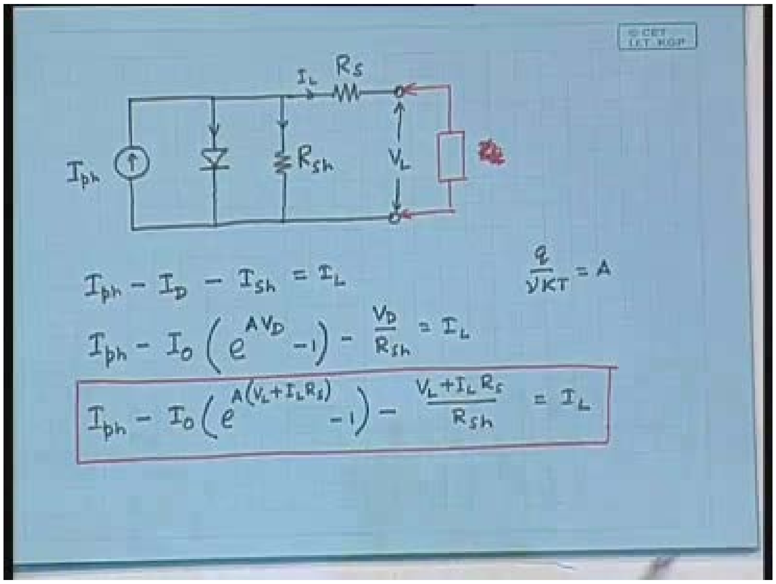


Let us try to think. Where are the things that we did yesterday? There? I have to pick them up may be. So, when I am talking about the short circuit current what exactly is seen as a short circuit current? I am short circuiting here. If it is short circuit current, the diode voltage is essentially how much? I L R S, right. Here is the voltage plus I L R S is the diode voltage. There will be some amount of current flowing through this, therefore the short circuit current is close to the photo current, but not exactly the same as the photo current, photo current minus a small amount of diode current flowing because of this I LR S. If R S is sufficiently small, then you would say that no, the photo current is almost equal to the short circuit current and the photo current is dependent on what? The amount of solar radiation coming in; so, as the solar radiation goes up and down, we can logically expect the short circuit current also to be linearly going up and down with the amount of solar radiation incident on the photovoltaic panel, right.

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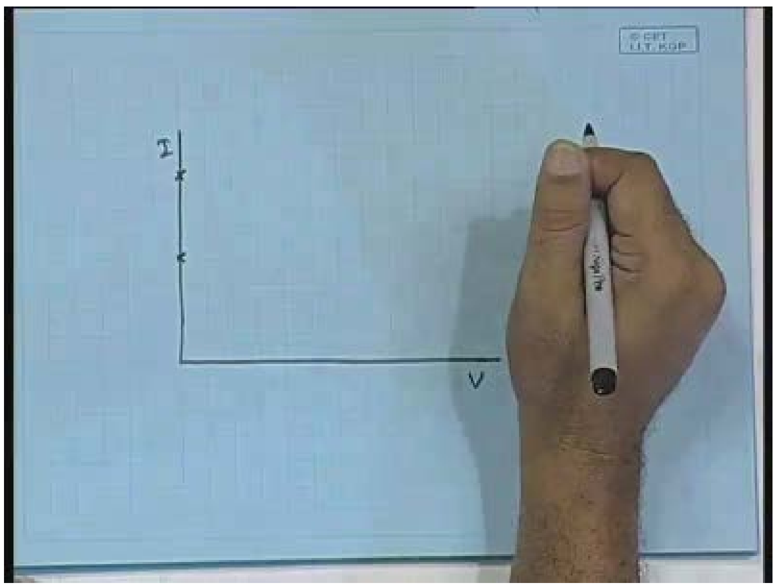


So, you would expect here that this point will go up and down. Now, let us assume that we have reduced the incident solar radiation called insolation by half. So, in one case it was here, in another case it would be just linearly half down. That stands to reason. How much will be the change in the open circuit voltage? Open the page in the last class; it should be somewhere here, just keep focusing on this.

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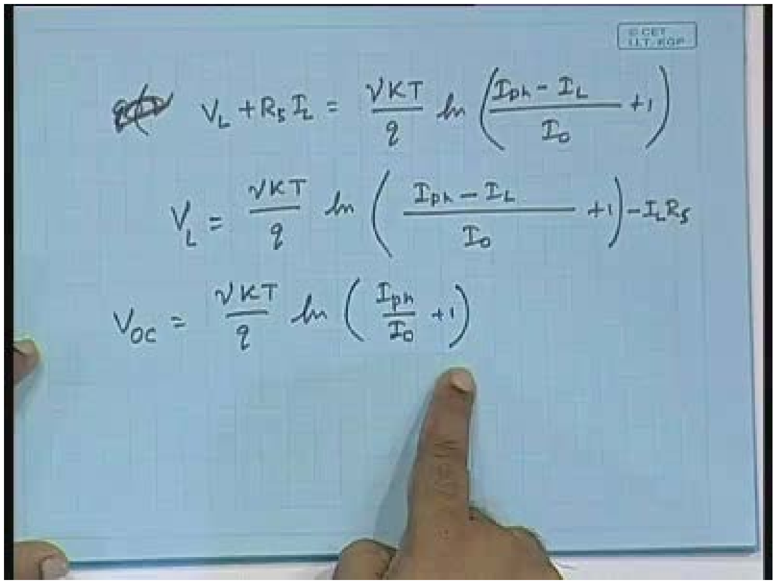


In the last class, we have derived that the open circuit voltage is given by this. This fellow is a constant. Then, the relationship between this and that, obviously this is far larger than this, so 1 can be ignored. So, ln, this fellow is constant, ln of the photo current. Obviously, if the photo current becomes half, how much will the logarithm reduce? So, how much?

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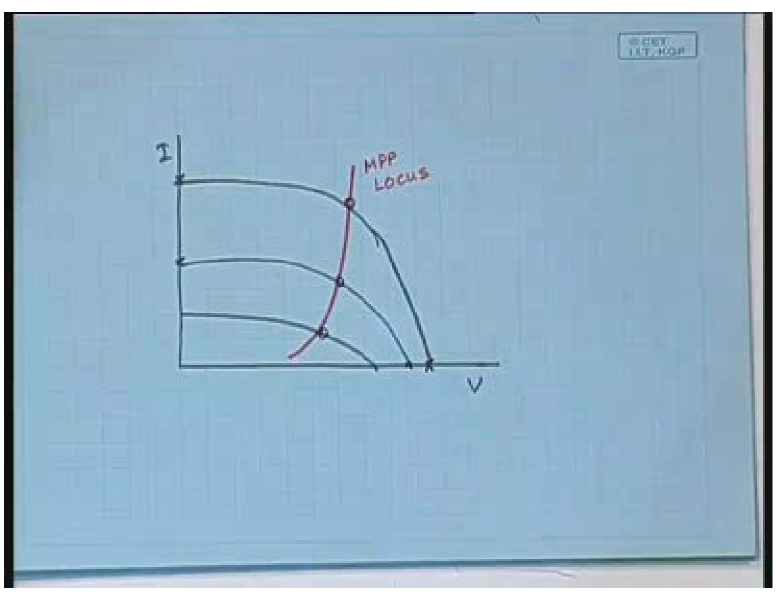

Small, small amount, right and that is why what will actually happen is that this, if this is the amount of open circuit voltage for this amount of incident solar radiation, for this one having reduced to half this will only be slightly different from the earlier one, not much.
So, if, it will be like this, in the next case it will be like this; reduce it further, it will be like this, clear and as the incident solar radiation changes, goes up and down, what happens to the maximum power point? Here it was here, in this case it was here, in this case it was here; you would notice that it follows a curve something like this. It has to move this way, because ultimately when the incident solar radiation becomes zero, the output voltage also becomes zero. So, when it reduces to small values, then this fellow, the logarithm reduces fast. That is the character of the logarithm. So, while we studied logarithm in the school, this typical characteristics of the logarithm function we often did not realize. You can see it happening in case of the photovoltaic panel. So, this is the trajectory of the maximum power point, locus of the maximum power point.

Now, the incident solar radiation is varying continuously. You have no hand on that, you cannot really change it; it will do, it will change. You keep it exposed, but when a cloud cover comes, when a cloud cover moves away, all these are not in your hands, so as the photovoltaic panel is really exposed to the natural environment and you are trying to use its energy, it will always go up and down. As a result, the maximum power point also goes up and down through this kind of a locus. How to use the lows, so that you have, you are always working very close to the maximum power point, it is not a, it is not a trivial problem; it is not a trivial problem.

The way people try to overcome this problem is as follows: either if you are using a resistive load, then obviously you have to vary the resistance trying to keep it on the maximum power point.

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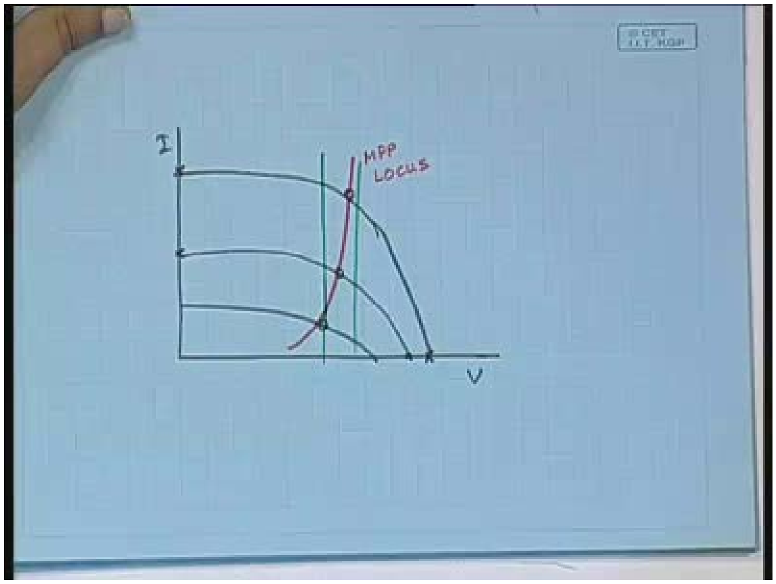


But, a simpler option is you would notice that for most part, for most part, unless it has become very close to the zero level that means it is very close to the dusk or dawn, the maximum power point is within a relatively short range, right. So, somehow if you keep the voltage constant, then you are not likely to go very much away from the maximum power point. Now, what kind of the load is there where the voltage is more or less constant? Battery recharging load, battery recharging load is where the voltage is more or less, more or less constant. When it is more discharged the voltage is less, when it is fully charged voltage is more. But, you can always tune the voltages such that it is within this band. So, the most predominant use of the photovoltaic panel, simplest use is to use a battery charging.

The photovoltaic panel produces a DC voltage, battery is a DC device, so simply connect. But, remember, very important that many people do not know that is the choice of the range of the battery, the rated voltage of the battery, the discharge to charge range, all these should be very properly tuned to the specific characteristic of that panel, else you are nowhere close to the maximum power point. That is what many people do not understand. They simply take a battery and connect to the photovoltaic panel. The photovoltaic panel, after all the specification says that it produces 24 volts and I have got a 24 volt battery, just connect them. Very bad way of doing it, very bad way of doing it, because there has to be some kind of a matching between this thing and that thing and that is what any energy engineer should know properly.

You cannot simply connect any battery to any panel. You first have to measure the characteristic of the panel at various insolation, levels of insolation, look at the trajectory of the maximum power point and then identify the range in which it will work close to the maximum power point and then choose the battery whose range of oscillation of the voltage, change in the voltage, variation of the voltage is within that range, clear. Naturally, it brings us to the point how to measure this characteristic, measure this characteristics in a photovoltaic panel?

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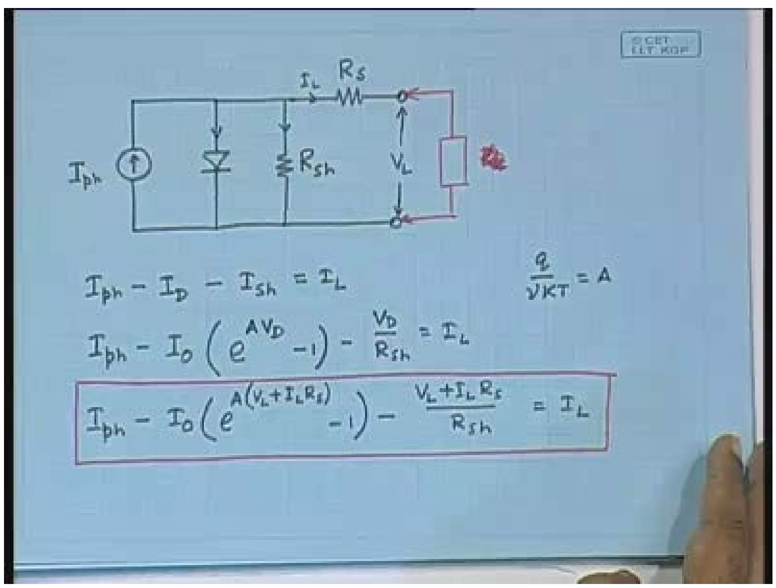


If you know these parameters, obviously you can, you can derive. As I told you, all you need to do is to write in Newton-Raphson solver, which is trivial. You have attended some course on numerical analysis, right? So, you know how to do that, but if you are given photovoltaic panel you do not know these parameters, you have to estimate.

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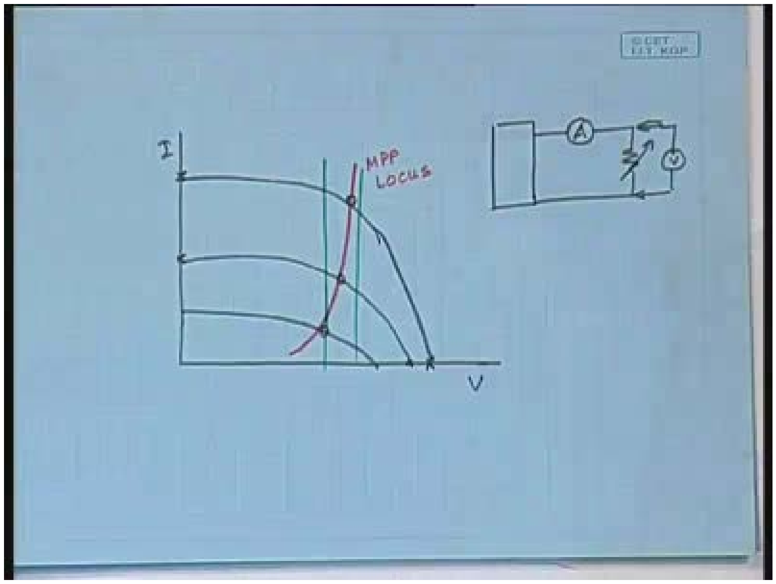


So, all that one needs to do in this case is simply connect the photovoltaic panel through an ammeter to a load and have the voltage of the load measured. That is it. Now, this load is a variable load, so if you vary then you are actually going this way. So, if you simply keep on taking the readings of the voltage and the current, you get the curve, though it is not as simple as it looks. Why, because what do you choose this resistance to be? You have seen such rheostat in the laboratory, right. You have seen 10 ohm rheostats, you have seen 370 ohm rheostat, you have seen 1000 ohm rheostat, which one do you choose? Which one do you choose?

It is not trivial, because if you choose a 10 ohm rheostat, the variation will be very close to this point. If you choose a 1000 ohm rheostat, the variation will be very close to this point. So, in either case, you will get only this part or this part, not both and moreover in order to get the MPP correctly, it is necessary to measure this part in various close points. How to choose this? Actually it is necessary to choose two, at least two, may be three rheostats connected in series.

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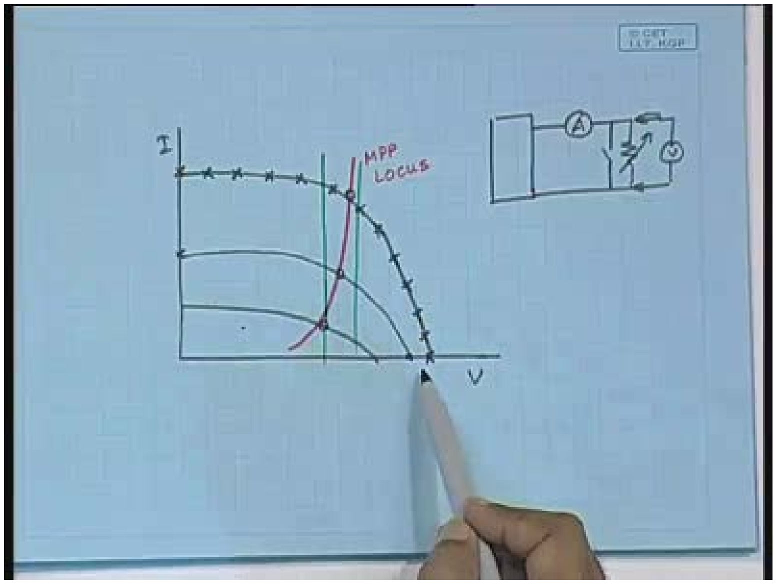


The smaller rheostat, small value of resistance is meant for this part, the larger value is for this part and the intermediate value for this part, clear and moreover in experiment, it is normally desirable to have points located equally distant, right. You would like to do it like this. So, if you, if you do it like this, then you know that okay, I am fine. But, it is somewhat difficult to obtain points equally spaced, because what do you normally do? You normally take a rheostat and move them equally and keep on taking readings. If you do that you will find that they are not coming equally spaced, because it is not linearly, the positions are not linearly dependent on the resistance that you take.

So, while you do the experiment, the energy students will have to do experiments sometime later when you come to that particular course, the laboratory course, there actually you will have you to plot it while taking each reading. So, each reading is taken. Take the value of the voltage and current. There is no point writing there, just plot, thereby you see whether I am getting equally spaced points or not, whether I am getting the proper curve or not and then simply open this you get this point, simply short circuit this with a switch and you get this point, clear. It is not simply making this resistance zero, because some lead resistance will remain. Simply connect it with a switch, this has to be there, to get the short circuit point and that has to be carried out not only for one curve, one value of the incident solar radiation, also for different values of incident solar radiation.

Another point, while taking this curve, the incident solar radiation must remain the same which means if you are exposing it to sunlight, you have to make sure that right now, no cloud cover is going to come, absolutely clear sky, else it is going to fail. Also, since the sun moves, you have to do this experiment over a period of at most 15 minutes. So, those who will be energy students remember this, you have to do it fast and then go to, go to a different inclination that will mean a different incident solar radiation, do it, all right. Remember, for every photovoltaic panel this has to be done in order to identify its characteristics and then to find out what kind of load would be suitable for it. Just any kind of load, blindly connecting will not help; you will be actually loosing most of the energy that you are collecting, clear.

Nowadays, many companies have very simple way of obtaining this V-I characteristics. But, often you will find that not mentioned in the, in the, when you buy, you simply do not get the specific V-I characteristics of the specific panel, but that is very simple to measure.

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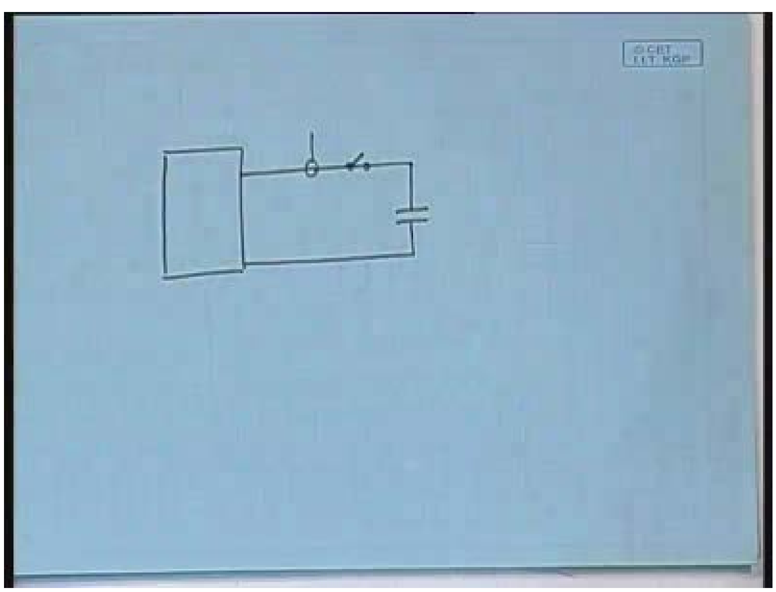

All that you need to do is if you have a photovoltaic panel that will require an online data acquisition system which will measure the current and the voltage, but here you have nothing but a reasonably large capacitor and here your switch. When the switch is open, it is open circuit voltage you get, right. The moment the switch closes, what will be the condition? Across the capacitor, across the capacitor there is no voltage as yet. So, how much current will flow?

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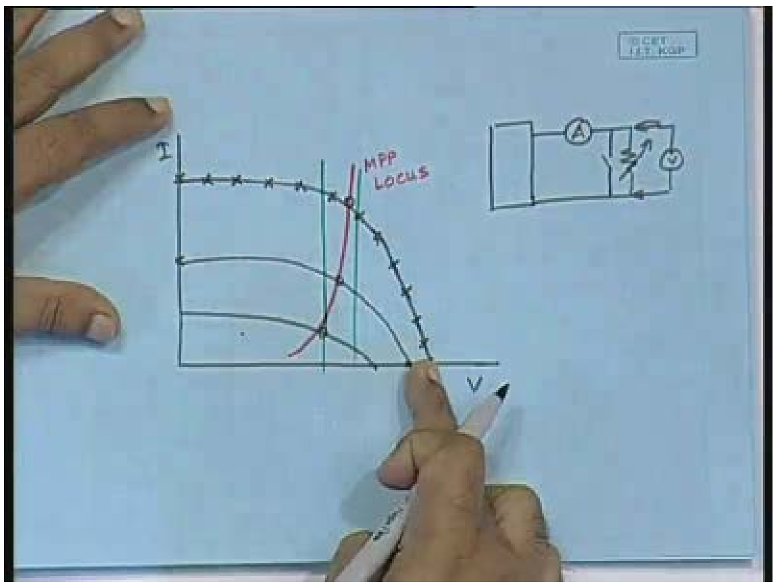


Actually the short circuit current, because at that point the resistance will be, the capacitor will be seen as short circuit and then as the capacitor keeps on charging, it will move along this and finally when it is fully charged, it will come here. So, all you need to do is to have a continuous data logging of the voltage and the current and that automatically draws it. There are equipments, in fact some of our earlier projects in this department were this that making a continuous assessment of the photovoltaic panels characteristics by simply this method, fine.

Where are the photovoltaic panels used? As I told you, one important application is for charging the batteries and then using that charged battery for either lighting purpose in the evening or for various other purposes. For example, these days you will find in many of the remote locations you have the solar street lighting systems. So, you have got the solar panel, at the bottom there is a battery and when the light goes down, the tube light automatically starts, there is a charging. Now, again for this remember the characteristic of the battery and the characteristic of that particular panel have to be matched. You can also have photovoltaic panels as the substitute for, you know, many homes, because of the places where there are more load sheddings, people generally use invertors, right. So, when there is power they store it in a battery and when there is no power, you use that power using invertor.

Now, that can be charged using a photovoltaic panel also and that is, sometime in many places that is being recommended or encouraged. That means there are government subsidies if you want to do that. The irrigation, the irrigation load is high at the times when there is high sun light, right. When there is high amount of solar energy being received in summer months that is when you need to do more of the irrigation. In the winter time where there is no rain that is when you need to do more irrigation and there are systems available where the pumping is done by means a photovoltaic panels. That means you simply cart a photovoltaic panel to the place, it also has a pump there and then simply connect it using the, using the particular, using the amount of energy that is received, you have pumping.

In order to understand the pumping thing, have you done any course on electrical machines? None of you yet, okay. Then, it will be difficult at this stage for you to appreciate. So, I will leave that part. Some machines are suitable for this purpose, some machines are not, but that will be difficult for you to understand at this stage or I will have to go to the details of different types of machine. But, in the first year you have done the DC machines, right? You have done DC machine, at least this much you will be able to understand. DC machines are either the series machines or the shunt machines or they are separately excited machines. These are the three types that you have learnt, not more is necessary.

When you have to run the pump, firstly since the supply is DC, there are two possibilities.

Either you convert into AC by means of some kind of a power electronic interface or simply use a DC machine. Now, suppose you use a DC machine, then what happen? If you use a DC machine, let me draw the diagrams for three different types of DC machines.

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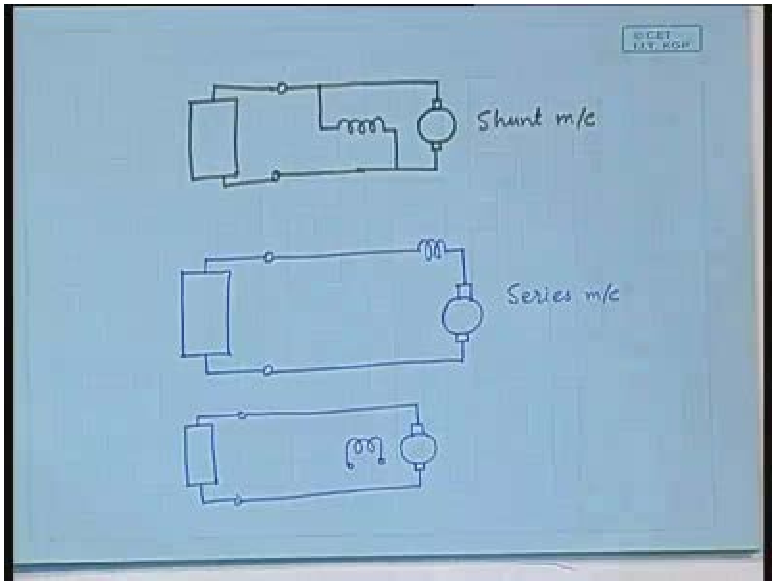


You have got the machine armature like this and the shunt field in case of the shunt machine like this and this is the terminal and we assume that you have connected a photovoltaic panel to give the supply. That is the shunt machine. Then let us do the, draw the series machine. In case of this, the series field is here and you have …, right and the third option is the separately excited or you can also say the same thing, the permanent magnet machines where you have … and you have the separately excited or permanent magnet. Now, imagine that you are first trying to put the supply to the shunt machine.

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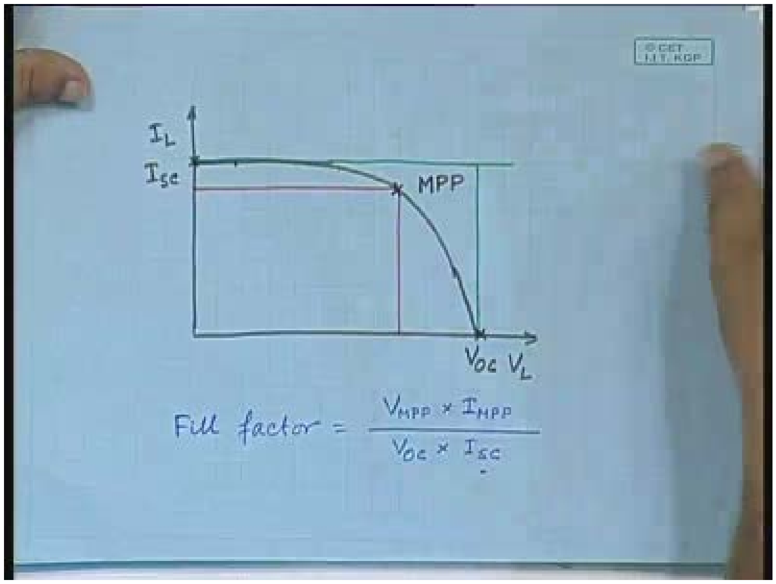


This is the characteristic of the, V-I characteristic of the solar panel. When you simply start the, simply give the supply, what will happen? Where will it be on the V-I characteristic? Remember, at that point of time there is no back EMF, because back EMF will be dependent on the speed. Back EMF is K phi n, speed of rotation; speed of rotation is zero, we are starting, there is no back EMF. Therefore, there will be large current flowing here. If it is large current flowing here, it will be close to the short circuit point and short circuit point means the voltage is very small. A very small voltage means how much current will flow through the shunt field? Very small, right; as a result, there will not be sufficient magnetic field produced in order to start the machine.

Machine would not run even though the panel is generating the power, because this and that these things are not properly matched. Therefore, there will be very little starting torque, it will not run. But that will not be, when you think of the series machine. See, the series machine, since this is actually a current source, therefore when there is no back EMF, here the resistance is very small and therefore, the current that will flow through this is again very close to the short circuit point but that is flowing directly through the series field and therefore, there will be high amount of flux produced, it will start running.

That is why when it comes to using the DC machine, for constant voltage sources, voltage sources it is better, it is more convenient to use the shunt machine, but in case of the current source type that means the photovoltaic panel is the current source type, there it is more convenient to use the series machine. Separately excited machine is of course different, because you have already given a specific amount of field, so that was fine. So, when it comes to using pumps, obviously you use motors, there these considerations have to be kept in mind. It is time, we have to stop now. We will continue in the next class.

Thank you!