Energy Resources and Technology
Prof. S. Banerjee
Department of Electrical Engineering
Indian Institute of Technology - Kharagpur

Lecture - 19
Photovoltaic Power Generation (Contd…)

So, in the last class this is where we were.

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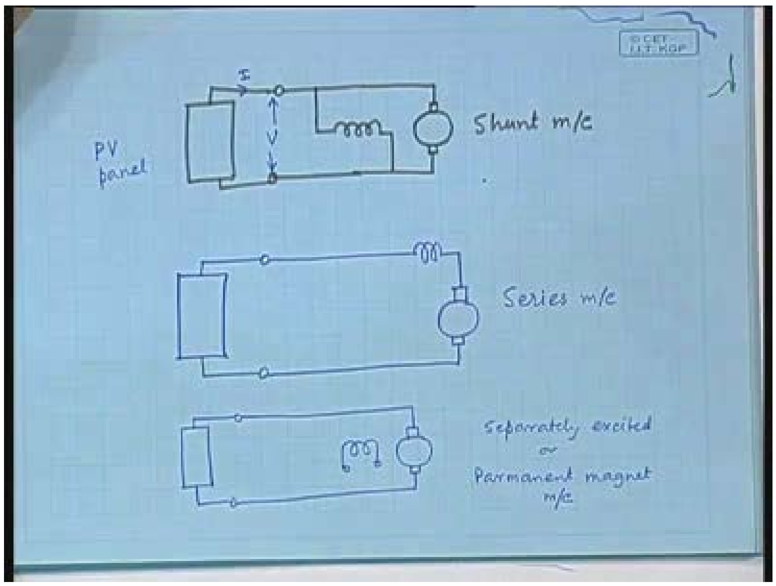

We are talking about the different types of electrical machines, DC machines that can be connected directly to a photovoltaic panel. So, here is your PV panel and there can be three different types of DC machines. The shunt machine where the field is shunted, connected in parallel with the armature, here the series machine where the series, where the field is connected in series with the armature and here is the separately excited or permanent magnet machine. Now, we were considering what will be the character, what will be the behavior of the different types of machines as fed from the photovoltaic cell.

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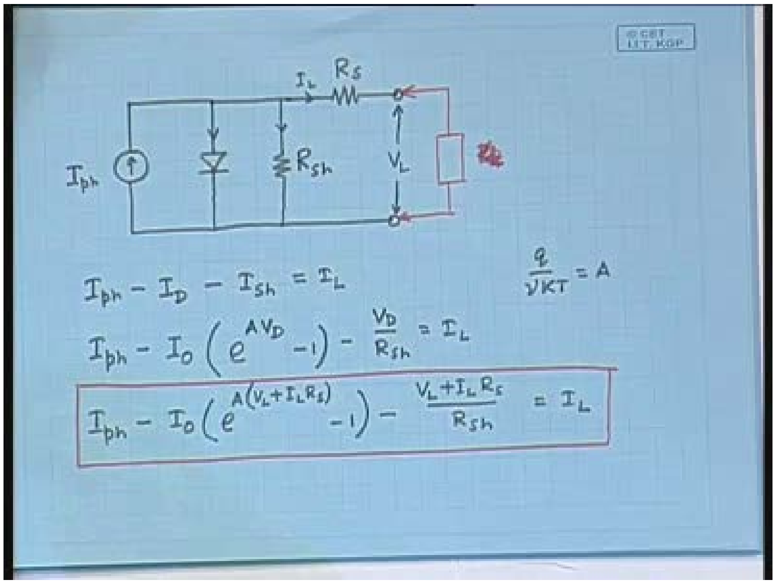

Now, this photovoltaic cell will have a current I, we will have a voltage, terminal voltage V and these two quantities are related by this, we have already seen that. This is the relationship linking the terminal voltage and the terminal current of the photovoltaic panel. So, in addition to that, the machine equations are, in any machine what are the phenomena in action? You have applied an input voltage due to which the machine is running due to which the back EMF is generated, right and the quantity of the back EMF is what is it?

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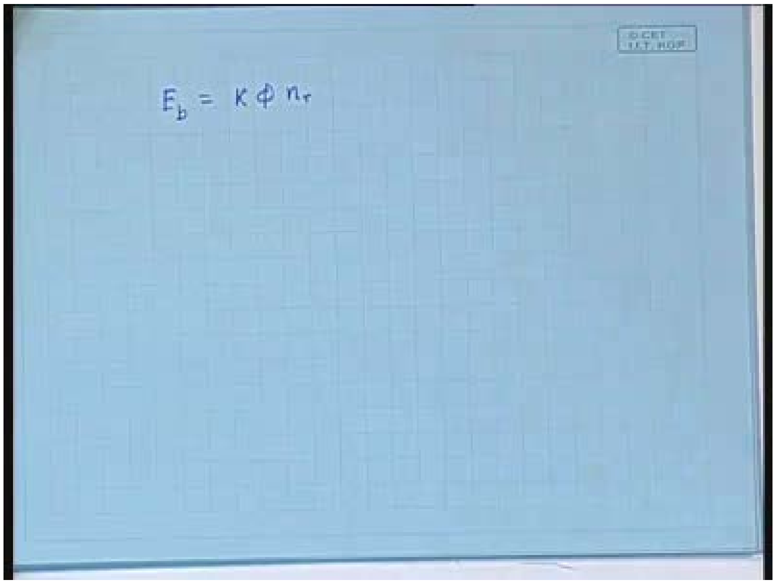

K phi and the speed of rotation; n is the speed of the rotation or sometimes this is called n r, speed of rotation. So, this is the expression for the back EMF, you have already learnt that and if you connect it something like this, then there is a terminal voltage.

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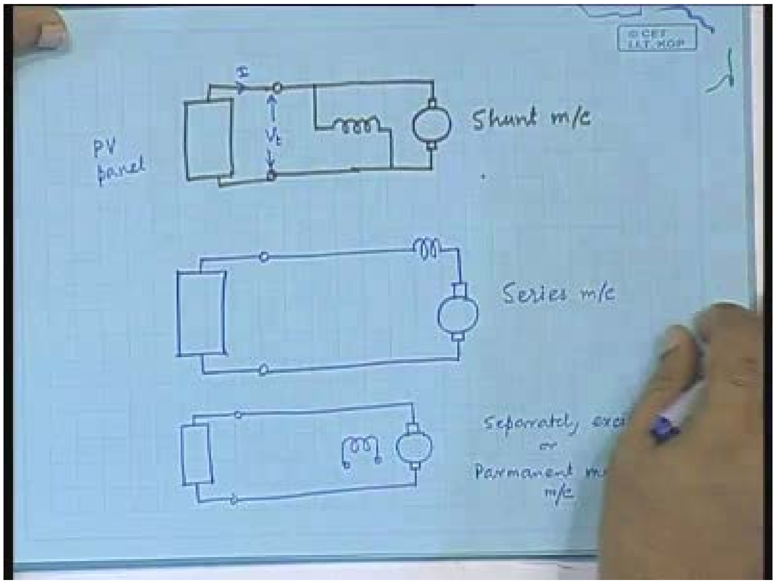

Let us call it V t, the terminal voltage and here there would be some drop because of the resistance of the armature and then you arrive at the back EMF.

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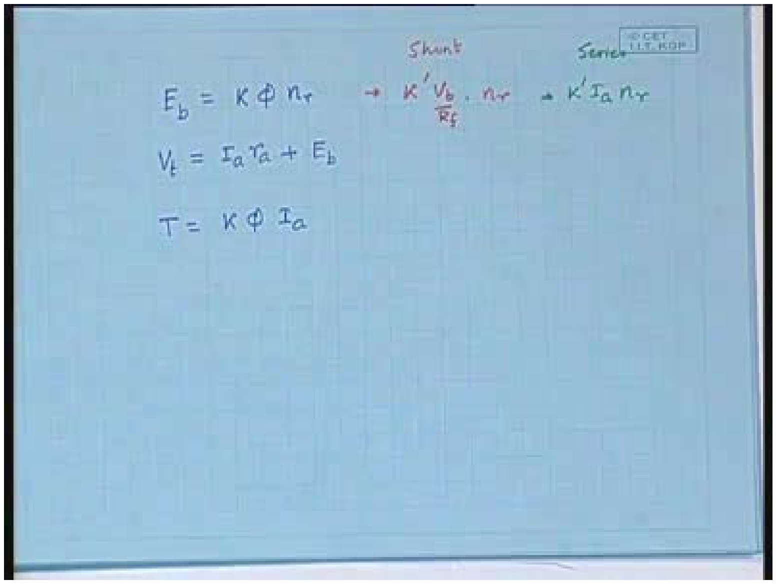

So, simply the equation is V t is equal to I a r a, armature resistance plus … that is it. In case you have the series machine, then the, in case you have the series machine then the series resistance R s will be added to the armature resistance and that is what will appear here, but nevertheless this is the elementary equation. What will be the flux, what will be the torque produced? T is again K phi then, it is proportional to the armature current. So, these are the three elementary equations giving the characteristic of a DC machine. Now, back EMF is this, always. Only if you have the machine connected in shunt, then the flux is given by the V t divided by R f that is the shunt field current and the flux will be proportional to that.

So, in case of the shunt machine, which I will write in red, this will be some K prime, I will put a different constant, times V t by R f times n r. If it is a series field, I will draw in series, I will, it will be K prime, phi will be, no, no, in case of series field it is proportional to I a, so for series and this is for shunt, right. Similarly, what actually is happening is that you are substituting phi by something and same substitution will occur here. But nevertheless, notice these are all details. What actually will happen?

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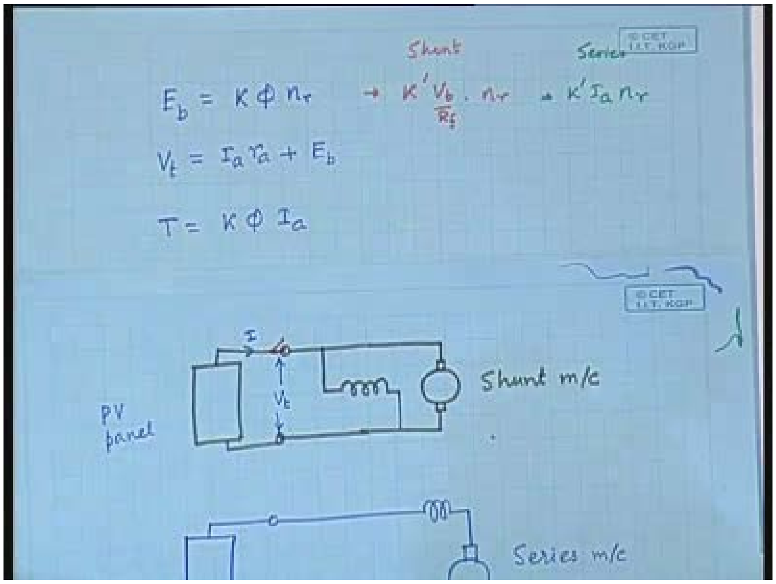

Now, keep track of this and look at the shunt machine circuit diagram. When the machine is started that means you just switch it on, suppose there is a switch here and you switch it on, then at that time the speed of rotation is zero. If the speed of rotation is zero, then the back EMF is zero, this back EMF is zero. If the back EMF is zero, then the V t is equal to I a r a and there is nothing here. I a is, r a is very small and therefore I a is large.

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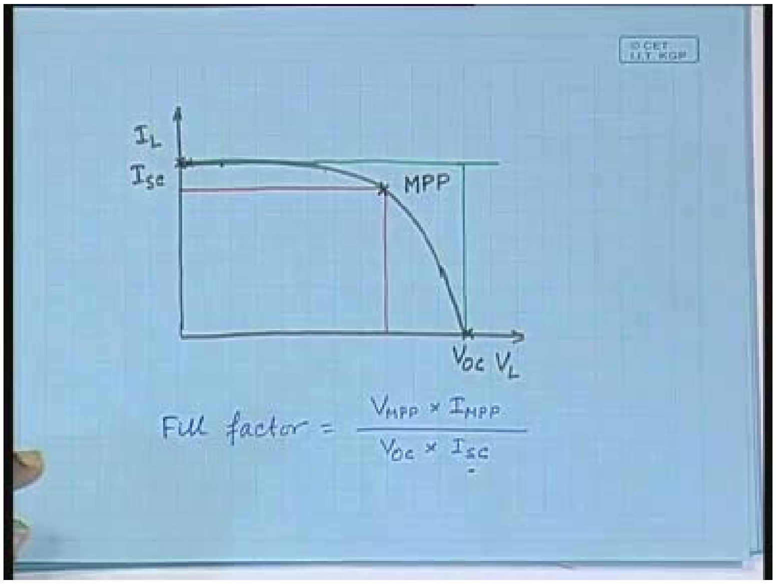

If I a is large, in the V-I characteristics where is it working? It is working very close to this point. If it is working very close to this point, then what is the terminal voltage? That is very small.

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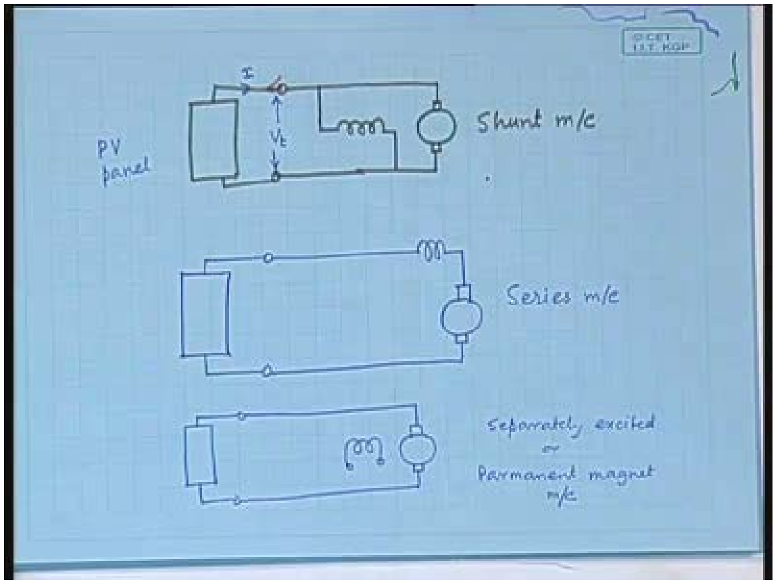

If the terminal voltage is very small, naturally very small amount of current will be flowing through the shunt field. As a result, insufficient amount of flux will be produced. The machine will not start. But, the same problem will not occur in case of the series machine because, when it is giving zero back EMF, still you have the current coming. In case of the constant voltage supply, you need to connect a series resistance here because or here, because at that time the armature resistance is very small, there is no back EMF, therefore a large inrush current flows through the armature.

So, in your lab experiment, you remember that you have connected a series resistance, but in case of photovoltaic cell it is a current source and therefore it cannot give just any amount of current.

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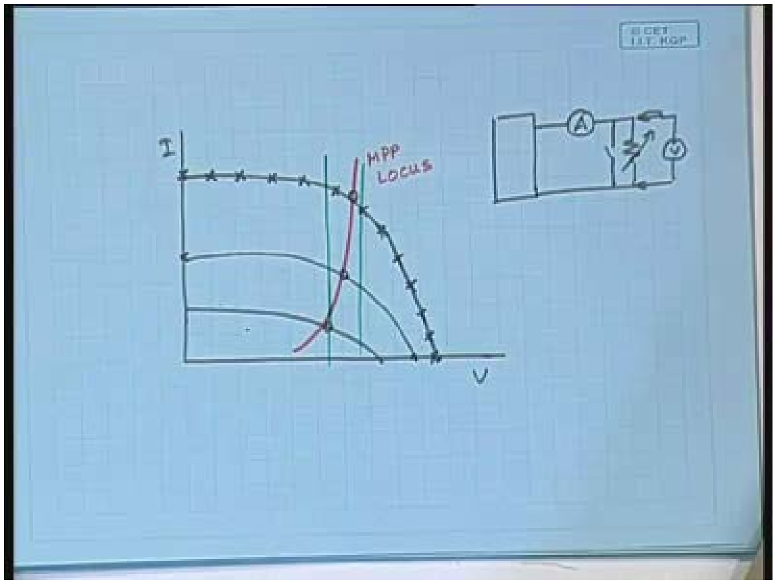

The maximum current is the photocurrent and therefore you do not really need to connect any series resistance there, because it is automatically protected, automatically protected because this current, this current, the short circuit current that is the maximum current that is possible. So, it can never exceed that and therefore, there is an inherent protection.

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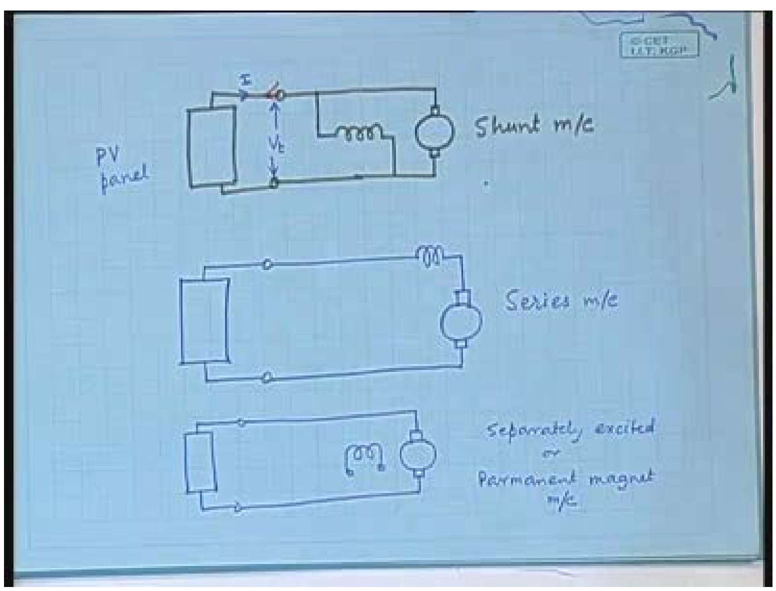

But, in case of the series machine, when the back EMF is zero, then obviously the current here is large and naturally it is working here. But that produces already a very high torque, because the current is, the flux is proportional to the current and if the current is large, torque is also large and therefore it will easily start. That is why for the current source kind of power sources, series machines work fine, but the shunt machines do not. Separately excited machine is of course a different story, because you have the field which is excited separately either by means of a separate battery or by means of a, some kind of permanent magnet machine. That means the field is already there. In that case, the field is constant and in such case you can simply use these equations.

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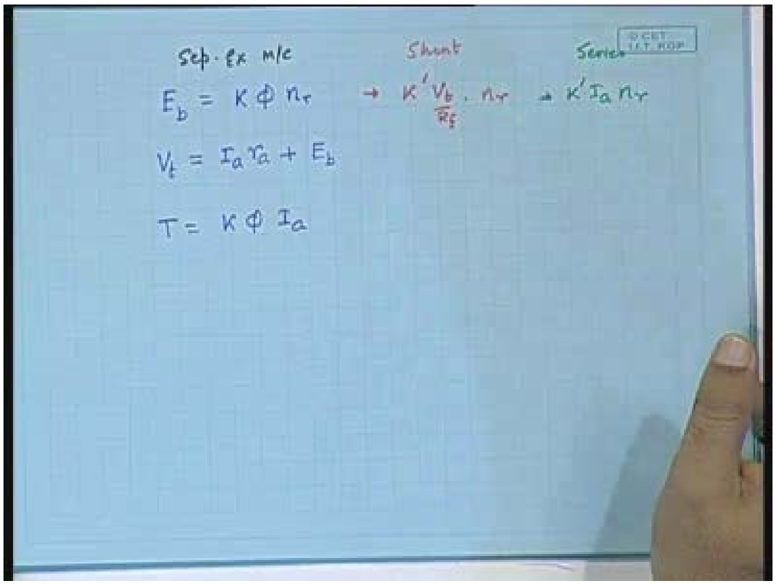

So, these equations are actually equations of, equations of the separately excited machine. So, this is the, these are the equations of separately excited machine, where the flux is held constant, phi and when the flux is substituted by some K V t by R f, it is the shunt machine and when it is simply another constant times I a, it is the series machine. So, in order to, in trying to understand any machine's characteristics, for example in your first year classes you have learnt about the characteristic of the series machine, characteristic of shunt machine, have you not? So, you have learnt that. For example, series machine has this kind of a characteristic; all these were fed from a constant voltage source.

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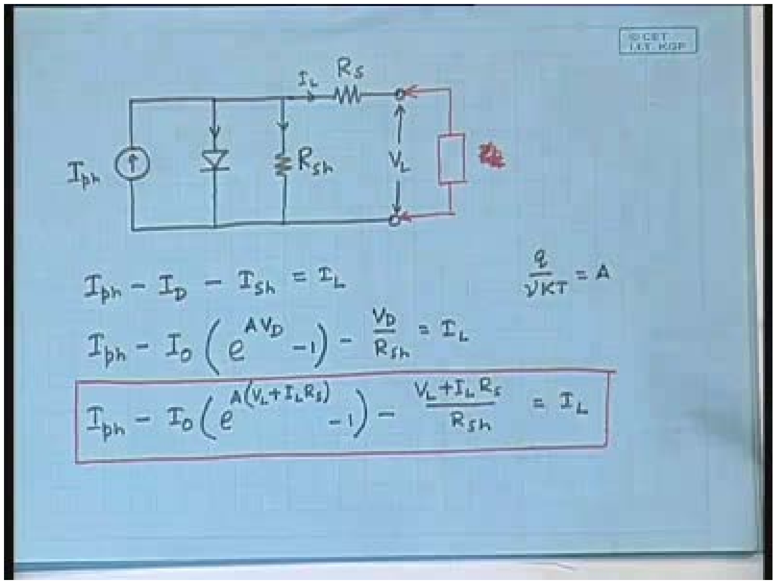

Now, if you want to find out what will be the characteristics if it is fed from the current source that means a photovoltaic panel, all you need to do is to link these equations with this; that is all and exercise that the final, the energy engineering students will do at the final year level, when you actually experiment with the machines.

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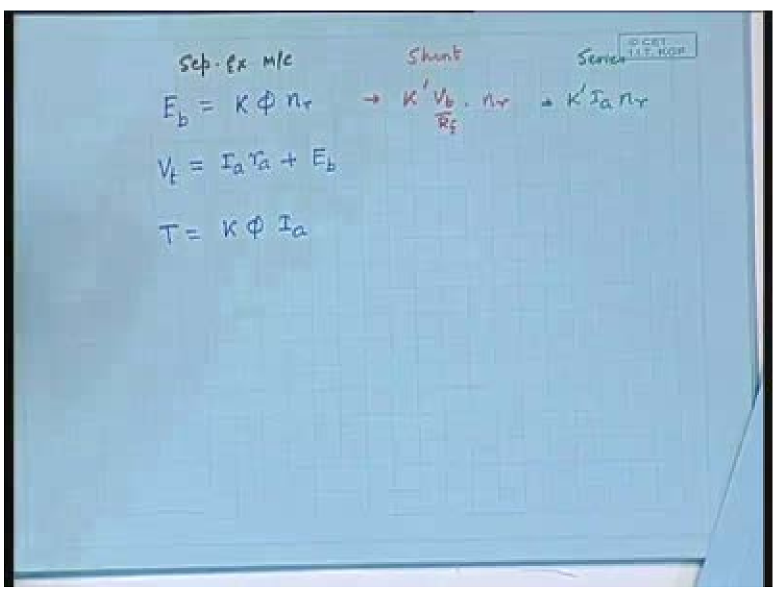

But, remember that this is the basic idea that these equations has to be linked with these equations to obtain the characteristic, actual characteristics of the series, shunt and separately excited machines as fed from the photovoltaic panel. But in general, you will, you might take home the message that series machines perform better with photovoltaic panels than shunt machines.

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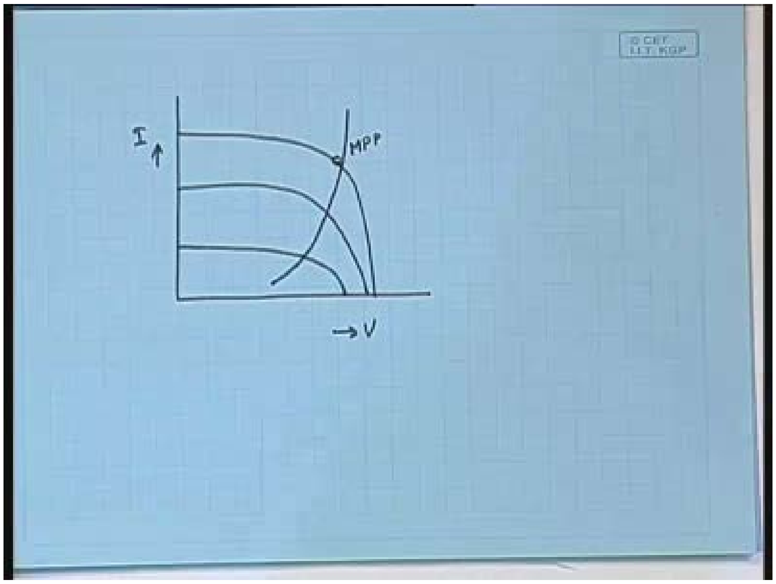

But now, you have noticed that the characteristic is something like this, the characteristic of the photovoltaic panel is something like this, where this is the voltage axis and this is current axis and here is a maximum power point. Depending on the load the operating point can be anywhere on this curve, but that means that if it is anywhere on this curve it does not extract the amount of energy that can be extracted. It extracts only when it is here. So, naturally it is necessary to have some kind of a maximum power point tracking. Why because, as the solar insolation changes, the characteristic changes to something like this, you have already seen that, right and as a result, the maximum power point has the characteristic something like this.

So, the maximum power point changes, the resistance that needs to be connected at the load to track the maximum power point that also varies with the variation in the solar insolation. Do you remember this word insolation? Insolation is not insulation. Insolation is incident solar radiation, insolation means incident solar radiation. So, depending on the insolation, you have a different value of load resistance that will give you maximum power. How to find out?

Now, one way as I told you is reasonably close tracking can be done, in case you are connecting a constant voltage at the load like a battery charging load, where the voltage is more or less maintained here, so that as it varies, it varies within a very small range and therefore, you are not very much away, but nevertheless there are other types of loads. For example, there can be motor loads, there can be heating loads, there can be various types of loads and then you need some kind of a maximum power point tracking mechanism. How can you do that?

This is normally done with the help of some power electronic circuit. Now, power electronics is something that you have not done yet, right, none of you have done? So, let me give you a very brief idea, because for energy engineers, electrical engineers, it will be a separate course altogether, you will learn in much detail, but nevertheless since not everybody will do that, let me give you some bit of idea, how it is done. See, there are a number of situations in which we need a DC voltage to be converted to another DC voltage. For example, all of you use computers and have you opened the computer, inside?

Those who say no, I will kick you off. What is it? You have to open a computer to see what is inside. You are becoming engineers, right you are not just users. So, inside you will find that there is a black box sitting in the back. What is it called? It is called SMPS, switch mode power supply and there are a few lines jutting out. These are actually 5 volt output, which means there are a numerous points that need 5 volt supply. In some computers there are also 12 volt supplies. So, you have in the input 220 volts and you need that AC and you will need a DC which is 5 volt and not only that, the input voltage can be variable, because you see, this normal power supply all the time fluctuating, but nevertheless a computer has to be protected and therefore output has to be fixed and that output has to be fixed at 5 volts.

How to do that? Not only that, the Pentium chip, most of you must be using Pentium chip, right, the Pentium chip needs a much lower voltage supply. Some of the Pentium chips need 1.2 volts. So, the 5 volt input has to be converted to 1.2 volt supply in order to give it to the Pentium chip. So, there has to be various level differences. If it were AC, you could have done it by simple transformer. But in case of DC, you cannot. So, there are situations where you need to step down a voltage, there are situations where you need to step up a voltage and these are simply done by, I will show two of the circuits by which it is done.

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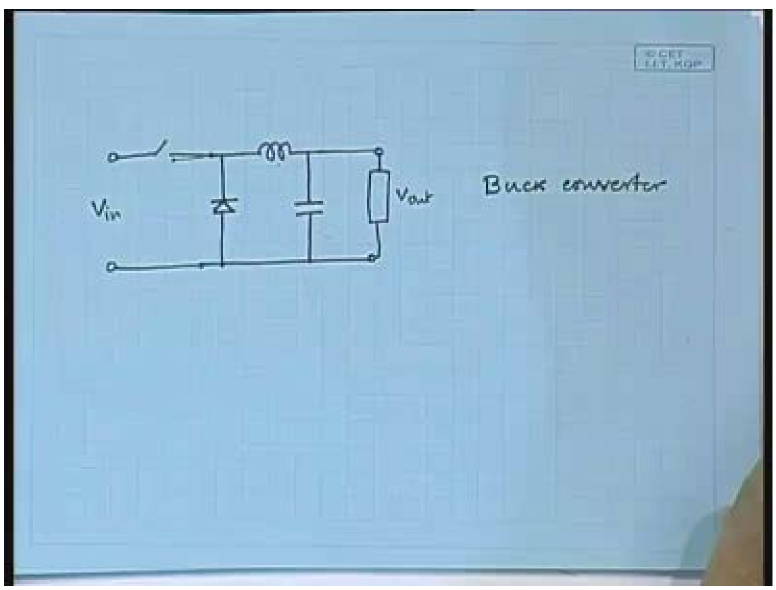

Suppose this is the input site, input voltage. You have first a switch. So, at this point you have what? If the switch is going ON and OFF, ON and OFF, ON and OFF, what do you have? Here you have a square wave and then the square wave is filtered and a simple filter can be just an inductance in series and a capacitor in parallel, so like this and here you have the load. Will it work? Let us see. When this is ON, then the inductor current goes up, the capacitor charges up and the current flows through this. When it is OFF, then what happens to the inductor current? No, you have, you have difficultly here, because the inductor current had some value before you switched OFF and therefore, the inductor has to, the current has to have a path, right.

You have learnt that the inductor current cannot be changed instantaneously. If you forcibly try to switch OFF, what will happen? The energy stored in the inductor will flash off across this. Somehow it will be, it will be dissipated. So, you need to allow the inductors current to have a path, so that it can flow, flow like this. So, when the switch is OFF, then this is the path and this switch is a not a switch where you can switch ON and OFF. It is an electronic switch that can go ON and OFF like a million times per second. So, you have very fast, not a million times, very standard values are 50,000 times per second to 1 lakh times per second.

So, you have the input voltage and here is the output voltage and since at this point you have the square wave and that square wave is filtered off, this output voltage will be smaller than the input voltage. The output voltage will be smaller than the input voltage, because the input voltage has been chopped. For some time the input voltage has been taken, for some time it has not been taken and then you averaged out. So, naturally the output voltage will be smaller than the input voltage and this is called a Buck converter.

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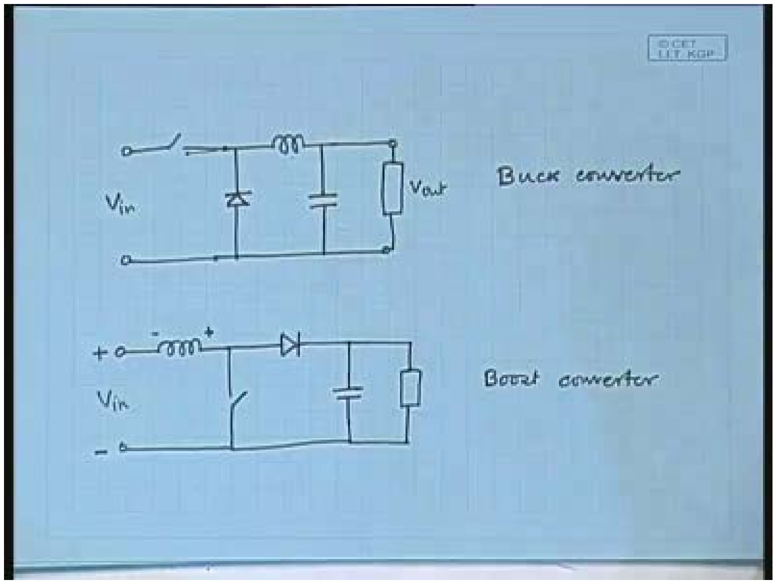

You might also imagine a situation where the circuit is something like this. Inductor is here, the switch is here, you have got the diode here, the capacitor here and the load here. Now notice, here is the input voltage. When the switch is ON, then it is only this, as a result of which the inductor current goes up linearly, because a voltage is applied across just an inductor. So, it will ramp linearly and after sometime when it goes OFF, then you have this whole circuit, then you have this whole circuit. When this whole circuit is connected, then the inductor current drops. The energy stored in the inductor is then delivered to the load, right. Inductor current drops, inductor current drops means the D i dt becomes opposite. So, here if the voltage polarities are like this, initially when it was ON it will be plus and minus, when it is OFF it will be reverse. So, this will be like this. As a result, this voltage and this voltage will apply across the load.

So, the load voltage will be higher than the input voltage and the capacitor has the effect of sort of smoothening out. So, what we see at the load is a voltage higher than the input voltage. So, this is called the boost converter. There are other converter topologies, but that I will leave for the later courses, but what is done in case of photovoltaic panels is that by means of either of these two you can have, at the output of the photovoltaic panel if you, if you connect this and then the load here, then by properly, you know properly switching you can fix the operating point.

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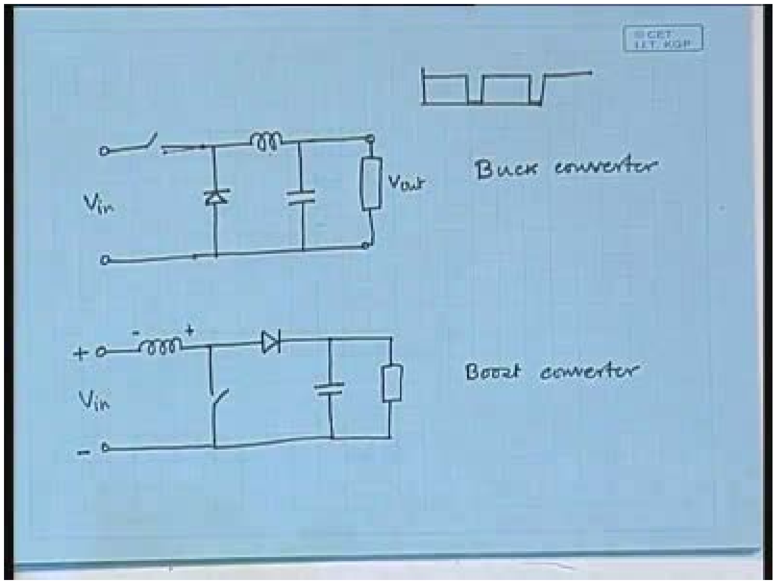

You can fix the operating point, because the load that this fellow will see, the load that this will fellow will see, depends on the switching or in other words, for example in this case, if it is switching like this ON OFF ON OFF, ON, so here you see ON is for a larger amount of time and OFF is for a smaller amount of time. So, if you change this ratio of ON and OFF, then obviously the amount of load that the input side sees will change. As a result, the operating point will change, fine; similarly here, similar in the case of the boost converter.

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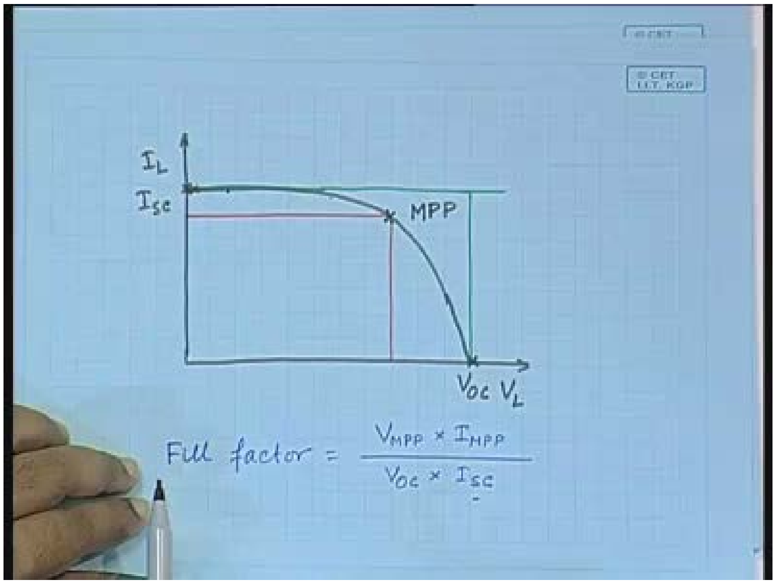

So, the point is that by changing the ON to OFF ratio, often this is called the duty ratio, the duty ratio, by changing this you can change the location of the operating point on the V-I characteristics.

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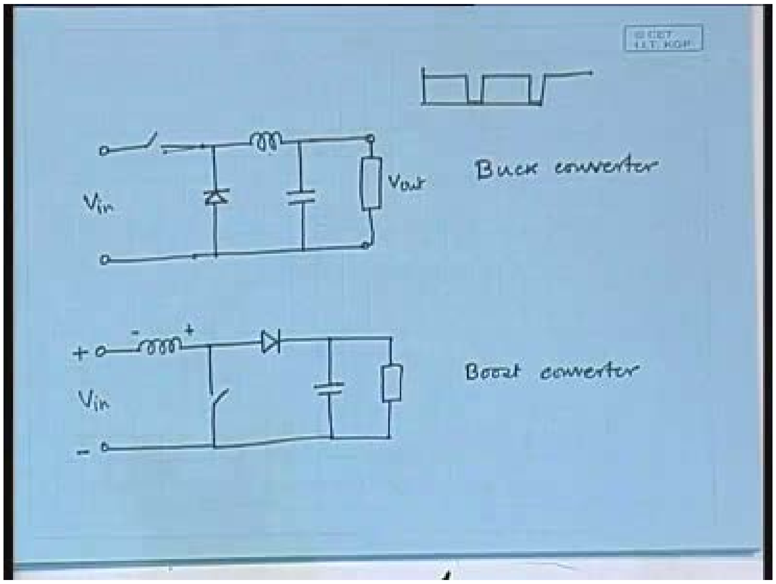

But one problem is there, you might notice, that in case of the buck converter, the switch is right at the terminals of the photovoltaic panel. This is a photovoltaic panel in this case input side and the switch is at the input of the photovoltaic panel, at the output of the photovoltaic panel, as a result of which when it is ON, fine; when it is OFF, there is no output of the photovoltaic panel. As a result, the operating point for some time it is here and for some time it is somewhere here; that is a loss. While that is not true for the boost converter, because the current is all the time flowing. All the time there is a voltage and all the time there is a, there is a current flowing.

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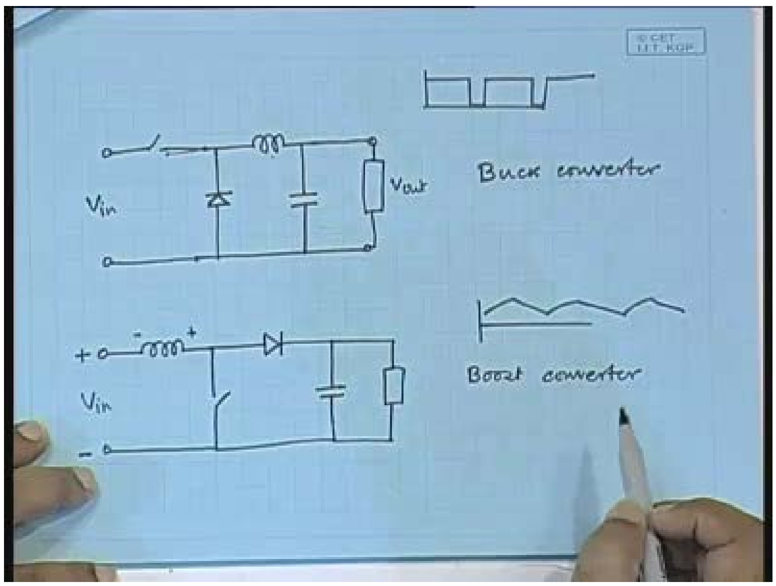

True, the current and the voltage will go like this, because when there is ON the current will go up, when there is OFF the current will go down and things like that. So, within a band it will go on oscillating. There will be a ripple and that ripple if it is adjusted to within a very short range of the MPP then, you are fine.

So, the next point is how to control the switching dependent on the position here. Now, there are a few strategies which I cannot detail with the current amount of expertise that you have. So, that you will have to learn at a later stage, especially the energy engineers among you will learn in at a later stage, but at present we can say that there are strategies and one of the simple strategies you can say in tracking any maximum, you might know the characteristic of this particular panel. You might know the characteristic of the particular panel means you might know the parameters that are used.

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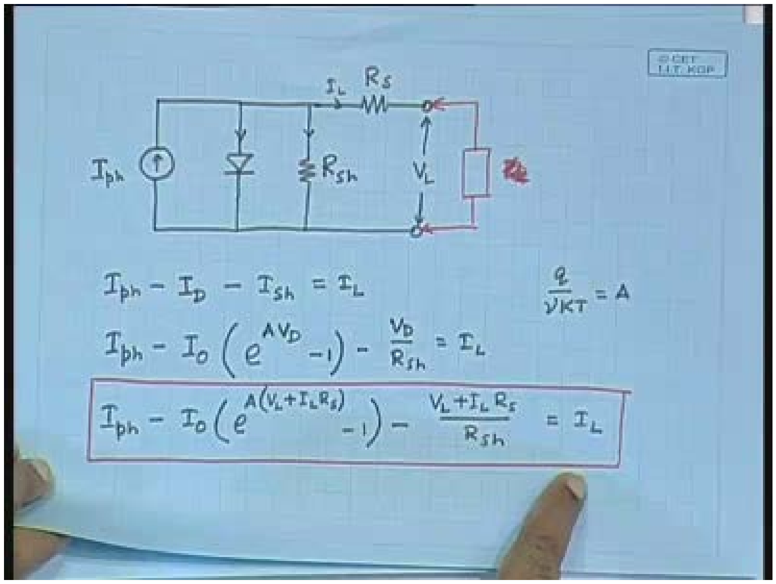

Where are they? These parameters as a result of which you are able to calculate this, as a result of which for any insolation you know where the MPP is and you track it accordingly, but that will require a bit of computation power. These are these days not a bit hurdle, because you have the required hardware very easily available. For any maximum tracking problem, the other approach is that if you multiply the voltage and the current that should be maximum.

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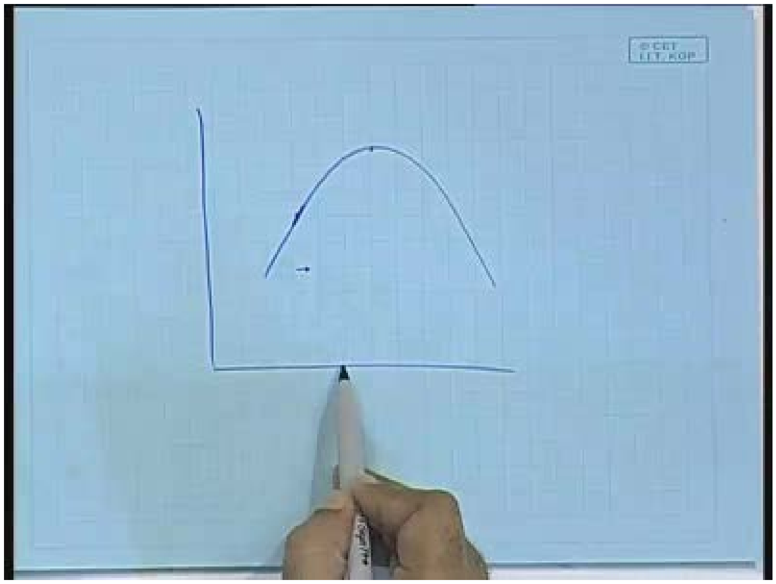

Now suppose you change; there was some duty cycle you change it a bit, as a result of which see the character of the, character of the power curve is something like this and you are trying to operate here. What is the character of this point, character of this point? See, if the point is here, then if you change it slightly, it varies by a large amount. But, if it is here, if you change it slightly, part of it slightly, it does not vary. That is the character of any maximum. So, wherever there is a question of maximum tracking, the simple strategy is that allow it to vary. In this case, allow the duty ratio to vary and observe what happens to the power? If the power does not change much means that you are on the maximum power point, but if it does change, then you know that you need to shift.

If it changes, if you increase this one and it increases, then you know that you will need to increase further, so, like so. So, this simple strategy can be built into the control loop, it is not a difficult business at all. So, the point is that for photovoltaic panels, in order to utilize the power maximally, you need to have some kind of a maximum power point tracking and this is mostly done by means of a power electronic interface between the actual panel and the load. Is that clear? Fine; let us come to the next point.

As I told you, each cell produces something like 0.8 volts which is insufficient for any use. So, we form a panel and in the panel there are something like 30 to 40 cells in series. That produces a panel, whose total voltage, voltage means which voltage am I talking about? The no load voltage that is the open circuit voltage that can be close to 24 volts to 28 volts. Now, this voltage can also be insufficient for some purposes. For example, if you are trying to run a motor that is rated at 110 volt, obviously you cannot have just one 24 volt source. You have to connect more of them in series. Similarly, if say you have a 24 volt motor, alright, but it needs more current, then you need to connect them in parallel. So, depending on the power rating of the load, the amount of power that you need to supply, you might need to connect the photovoltaic cells or panels in series or in parallel. What would be the character of that?

So, let us first consider the character of a, of two panels connected in series. Let us draw it by putting in the equivalent circuit of each panel.

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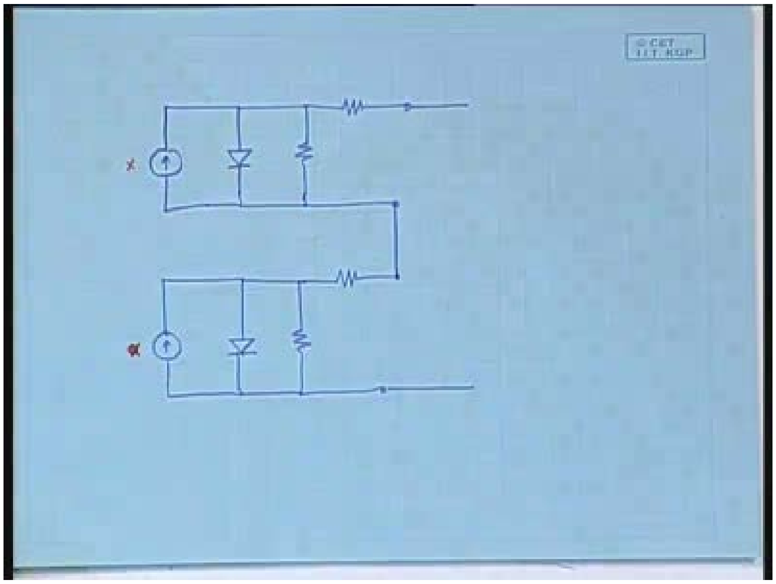

So, the first panel will be represented as this and the second panel will be represented as shunt resistance, series resistance, here. Now, suppose you connect them in series means what? Means you are taking …, right, fine. Now, so far so good, no problem, the voltages will add up as all series connections do, the current will be the same as in all series connections. Supposing you connect two batteries in series, the current, the voltage becomes double. But now, notice that both these are generating depending on the amount of incident solar radiation and it may so happen that one may be shaded, right. It may so happen that one may be shaded say, there are two panels and a trees shadow falls on one, it is possible.

When that happens, then this particular one will produce, say this particular will produce nothing or say, let this produce something and this produces nothing. This branch goes off. This is the photocurrent branch, this goes off, but this fellow is still producing, right. So, what will be the path then, path of the current? Notice my finger. This is not there, this one is not there, so it is going like this, going like this, a part of will be shunted, a part will be shunted, but the main branch will go like this and then it will try to go. Now, this is a very large value, so it does not have a path here.

This is a reverse biased diode, it does not have a path here. This is not existing, it does not have path here, which means the current will have no path to flow, alright and as a result, the performance of the whole system will be drastically reduced. Is that clear? The current will have no path at all and that is also true, because when you connect a large of number of cells in series in order to make a panel, if say one is shaded then that effect happens. If one is shaded, then there will be a drastic fall in the production of the panel. So, shading is a problem. If shading is done, if there is a cloudy sky, no problem, but then all has to be shaded similarly. If not, if you think that there are some active, but the others are shaded, now still the behavior will fall drastically.

So, sometimes in some systems, they add an additional diode across something like this.

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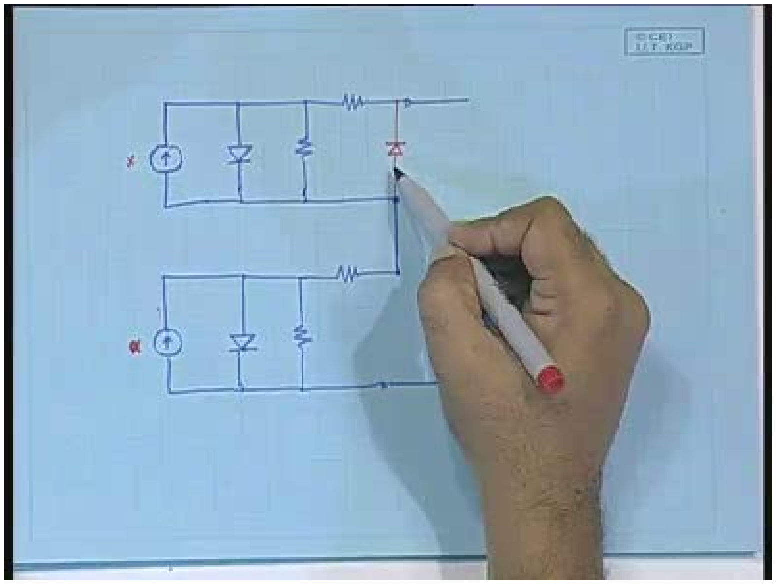

This is the terminal. If you add an additional forward biased diode like this, so when it is producing like this, this is reverse biased and therefore it will have no effect, but when this kind of things happen, then it is a path. This is necessary for two reasons. Firstly, firstly if say this is not there, then the amount of photocurrent that is generated has to be dissipated somehow in this one. As a result, a result of which, even though the current is small, this resistance is large, so there is a I square R loss here. So, there is sometimes hot spots generated.

A particular cell heats up. The one that receives no solar energy, which is shaded, heats up more and sometime that results in damage of the cell. This can avert that damage and moreover, whenever there is shading in a particular cell, if this diode is provided, then it can allow the path. But, providing a diode for each cell makes the cost high, as a result of which most of the panels that are produced today in India, you will find that this diode is not produced, not given. So, you have to be a bit careful about the shading problem.

Let us now consider the cells connected in parallel. So, if they are connected in parallel, for anything connected in parallel, there is a problem.

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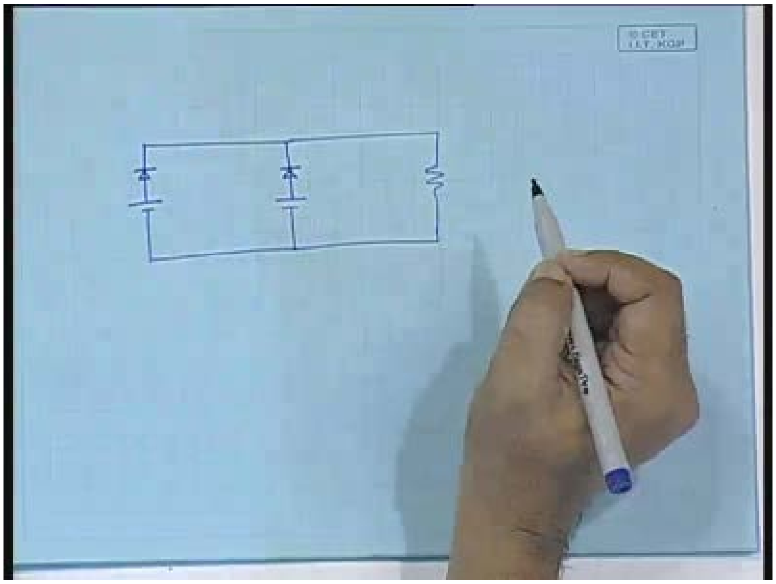

For example, there are two batteries connected in parallel to a load. Do you see a problem? Actually none, if the two batteries produce the same voltage, then the currents will be exactly shared and finally the total current will flow through this. But, if the voltages are slightly different, then there will be a circulating current. The circulating current will play no role in providing the load. A circulating current will be completely lost. It will result only in the heating of the two batteries and naturally that is detrimental to the health of the batteries. So, this kind of problem also has to be avoided in case of photovoltaic cells, because it is very rarely the case that two cells are absolutely identical, produces the same voltage, producing the same current.

So, one has to avoid the flow of circulating current into panels and that also can be avoided by producing, providing, suppose this is the current direction, this is the current direction. If you provide batteries, provide diodes like this, then obviously the flow of the circulating current can be avoided. The same thing is done in case of photovoltaic panels. This is just one diode provided for the whole panel, because the panels have to be connected in parallel. Individual cells are never connected in parallel, because you need a larger voltage, so individual cells are always connected in series. When there is a question of connection in parallel, this diode is mostly produced. For example, earlier in the, in the 80's many Indian manufacturer did manufacture panels without this diode, but nowadays the ones that are coming mostly have the diodes built in. So, this is another precaution that one has to take and obviously this problem will be larger if one is lit, another is shaded, because then the two voltage will be quietly different. Is there anything that I have not yet covered in photovoltaic cells?

The present status of photovoltaic technology is that because it is mostly dependent on the production of single crystal, as I told you the single crystal production process is very slow, you have to melt the material and you have to put the seed and the seed has to be drawn up very slowly, so that as it goes up the single crystal forms as a cylinder. This process is very slow and for any slow process, the production cost is very high and moreover the problem is that this ingot, as it is called, is not produced in India. So, all the Indian companies import this ingot and make the photovoltaic cells out of that. As a result, the total cost of production is larger than the cost of normal commercial power. But, the places where we do not have regular commercial power, for example the islands in Sunderbans, for example Ladakh, where it is extremely difficult to take the power lines, in those situations this is the most economical and convenient source, because we have sufficient amount of solar power.

India is thinking in terms of commercial generation of power by means of solar, by covering a large tract of area with photovoltaic panels. For example in the Rajasthan deserts, if you have a large amount of the, large area covered with panels, there is nothing actually produced there and the most convenient production is power production, because there is enough amount of solar energy that is available without any cloud cover and India is pursuing those options. Some of these relatively large projects are undergoing. But since, you might argue, that since the cost of the, cost of production of photovoltaic cells, photovoltaic panels is larger than the commercial power that means even though after it is used, after it is purchased there is no further expenditure on it, except for cleaning it occasionally, there is no expenditure.

On the other hand, if you buy commercial power, then that commercial power has a running expenditure. You have to pay. But, normally the way it is done is in terms of payback period, the calculation is done in terms of payback period. If I buy a photovoltaic panel, over what length of time does it pay for itself in terms of saving from the commercial power? Now that payback period is yet relatively high, but not prohibitively high. As a result, there are many situations where people are now going into a reliable source, because in India photovoltaic power is a very reliable source. In most of the rural areas, photovoltaic power is a reliable source; commercial power is more unreliable, ground reality is such.

So, in many states people are buying the photovoltaic panels out of loan and they are paying back out of the saving that they have from the regular supply. For example, one of our ex-student, he is based in Karnataka, there he is making those systems and people are taking bank loans and buying those systems and the whole thing is paying back over a period of say, 12 to 15 years. But nevertheless, over this 12 to 15 years, he has assured power supply, does not depend on whether or not the power is available to the grid and after the payback period, it is their own. So, obviously this is now becoming a commercial success. It was quite, quite surprising to me that something that is not yet commercially comparative with the commercial power is becoming commercial success, because of this factor that people do like to have a reliable power source in their house and these things are now readily commercially available.

In many states the government is giving subsidies. That means if you buy, the government will give you 50% subsidy, so that it actually becomes competitive with the, with the commercial power. So, there are many applications for which now we can consider photovoltaic panels as a source. Most importantly the rural irrigation; rural irrigation is obviously the nice area. Why because, when there is huge amount of solar radiation, that is the time when you need the irrigation. So, the timings are exactly the same. When there is cloud, cloud cover, you do not need it; you do not need any irrigation. So, if you have a couple of photovoltaic panels coupled with a simple DC series machine coupled with a pump, you simply take it to the site; that is enough. So, that is why photovoltaic power is now, you can say as a take home message, is becoming commercially competitive. Most of this, most of the other power sources are not. But, there are two sources which have now become commercially competitive with the conventional sources. One is photovoltaic power, the other is wind energy.

I will come to wind energy a little later, but photovoltaic power has now become commercially viable and commercially competitive. One of the things that might, you might see in some locations that is the solar street lighting system. What is this solar street lighting system?

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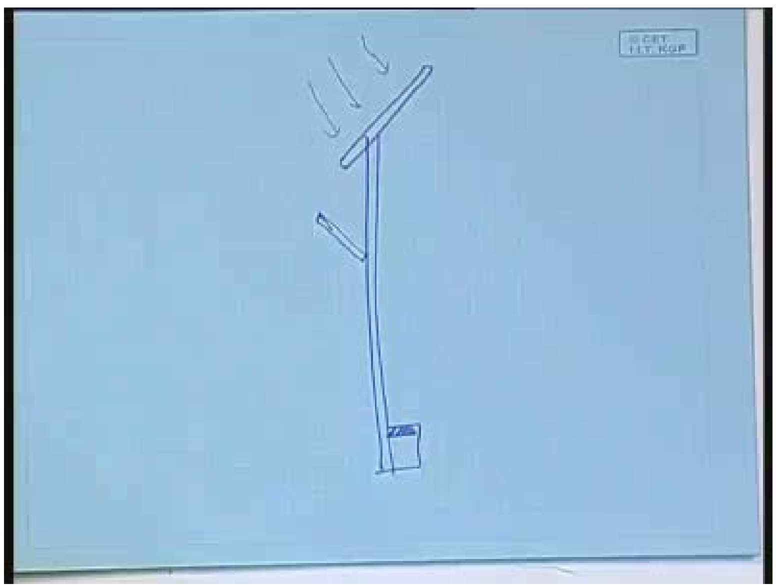

You have the pole for the street lighting. On top of it you have the solar panel like this, which is receiving the sun, inclined at an angle equal to the angle of latitude. Yes, inclined, because this is, this this cannot be moved all the time. It is at the top of the pole and therefore, it has to be inclined at the latitude angle and then the wire comes down. At this point you have got a simple box containing the battery and the, not only the battery, battery will give you a DC voltage, but in order to run a, what is the most efficient lighting system here? A tube light, right, so you have to have some kind of a system to light a tube light. It is not the normal incandescent lamp, because they are energetically less efficient. So, you have to have, the tube light will be placed somewhere here and you have to have some kind of a system as an interface.

There are two kinds available. Either you can use simply as a DC tube light. Tube lights also work in DC, I suppose you know, but for that the voltage has to be boosted up to the level that is necessary for the tube light and that is what is done by a small power electronic circuitry stationed here or it can be converted to AC and the tube light is used. In the house, in the home systems, you have the similar system with charging, but at the end of the charging you have got an inverter. That inverter puts the power back to the same line, same grid, so that when you have sufficient amount of solar energy incident on the panel, then you have simply some reduction of the power that you purchased from the grid; that is all. But, you have, when there is, there is a load shedding or something like that then, you have a reliable power supply. So, many households are buying this kind of a power supply.

In many such cases you have a relatively remote region in which you will need power for other reasons. For example, some community, community hall for which you need a power, place where students come and study you need power, place where you have the rural industries working, rural industries, what kind of rural industry you can think of? Cutting, cutting of straw, that is one of the things that is necessary, boiling of rice for the purpose of producing the, not eating, but you know, dried rice before it is milled, it has to be boiled in the, along with the husk. So, that stage can be done using the energy that is produced here. So, there are many stages that can be done in remote locations by using the photovoltaic panel, because photovoltaic panels are so easily available these days.

In India, we have 3 or 4 companies producing single crystalline photovoltaic panels. There are 1 or 2 companies producing polycrystalline photovoltaic cells and as yet there is none producing amorphous silicon photovoltaic cells. Amorphous silicon, as I told you, can be made into thin sheet, thin films and naturally the cost is very less. But, also the efficiency is low, but that offsets itself. Amorphous silicon solar panels we do not have as yet. Now, the research is going in a few directions in this line. One, how to make more efficient photovoltaic cells? People have reached efficiencies close to 30%. 30% is quite good efficiency, but that is only with the single crystal photovoltaic cell, single crystal silicon cell.

Other materials are being considered. For example, cadmium telluride is a material that is being considered for thin film solar cells. Cadmium sulphide, copper sulphide is a material; cadmium sulphide and copper sulphide as two p and n layers that is being considered as a material. All these are considered for production of thin film solar cells, where the idea is that if you have any surface you can simply coat it with a photovoltaic panel. For example, your car, the top of your car is coated with photovoltaic panel. So, when it is stranded, it generates power. So, you can have such systems also and the technology to use that power for a, for a, you know, traction system that is also maturing in the sense that in many countries, they have solar powered cars race.

For example, in Australia there is a race, in USA there is a race and typically undergraduate students have to take part in that race. That means they have to make a car in which they have to put the photovoltaic panels in a proper place and the rest of the things to make the car, to make it run and the car that wins the race is maximally using that power. So, there is a race, I mean there are awards for this race. So, in fact, some of our old students have made photovoltaic powered cars and they have participated in such races in USA. So, you might also consider making a car yourself here and show people that that such things can run. So, there are a large number of ways in which the photovoltaic power can be effectively used in industry as well as household as well as in various areas and when you become full grown engineers, the picture is definitely going to be more rosy, because with every passing year, the cost of generation of photovoltaic panels is going down. As a result, this is becoming more and more competitive and since it is pollution free, nice system, about pollution free, one thing you have to remember.

Many of the materials that are now coming to the market like cadmium telluride, copper sulphide, cadmium sulphide, these things are toxic. So, disposal of the photovoltaic panel poses a problem. So, in case of the silicon cells it is not all that a big problem, because silicon is not a toxic substance. It is everywhere, silicon oxide is everywhere, sand is silicon oxide. But, the other materials pose some disposal problems. That one has to keep in mind, but otherwise photovoltaic power is completely clean without any problem. So, you need to have a proper development of the technology, in order to use it more effectively in future.

Take home message is photovoltaic power is in. Out of all the different technologies, photovoltaic power is definitely going to stay with us for a long time and you should be very well placed to understand and to be able to use it as an energy engineer. That is all for today.

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Photovoltaic panels, both manufactured in India. The right one as you can see, both were initially manufactured with circular cross sections. The reason is very obvious, because the ingots from which these are made are all made in form of cylinders from which these are cut. So, these are circular cross sections. The ones to the left were of larger circular cross section from which these were constructed. Now, if you look at each individual, individual cell, you will find that there is a grey part which is actually the silicon that is exposed to the solar light and there are the grids. These grids are, as I told in the class, these are, these are later put over the surface by means of some kind of a lithographic technique, screen printing like technique and there are different designs of those fingers, top fingers in order to collect the charge. At the bottom, you have a simple substrate, metal substrate on which the silicon is laid and that metal substrate acts as the charge collector. All these individual cells are connected in series in order to make this complete panel and each panel would produce something like 30 volts and therefore, if you need a larger voltage, panels have to be connected in series or parallel in order to get the proper voltage and current needed for that specific application.