Fundamentals of Power Electronics

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Lecture - 01
Familiarization with Power Electronic Systems

I am Vivek Agarwal, I am a faculty at IIT, Bombay in Mumbai, and welcome to this course. I am delighted to have you here for this course we will try to cover several aspects of power electronics in this course.

Before starting with the formal content of this course I would like to do a Layman's discussion, some questions, some suggestions, some answers. Let us try to start with some of the very basic things related to power electronics. And what we will do is we will just try to first see some of the very common examples around us which we do not know by the name of power electronics, but they actually come from power electronics. This will strengthen our belief that power electronics is an important area, it is a very important subject.

Now, I am not sure how many of you have very deeply thought about the power electronic applications around you, but let me ask you a question have you ever wondered what goes inside a power supply that is used in a laboratory. When you were in your junior classes I am sure in even in your class in your high school, and you know even higher classes senior school and so on, I am sure that you were doing experiments which were involving power supplies.

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So, for example, you must have seen these kinds of you know equipment in your lab and I am sure that you have played with some of these knobs. What you see here which are basically you know this is for the voltage and the current adjustment which is coming out of this power supply. And here there are displays where you can see how much current and how much voltage is being is coming out; how much current and how much volt is coming out, and these are the two terminals from where you tap the power supply.

So, you adjust your voltage to 5 volts or 10 volts or 12 volts or 15 volts, whatever you like by using this knob and through these terminals you actually are able to feed the load. So, this is what you did in your lab experiments in your junior classes and even later on. So, these supplies are actually used under all you know at all stages of you know our academic and research work.

Now, let me just ask you another question the desktop computer, everybody is using a desktop computer today; are you aware that what kind of power supplies they go inside this desktop computer to make it run. Do you know what are the various voltages and the currents which are required by the various portions, various sections of this power supply or the or your desktop computer? Are you aware of this?

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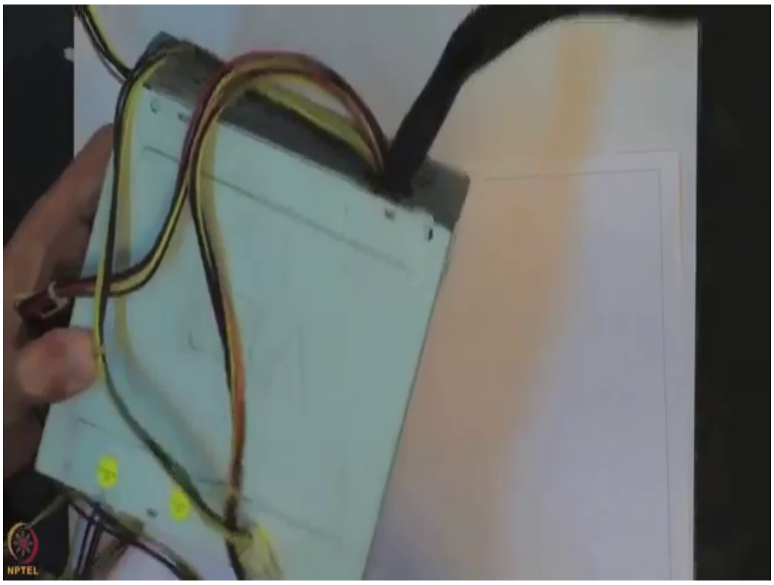

So, let me just show you one supply which I just took out from a desktop computer, ok. Here, so this is the supply, it is a box as you can see which takes you know a 230 volts, 50 hertz AC supply at one of its ends here, the input socket and it gives out these are the various outputs which are coming out, it gives out voltages various ranges 3 volts, 3.3 volts, 12 volts and so on. So, have you ever wondered what goes to make up this kind of supply, what is there inside this supply. Let me explain to you.

Now, I showed you in the computer power supply that there is a 230 volts input AC inputs, so that is a primary supply. And this has the AC supply, this is actually a result of a war which was fought in the late 19th century which is called the war of currents where there was a war between the AC systems and DC systems, where people like Thomas Alva Edison supporting the DC kind of power systems and people like Nikola Tesla and Westinghouse support the AC systems.

And eventually it was the AC system which won and as a result of this you now see AC systems everywhere in the world. So, that is the reason. So, we get AC supply, it has lot of advantages. For example, boosting you know of the voltage is possible, transmitting over long distances it makes the efficiency very high, if you boost the voltage before you transmit it over a long distance. So, it actually gives you all those advantages. So, that is why you have a AC system everywhere followed in the world.

Now, you have the AC system but inside the computer you need various DC voltages. So, what do you do? So, you have a 230 volts AC voltage which is coming in which you plug in to your computer and inside there is a system which converts just like a box which I showed you it converts this 230 volts AC into the appropriate levels of the voltage which are required in the various sections inside the computer. So, let us just draw this and see what exactly is happening.

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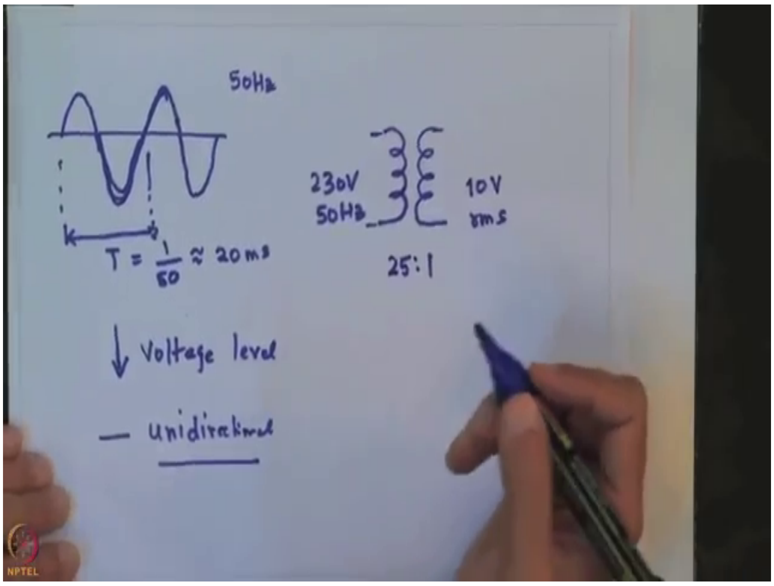

So, what we are getting from the AC wall sockets is 230 volts rms AC supply this is what we are getting. And in India the frequency of this AC is 50 hertz which means that if I just take one of the time periods between that is for one cycle if I take the time period and I call it T this is equal to 1, T is equal to 1 over 50 which is about 20, which is exactly 20 milliseconds. So, this is the kind of voltage that we are getting from the AC wall socket.

Now, what we have to observe here is that this is a bipolar voltage, it has both positive and negative sides. We are looking at a DC voltage. So, first of all we want to limit the direction of this waveform to only 1, we want to make it or keep it only positive we want to make it unipolar that is one thing. Secondly, the voltage range which is required in the computer for the various parts of the computers its various circuits is very low, it is about 3 volts, 12 volts, or maybe at the move some 18 volts and things like that its very low.

So, we are getting a voltage which is having an rms value of 230 volts and if it is a sinusoidal voltage we can say that the peak is 230 into root 2, that is the peak of the voltage. Now, we want to derive from such a waveform from such a voltage we want to derive very low DC voltages. So, there are two things that we can say here that we are going to first of all we need to reduce the voltage level and the second thing is we want to make the excursions of the voltage which is currently both positive and negative in the AC, we want to make it unidirection or unipolar. These are the two things we want to do.

Now, we all know that to reduce the voltage level we can use a transformer. In advanced modern systems voltage transformation is achieved using high frequency transformers which are integrated with the power electronic systems itself. Low frequency transformers like the one I will describe now are seldom used; however, to keep the explanation simple and till we cover the high frequency converters in this course I will explain this computer supply problem with the help of the ordinary 50 hertz independent transformer.

So, let us say we now apply a transformer and we are looking at something like let us say 12 volts and we are looking at something like 12 volts DC that we wish to apply to one of the sections, to one of the portions of these circuits which are employed in the inside the computers. So, this is the transformer. Now, if I apply the incoming 230 volts, 50 hertz to this transformer and let me just decide the turns ratio of this transformer as something like 25 is to 1, approximately. So, what we will get is we will get approximately 10 volts rms on the secondary side of this transformer, approximately. So, voltage reduction is possible, but then as you can see with the transformer once you have placed the transformer you will get a fixed output, given input voltage of 230 volts you have fixed the output voltage once the turns ratio is decided.

Now, how do you make it DC? We have the AC coming in how do you make it DC, how do you make it unidirectional. So, for this let us try to understand and recall. I am sure we have all seen the operation of a diode rectifier. The diodes are semiconductor devices which came up in the last century and they have kind of revolutionized the way we process power. So, they are very very fundamental and basic units which are used, devices which are used in power electronics. So, I am sure that we have all seen diodes.

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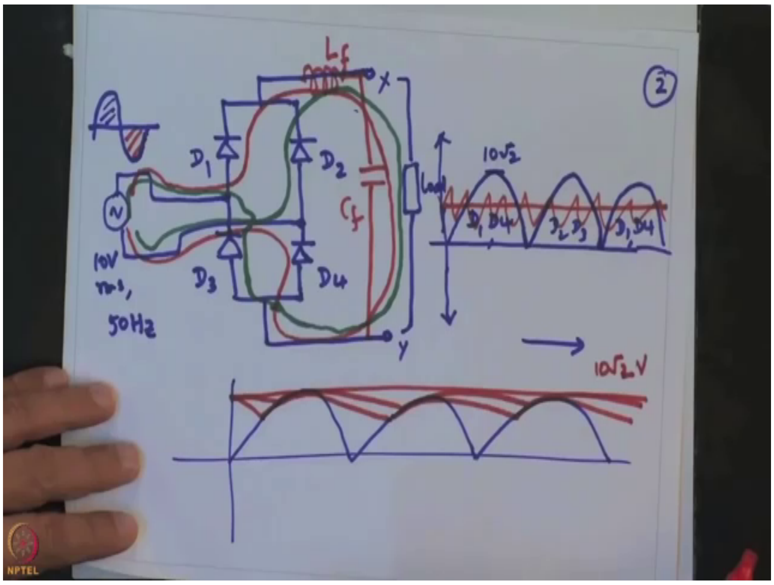

So, let me just form this is very customary, very very familiar looking circuit very very familiar circuit, we have done it at very junior classes as well. So, everybody is aware. So, this is nothing but a diode bridge rectifier circuit what I have drawn. And what you see are these D 1, D 2, then D 3 and D 4, these are the four diodes which are used in this rectifier circuit. These two points are tapped outside. Let me just mark them as X and Y and these indicate the output of the diode bridge rectifier.

And what goes to the input of the rectifier? So, the input of the rectifier we now supply the voltage that we got from the transformer which is about 10 volts rms. So, we have a AC supply of 10 volts rms. Mind you the frequency is 50 hertz, we did not do anything to change the frequency. So, it is original 50 years that we are getting with our wall socket of 230 volts. Now, this voltage is what we are applying, this AC voltage is what we are applying to these various these two points of our diode bridge rectifier. Now, if I activate this circuit then what would I expect to see at terminals X and Y. Let me just draw the waveforms what you will observe at terminal X Y. We will just see what waveform we will see here.

So, now, if I was to draw the AC voltage that we have obtained in the on the secondary side of the transformer then you can see that during the positive half of the cycle the diode D 1 and D 4 would be conducting. And the path of the current in that case would be as shown here completes the path. And of course, we can always assume that between

X and Y there is this load, this is that section it represents that section of the computer where you want to apply the voltage 12 volts where you want to apply the 12 volt, for which you are doing all this arrangement.

So, let us just call this as load here, ok. So, when during the positive half cycle of the input supply D 1 and D 4 they get forward biased and they when they conduct its like opening the gates, ok. The D 1 and D 4 they are now able to conduct and basically somebody is standing at terminals X and Y is able to see what is there on the input side through D 1 and D 4. So, basically whatever it is a portion of the input supply at that time when D 1 and D 4 are conducting would appear across the terminals X and Y. So, this is what you will see.

Now when the voltage, the applied AC voltage becomes negative as here in this case, now you will find in this case that D 2 and D 3 will get forward biased while D 1 and D 4 will be cut become reverse biased. And now when D 2 and D 3 are forward biased the path of the current or the conduction would be as shown here with a green color, through D 2 anode causes the cathode through the load back, and now this time it is not going through D 4 it is actually going to D 3. All the way here and then back this is how it completes the path.

So, what do you see a terminals X and Y during this time though, what would we see? So, what we will observe is now we will get another lobe because as far as terminal X and Y is concerned if you notice that whether it was D 1 and D 4, when they were conducting or whether it is D 2 or D 3 when they are conducting they are seeing a current which is going from X to Y the direction of the current has not reversed. So, basically it is a unidirectional current that is flowing they will see correspondingly.

Now, a voltage the input AC voltage which is the negative part but will be seen here as inverted and so you will find this lobe which will appear now the second one and the cycle repeats. So, D 1, D 4 conducting here, D 2, D 3 conducting here, and again in the next half cycle of the input AC supply you have the D 1 and D 4 conducting, and again D 2 D 3 and this goes this cycle goes on, alright. So, now, what would be the peak of this voltage or approximately what can we say about this voltage? So, this voltage would be having some value which we can say is about 10 root to peak value or we can say that the average or the DC value of the voltage across terminals X Y will be let us say some way at midway between 0 and 10 root 2 volts, approximately.

And I can probably if I was to draw this voltage, I will probably draw like this. But the problem is that it is not so nice and constant as it appears in this diagram because of this vast variations here the peaks and the valleys as you can see this voltage is not going to be like this. So, the load will actually see a highly pulsating DC waveform this is good for the load. People who are working in this area for a long time they know that what would happen to the various equipment when you apply this kind of voltage across them, their life will be shortened, they will be heating effects for example. So, one has to reduce them. So, what is the solution for doing this? The simplest solution for this is to basically place a capacitor.

So, what we do? We just place a capacitor across terminals X and Y and we just call it in a C f, we just call it by we just denote it by C f. It is the term which is used for filtering. So, basically you put this capacitor which filters out this very large ripple which is there in this DC voltage. Now, if the ripple is very large your capacitor value C f tends to be very large and to reduce that value some people, they actually implement little different forms of the filters. There are various different forms of the filters and one of the very common is where you just actually insert one additional L, here L f as part of the filter which tries to reduce the current ripple and hence the capacitor has to bypass a lower amount of ripple current and its value can be less. So, if you want to reduce the value of C f you can use some inductor a filter inductor L f also as part of the filter in the circuit.

So, what is the result of putting this L f? If we look at our diagram, so let me just redraw my diagram where I showed the output voltage across terminals X and Y. So, it will be something like this, it is the original waveform but now with the placing of the capacitor C f it would become like this. If I still increase the value of C f it will become like this. And if I also put one L f along with it then it will become still flatter. So, basically I will be able to get assuming that we have put good enough values of C f and L f, I will be able to get a nice waveform here whose value will be 10 root 2 volts, approximately, that is what we will get and this is what we can think of applying to the various to the required to the concerned section of the computer power supply.

So, basically you know there are various such circuits that you can imagine are present inside the power supply of the computer which I showed you. So, let me just open that supply for you and try to let us try to see what is there inside, ok.

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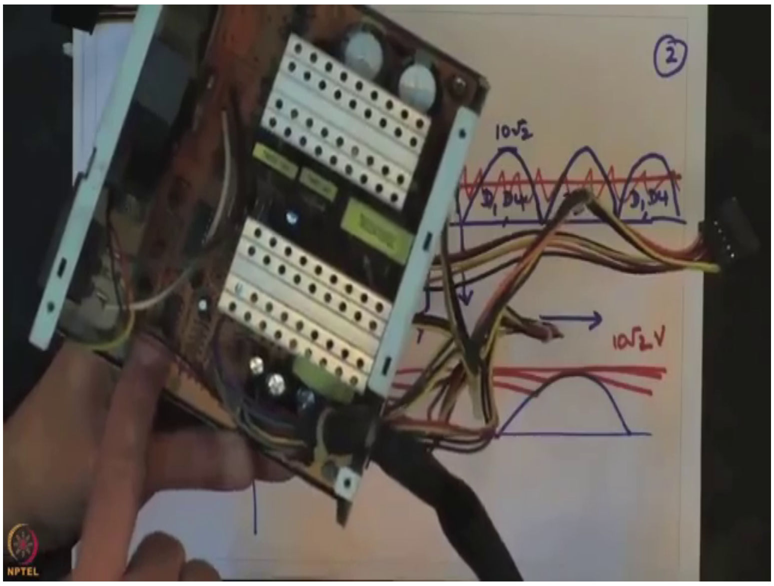

So, I can see some transformers there and I can see some huge syncing here. So, there are some heat sinks which are for dissipating the heat away from the devices which are used in the power electronic circuits, I can see you know the device is mounted there, I am not sure whether they are very clear but actually they are right there some of the devices. There are capacitors, they are very small capacitors.

And what you see other than that is you know some electronic components, some integrated circuits ICs, some resistors, some diodes very small diode they are called small signal diodes. I can see a fan here which is actually used for fan cooling for cooling forced cooling of the devices which are used in this circuit.

So, these heat sinks will provide limited protection against heat, even on top of that we would need additional cooling which is done through this force convection through the fan. So, there is a fan there if you can see. So, I will come to the details of this in we will actually look in into many more details, much more details of these various components, various things which are used in the supply as we go on in this course, but it is just to give you the field. So, this is all power electronics. So, as you can see how electronics is used extensively to achieve these various voltage levels from a given voltage supply, ok.

Now, one of the problems that we have with the power supply that we have seen as an example just now we kind of analyzed we look at its working and so on, one of the issues is that for a given input AC voltage which was about 10 volts rms we were able to get a fixed value of the output voltage across terminals X and Y. It is frequently the case that we have to vary the voltage across a load for controlling it. For example, a motor or a light bulb etcetera. The uncontrolled AC to DC system we discussed so far cannot achieve this, we not only need different voltage values to apply to the loads but also need to regulate them or hold them constant with changing operating conditions, irrespective of the changing operating conditions.

So, this is the voltage regulation problem which is a very very fundamental problem which is addressed in many, in fact most of the power electronic systems in were some form or the other. So, what is the solution? And what exactly happen? Why is it that we are not able to vary the output voltage? Well, the reason is that you are using diodes, and these diodes the moment there is a forward voltage occurring across them they conduct and they cannot be controlled you cannot once the voltage is a pencil for it what would voltage is appearing across the diode you cannot control the diode anymore, it will conduct there is nothing you can do to prevent that.

So, the question is if I can control the diode, so I can somehow have a mechanism by which I can have the forward voltage held up, or opposed by the diodes. In the face of a forward voltage also there is a way that this device does not conduct till I ask or till my circuit requirement asks it to do then I can probably achieve what I want to achieve that is to get a constant voltage at terminals X and Y which appears across it.

Now, going further ahead let us assume that we are using this imaginary device. And let us just for a minute we say that you know these are the properties of this device. So, I will just redraw the device which I introduced last time.

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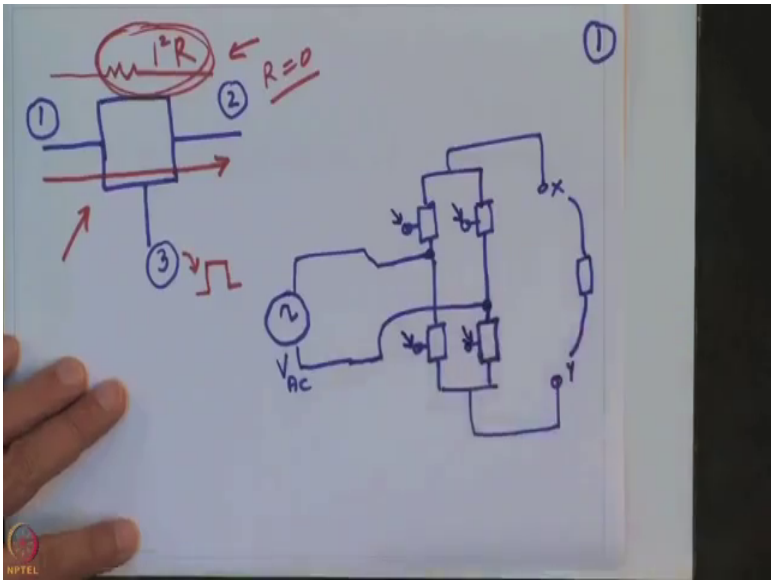

And it is a three-terminal device where the terminals are marked, like this. Now, let us make certain assumptions about this device, let us say that the conduction of current through this device can only take place from 1 to 2. Now, this is quite understandable if you contain it with a diode the conduction of current in a diode can always take place from anode towards cathode. So, based on this is the assumption that this device can conduct only from terminal 1 to 2, it cannot conduct from 2 to 1. It can conduct only when you apply a control pulse to terminal 3, ok.

Now, based on these assumptions and probably another assumption we can make is that when there is a conduction taking place across this device from 1 towards 2, let us also assume that there are no net I square R losses which are taking place. Now, why do I talk about this? This device after all is made up of some material, and we will see eventually that this is nothing but a semiconductor device and this is made up of some material. So, depending on the technology used the material used and its operation, and its mechanism, it will actually offer some resistance to the current that is going to go from 1 to 2. And they will be I square r that joule heating we know joules heating effect that loss will take place, and actually it is this loss which appears as heat across the junction of the semiconductor devices which actually make the what is called thermal management very important.

So, in the computer supplied, power supply which I showed you I did try to tell you that there was a heat sink onto which these devices were mounted, and I also mentioned about forced cooling. These are all components of a thermal management system which are trying to take care of all the unwanted undesirable losses like the one shown here the I square R losses.

So, let us say for at least for now that this is not there. So, we have actually an ideal device where R is 0. So, it does not offer any resistance to the flowing current. So, such is this device. So, let us say we are talking about an ideal device all these devices which I mentioned they have if they are ideal, they will fit this description which I just gave for this device.

Now, let us go back to our example of the rectifier but now replace with this special device. So, let me just redraw this modified rectifier with some voltage V AC and I am just showing another terminal. So, instead of diodes I am putting this third this is a special device, later on we will see that some of these semiconductor devices which I mentioned to you they could be actually replacing this device. As before there is a load which is connected to X and Y which are again marked here and my AC supply goes here and goes to this midpoint. So, for all the devices I have marked a control terminal. This is the terminal three of the special device.

Now, let us see how the operation of this circuit would take place and what we will achieve or obtain at the terminals X and Y in this case.

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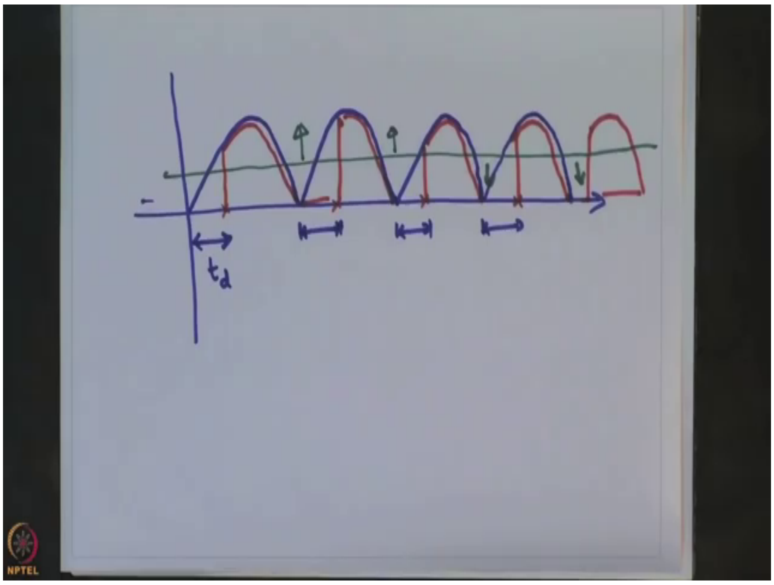

This is just the background waveform this is not what is going to appear this is just for reference. Now, let me just use a red color and let us say that the pulse control pulse through to the third terminal the control terminal is not applied up to this point. The individual pair, the corresponding pair of these special devices they are not supplied up to this point which is marked as cross, ok.

So, what actually we will see at the output? Assuming that this load is very nice and a purely resistive load for now for our understanding. We will be; now it is very easy to see that by adjusting this delay that we give to the control pulse before we apply it to the control terminal of the device, let me just call this as t d delay time. So, we can say that as the t d is increased this red waveforms or these red pulses they become narrower which means that the net DC voltage will come down, will keep coming down as you increase the value of t d on the other hand.

If you decrease the value of t d you will find that this value goes up. So, basically therefore, we can conclude that by suitably adjusting this delay time or by soup suitably adjusting the control pulses applied to this devices, the controllable devices, I can then control the output voltage or in other words I can control the voltage or I can regulate the voltage across terminals X and Y. So, as the load varies I can still vary this voltage to and I can control this voltage to remain constant at the desired value. So, if I want to keep it at 12 volts, I can keep it at 12 volts irrespective of the load that appears across the terminals X and Y, this is what I mean. And this I can do by adjusting T d, ok.

So, having understood this part let me just now explain to you the very basic voltage regulation problem. So, basically now what we have is I can just explain this in terms of the block diagram.

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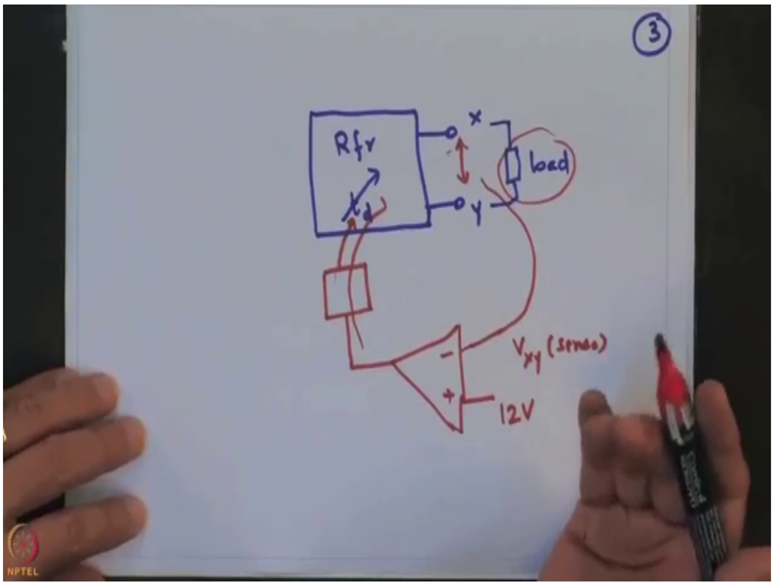

So, I have a block which represents a rectifier system where I have the capability to adjust t d. So, this t d can be varied. So, I have a rectifier here, this block represents a rectifier, and these are the two terminals X and Y. And I can all the time irrespective of the load I can sense the voltage across X and Y, I can sense the voltage, I can compare it, this is basically a comparator block this is a representation of a comparator. And if I want to always keep the voltage across the terminals X and Y equal to 12 volts, I compare it with a 12 volt signal which I call as a reference and then based on the output of this error amplifier, I do something, I do some calibration, I do some manipulation of signals and I control t d.

So, basically what I do is that by adjusting the value of t d in response to the difference I obtain between what I get at the output. And what I actually want at the output which is nothing but 12 volts based on that difference, based on that error, I can adjust the value of t d in such a way that I can get the desired voltage of 12 volts, I can get the desired 12 volts out for now, that is the irrespective of this load. This is what is called the voltage regulation.

Now, what do you see here is that there is a closed loop which is involved in the system. You can see that there is a signal which is sensed and fed back into the system which then governs the control action which takes place, and which corrects the output voltage as per that. So, basically the regulation problem, the voltage regression problem is basically a control problem and there are various aspects of it that we will study as we move ahead with the course.

So, let us just now assume that for a minute we have a device which is controllable, which can block a forward voltage. So, it is a modified we let us say that it is a super diode, super form of diode which actually can block the forward voltage.

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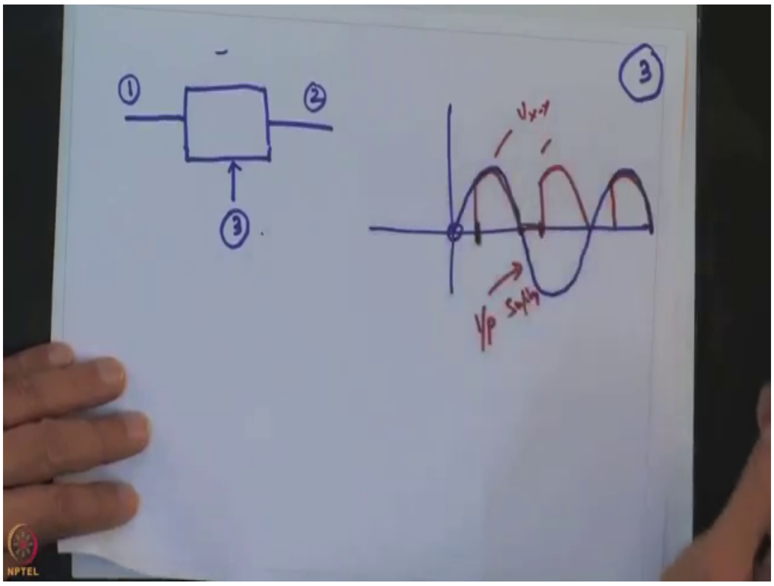

And let us just say that this device let us call it or show it just by a block. So, instead of a diode now you have this block which is representing the device. You have the terminals let us call them as 1 and 2, the two terminals and let us have a third terminal here the diode did not have a third terminal, the diode has just two terminals as we know it is having a anode and it is having a cathode. So, it has got only two terminals.

But now in this device let us say a third terminal also. And the purpose of this third terminal is that even though you have applied a forward voltage across 1 and 2 as in a diode, you have still not supplied the activating pulse through the control terminal 3. So, what will happen in this case? In this case what will happen that the input supply which is going like this, the input supply which is going like this now at this point looking at our previous diode rectifier circuit our D 1 and D 4 they would get forward biased and they are ready to conduct. But now instead of these those diodes, those four diodes D 1, D 2, D 3 and D 4, we are using this special diode device switching device, which is shown here with an additional terminal third terminal which is called the control terminal.

So, what will happen if I have not applied if I have used instead of the diodes, I have used this device but I have not applied any control signal to 3. So, my circuit would keep waiting for a control signal to appear across 3. Now, let us say we apply it at this point, ok. Let me just show you with a colored pen. So, let us say we apply the control signal at point 3 to diodes D 1 and D 4. So, to the device this special device which is in place of diodes D 1 and D 4 we apply it at this point. Immediately as soon as we apply this control now this device works as a diode, and you will find that at the output terminals X and Y of the previous circuit you will get a lope of this type.

Now, similarly let us just replace diodes D 2 and D 3 also with this special device and we again at this point you will see that this point of the input AC voltage, the device would become for all these two devices which are placed in place of D 2 and D 3, they will be forward biased and they will be ready to conduct. But let us say they are not given a control pulse till another point which is up to here, which is symmetrical to the first flow let us say. So, as soon as you give the control pulse to the terminals 3 of the 2 devices placed in place of D 2 and D 3 you will find that a lope will appear at the output terminals X Y which will look like this.

So, what you see here is your input supply. And what you see with the red on top is the voltage X Y, and the cycle continues. So, again in the third lope suppose you have not given you have delayed the pulse, control pulse through terminal 3 to some point you will get. So, this train would continue, ok. So, this leads us to the understanding that if we can control the pulses which are applied to terminals 3 of all these special devices which are now constituting or comprising our rectifier, we can actually play with the output voltage value. So, these pulses will become closer or they will separate out, ok.

Their portions will be more and more portions of these output voltage waveforms we will be cut out, and you will be able to play with the output voltage.

Therefore, the conclusion is that if we can use a controllable device rather than a diode then I can vary my output voltage by controlling the pulses applied to the control terminals of the various devices. A device a switching device like a diode is called an uncontrolled device, because there is no way to control this device once a forward or a reverse voltage is applied across the diode, it is no way to further control this device. But if you look at this special device, I talked about there is a provision through terminals 3 that we can actually control this device. So, it is not just a matter of applying a forward voltage across it. It is also a matter of applying the control pulse to the device. So, when we apply the control pulse would determine what exactly appears to the output.

So, this leads to the development, this leads to the first I should say requirement and then development and inventions of the various types of the power devices which can then be used as controllable devices. So, the special device that I described to you as a fictitious device actually subsequently as a research progressed on semiconductor devices, they all develop into devices such as the silicon-controlled rectifier.

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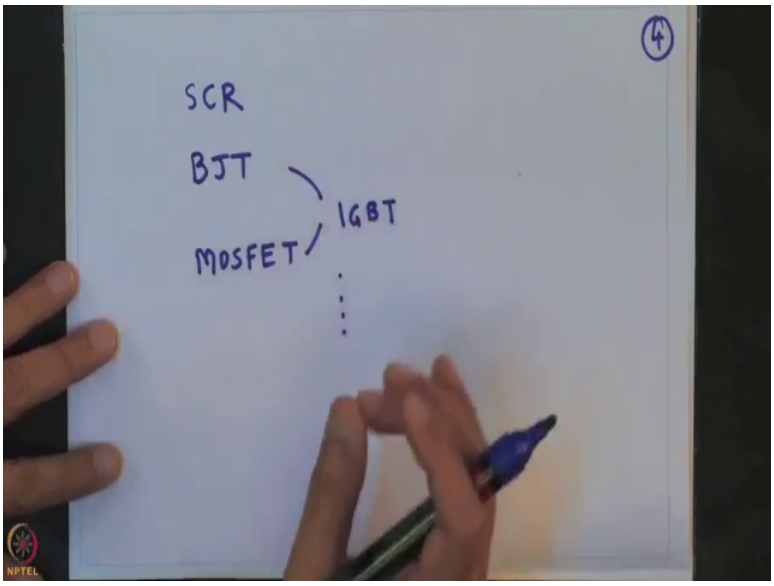

The bipolar junction transistors, the MOSFETs which is the metal oxide semiconductor field effect transistor, and a combination of some of these devices like the BJT and the

MOSFET it led to what is called an insulated gate bipolar transistor and so many other devices which came up.

So, as the course will proceed further, we will see the development of these devices. We will study the properties and behavior of some of these devices. But one thing is clear at this point with the help of the example I gave you that it is these controllable devices by virtue of their controlled terminals, they are the ones which are going to give us the flexibility obtaining any desired power levels or any desired voltages or currents that we need for our application.

So, in the next lecture we would see some more examples, we will try to understand power electronics in very basic terms we will continue to do that and then we will start with the formal content of the course.

Thank you very much.