Power Electronics
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Lecture 4 - Power Devices: BJT, MOSFET and IGBT

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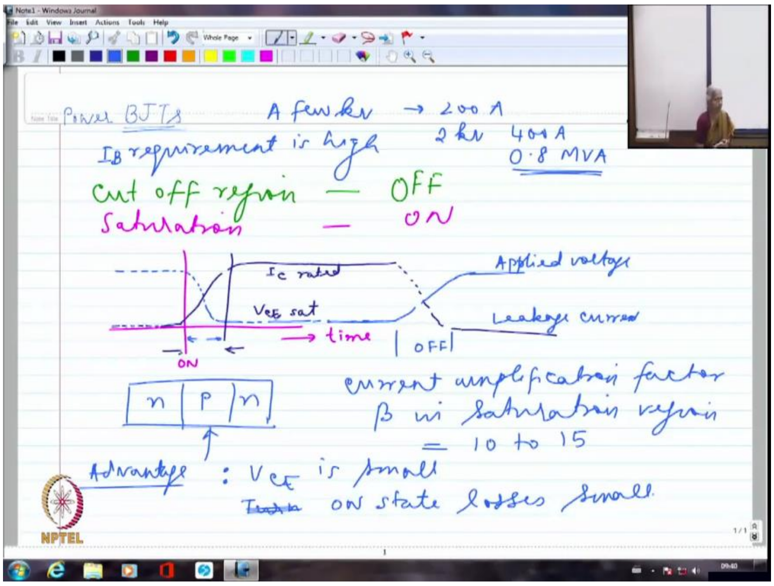

We had started talking about BJTs. So, we had told that BJTs or power BJTs in particular are very similar to the normal BJTs we see in the electronics application, only thing is that they have to be definitely carrying a larger collector current, which means the base drive expected is also very high. So, the major difference is I_B requirement is high, one thing, and the second thing we talked about is hardly ever we are going to operate it in active region.

It will be operated always in either cut-off region, in which case we would say the switch is OFF. If it is going into saturation region, then the switch is going to be ON. So, we would have essentially transition from OFF to ON and ON to OFF, which means it will go from the cut-off region, maybe momentarily it will traverse through the active region, momentarily, very short duration and then it will go into saturation region and vice versa. So, you might see generally if this is the time versus, I am going to plot what is the current or voltage, this is the time at which I am turning it ON, I would see that the voltage until then must have been at some value.

But it will come down and then it will probably go to 0.7 volts or whatever, somewhat like this. This is how it is going to transition. When it is transitioning, it is going into the active regions, similarly if I try to look at the current, current might start off like this, so it will be very very small which is equivalent to the leakage current and it has to essentially increase like this and go to whatever is the rated Ic value. So, this is Ic rated, this is V_{CE} saturation.

So, the voltage that will be corresponding to the saturation voltage, that will be 0.7 volts or something, whereas the current, whatever is the rated current of that particular device. So, this particular region if I try to multiply voltage and current together, during this duration, this is turn ON losses. When I talk about turning on the device, during turn ON whatever the device incurs as losses which is voltage multiplied by the current during the turn ON duration, so it is $\int VI\,dt$, that will be termed as the turn ON energy loss if I am talking about $\int VIdt$.

But VI, simply if I get the product for the entire duration, that is essentially the power loss that is incurred by the device during the turning ON duration. The same way, turning OFF, it has to essentially come from this value of current to again 0 value of current. Similarly, the voltage slowly has to go from this minimum value like this to again whatever is the normal applied voltage value, whatever is the applied voltage between collector and emitter.

So, this will be during OFF condition, so this is applied voltage across collector and emitter junction, whereas this is going to be the leakage current. So, this is during OFF condition. So, turn ON and turn OFF losses, most of the times as power electronic engineers we neglect when we actually calculate because it is for a very very short duration. But that can be really acceptable only if I am turning ON maybe once in a complete cycle and turning OFF in once in a complete cycle.

But if I am going to do it several times for some reason, then definitely that is not acceptable, so that is where generally we get into loggerheads with many of the industries. The industries say that the efficiency that you have calculated is not correct because you have not taken into consideration the switching losses. So, the switching losses generally need to be accounted for especially if I am talking about multiple number of switching taking place during one cycle duration itself. Which we will talk about eventually when we are talking about inverters, rectifiers and so on, we will look at that and then we will be able to appreciate this better.

But turn ON and turn OFF losses are there in almost every device which we talk about, whether it is thyristor, whether it is diode, whether it is IGBT or BJT or MOSFET, anything we are going to have it. So, this duration, the lesser it is, then the overall energy loss is going to be smaller. So, that is why we are also looking at reducing the turn ON and turn OFF time from the point of view of improving the frequency of operation, from the point of view of overall incurred energy loss, that is also important.

And apart from that, if we can make sure that the leakage current is smaller, then even during OFF condition, whatever is the incurred loss, that will come out to be very very small. Similarly, if I try to reduce probably what is the forward voltage drop that I am having across the device, if that can be reduced, again during ON condition, the losses across the device will come down. Ideally, we assume during ON condition the voltage is 0. If it is 0, obviously the power loss will be 0, which is not so.

So that is why I am saying that we always deviate from the ideal required characteristics, we never achieve the ideal characteristics. So, coming back to BJT as it is, we are going to have most of the times NPN transistor. So, if this is my NPN transistor, I have to give the gate drive, only then I am going to be able to forward bias both the junctions so that we are essentially going to look at the entire thing going into saturation region.

So, once it goes into saturation region, I am going to have invariably the device having very very minimal drop and the large current being carried. And once it goes into saturation region, normally the current amplification factor in the saturation region, which is generally termed as β in saturation region it will be only between 10 to 15, nothing more than that. This will be between 10 to 15. So, if it is only 10 to 15, If let us say I am talking about 1 kiloampere device, I will have to inject about 100 amperes or 80 amperes of current minimum to make sure that the device is driven into saturation.

So, the current requirement from the base side becomes extremely large in the case of transistor which is one of the major disadvantages of the bipolar transistor which is being used as a power device. Because power, the moment you say power device, the currents are going to be very large. So, you expect the base drive also to be designed in such a way that this will have its own heat sinks and everything. So, it is a big problem to manage the base driver circuit of a transistor. So, that is the reason why power BJTs have not really become extremely popular for power electronic applications.

So, if you actually look at the ratings as I told you, this will have only a few kilovolts, nothing more than that, 2 or 3 kilo volts at the most. And if I look at 2 or 3 kilovolts, correspondingly the currents may be only of the order of 200 or 300 amperes. But if I look at just 1 kilovolt, then I will be able to have some 500 or 600 amperes. So, both current and voltage ratings are not simultaneously increased. If one is very high, the other one is somewhat low.

So, overall power capacity of the BJT may be only about, so if I say it is 2 kilovolts and say 400 amperes or something, how much is it? 0.8 MVA, nothing more than that. So, I would have less than 1 MVA rating or even much less than that. So, BJTs are not capable of handling extremely large power like thyristors or GTOs what we talked about so far. So, I would say that the disadvantage of BJT is twofold, one is I am going to have IV requirement to be very very large and because nothing much has gone on in the form of too much of research in power area in BJT, the ratings are really limited.

And one more thing is because it is really going into the saturation, hard saturation region, to turn it OFF even if you remove the base drive it is going to take a while before all the charge carriers that are just spread out all over the place, they have to be combine and the depletion layer has to be built up once again, it takes some time. So, turn OFF time is somewhat a little larger as compared to some of the devices that we are going to talk about a little later.

So, let me say the advantage is, let us talk about the positive points first, VCE is small, so I would say the turn ON, rather I would not say ON-state losses, not turn ON losses, ON-state losses are somewhat small. Disadvantages I have already mentioned, I_B large, not very high rating possible, turning OFF takes a while. So, these are the disadvantages.

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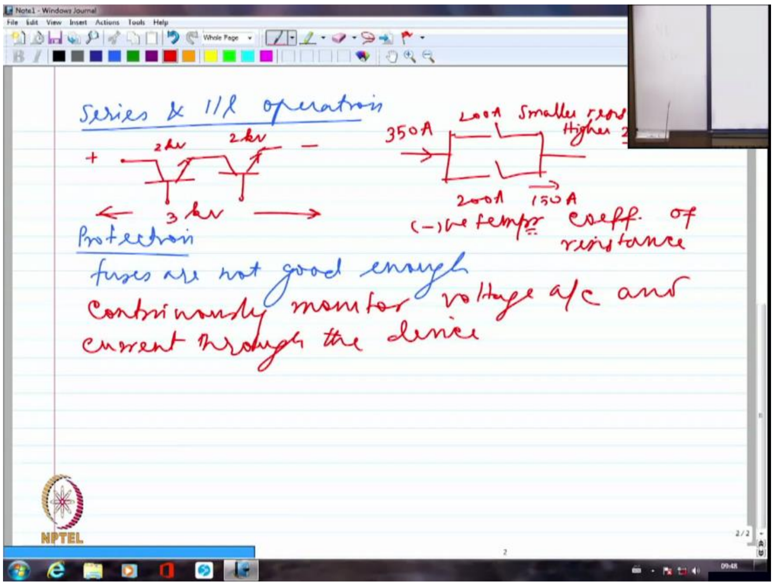

Apart from that I should also mention about series and parallel operations. Generally, we hardly ever operate a BJT or multiple BJTs in series or parallel. BJTs are generally definitely faster than thyristors at any rate, because thyristor devices themselves will be much bigger. You normally use thyristors mainly for larger rating, so devices themselves will be bigger, so it takes a while for turning ON and turning OFF, get pulse have to sink in and then it has to start conducting. So, it takes a while, whereas BJT is somewhat faster compared to the thyristor.

Which means if I put a fuse for protection of BJT, I am not going to be able to see the fuse actually you know responding even before the BJT, because BJT is too quick compared to a fuse. So, I would say that protection is also a major issue, fuses are not good enough. Because of this, we will have to continuously monitor the voltages and currents across the BJTs. Continuously you have to monitor and if you have to see that the current is going to extremely large values, then maybe pull out the base drive, that is what we need to do. Before the device conks out, pull out the base drive.

So, only the way of protection is continuously monitor voltages and currents, voltage across and current through the device. Now because of the quickness of operation of the BJT, if I put 2 BJTs in series, the same thing holds good, when I put 2 of them in series, the gate drivers have to be exactly matched in terms of timing and everything. And it is very difficult, because even if we take 2 components from the same batch, sometimes there will be very minute differences. So, if they are not exactly matched and if I am going to put 2 transistors in series, like this, so this is also an NPN transistor, this is also an NPN transistor and I am giving base drive independently for each of them.

Although I have designed them exactly in a similar manner, if one of them turns ON first, the other one has to essentially bear the brunt of the entire voltage. So, if I apply, let us say each of them is rated for 2 kilovolts and 2 kilovolts and I am applying totally 3 kilovolts from here to here, say I am applying 3 kilovolts, if one of them turn ON first, the other one definitely will have the entire V_{CE} coming out as 3 kilovolts and it will conk out, because of nonmatching of the driver circuit.

So, that can really create a major issue in transistor because it is quick and because of which you do not have time to respond, you do not have any of the protection devices that can respond right away. So, you are not going to be able to protect any of them very very quickly. Similarly, if I have 2 transistors in parallel, so let us say this is one transistor, this is another transistor, both of them in parallel, I am just showing the switches. So what is going to happen is let us say each of them can withstand 200 amperes of current.

What I am sending here is say 350 amperes. Maybe I am going to have one of them slightly different in terms of their ON-state resistance. During ON state also it will have a small resistance. During ON-state, let us say the resistance in one of the BJT is a smaller, the other one is having a little larger resistance. So, obviously it will follow parallel current division rule. So, whichever has a smaller resistance, that will get more current.

So, let us say this is having smaller resistance, so because of which maybe this is going to have a higher current, rather than taking 175, maybe it is taking 200 amperes. So, rest of 150 ampere is flowing through this. Let us say out of the total 350 amperes. Now, this 200 ampere will cause definitely a higher I^2R loss within the device itself. So, the heat is going to be higher in terms of the I^2R loss incurred across that particular device, whereas the second device is going to have lesser I^2R loss.

In semiconductors, when the heat increases, the temperature increases, more charge carriers will be released. So, the resistance is going to come down further, unlike metal. In metal you will see that resistance as the temperature increases, the resistance is going to increase, whereas semiconductor devices normally have negative temperature coefficient of resistance. So, because of negative temperature coefficient of resistance, you are going to have the resistance coming down further and further. So this will come down further and further.

So, as the resistance comes down further and further, you will see more and more current goes through that device. So, it goes towards the runaway condition. So, this essentially creates the major problem to use the transistors in parallel. So, series and parallel operations, if the ratings are not so high, we could have used them in series and parallel if it was admissible. But because of the inherent property of negative temperature coefficient of resistance, we cannot use them in parallel. Series operation becomes a little difficult because drivers cannot be matched very exactly.

So, generally BJTs are not used in very high-power applications. When I say very high power in power electronics, we talk about the few tens of megawatts at least. So, we generally do not use them for beyond a few hundreds of kilowatt application.

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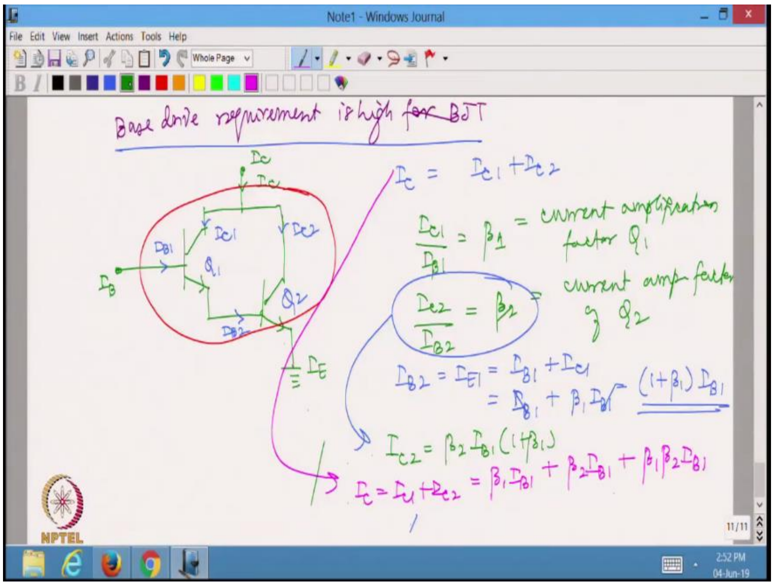

We had told in BJT that the base drive requirement is very high. This is one of the major drawbacks of BJT. Can we reduce this base drive requirement by any means? For this we use something called Darlington pair. Let me draw the configuration of a Darlington pair system. So, here essentially there are 2 transistors which will be connected in a cascaded manner and we are going to have the 2 collectors connected together. And then this is going to be the total collector current of the Darlington pair and this is going to be grounded here.

So, you can look at this entire thing as though, if I just look at it as one unit, I am going to have both this transistor putting up as one unit and I am going to have this as the overall base, this as the overall collector current and this is going to be the overall emitter terminal of this particular transistor pair. How do we really reduce the base drive for this particular pair? Let us try to analyse this. I am sure looking at this you should be able to say that if I have this as I_{C1} and this as I_{C2}, let me call this as device as Q_1 and this as Q_2, these are the 2 transistors.

So, I should be able to say that overall $I_C = I_{C1} + I_{C2}$. And if I call this as I_{B1} for this transistor, I should be able to call this as I_{B2}. Now, I can say $I_{C1}/I_{B1} = \beta_1$, which is the current amplification factor of transistor 1. Similarly, I can write $I_{C2} / I_{B2} = \beta_2$ which is the current amplification factor of Q_2. Now, if I look at what is I_{B2}, I_{B2} is same as I_{E1}. Which is actually, if I look at this as Kirchhoff's Current Law equation, I should be able to write this as $I_{B1} + I_{C1}$, this is what is I_{B2}. So, I_{B1} let me write as it is, but I have to write this as β_1 times I_{B1}.

So, I should be able to write this as $(1+ \beta_1) I_{B1}$, that is what is I_{B2}. Now I can write $I_{C2} = \beta_2 I_{B1} (1+\beta_1)$. From this equation I should be able to write that, because I have written $I_{C2} = \beta_2 I_{B2}$

and I_{B2} is this. So, I have essentially written this. Now let me try to write from here what is I_C. $I_C = I_{C1} + I_{C2}$, $I_{C1} = \beta_1 I_{B1}$ and we wrote for $I_{C2} = \beta_2 I_{B1} + \beta_1\beta_2 I_{B1}$.

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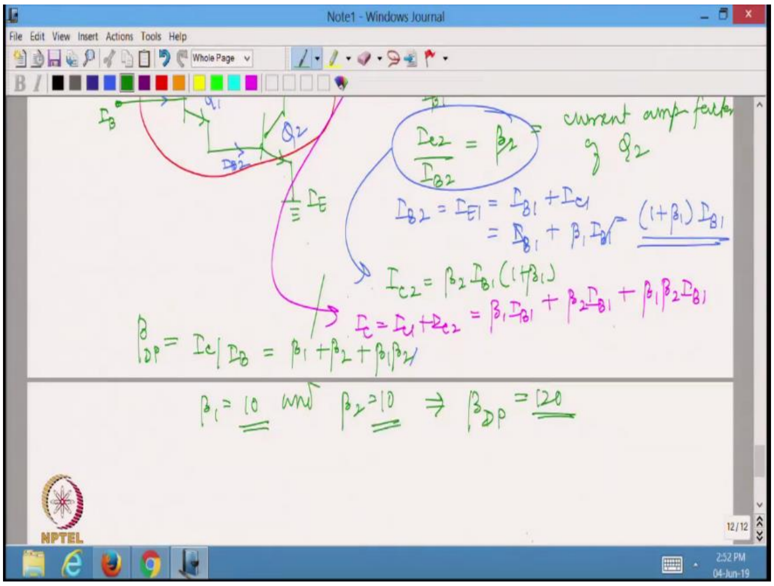

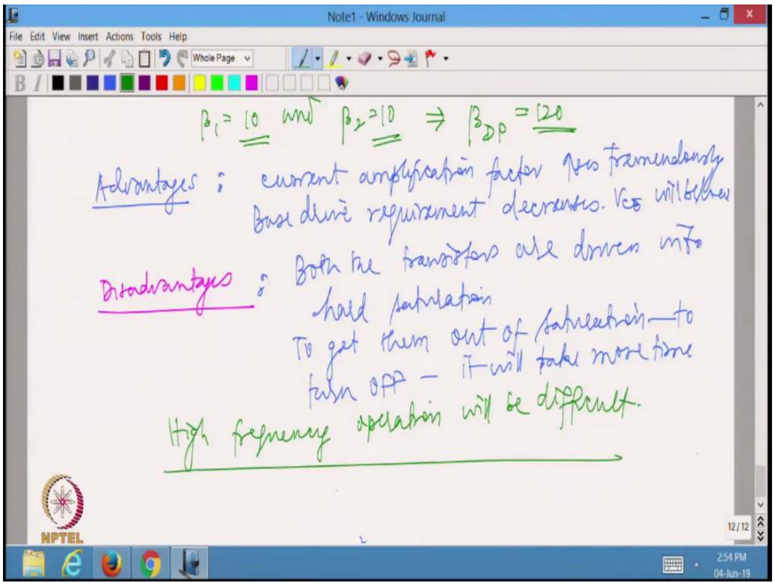

So, I can say in general for Darlington pair, I should be able to write this as overall, $\beta_{DP} = I_C/I_B = \beta_1 + \beta_2 + \beta_1\beta_2$. So, if I am going to have let us say $\beta_1 = 10$ and $\beta_2 = 10$, I am going to get essentially overall β for the Darlington pair. So, I am going to get overall β for the Darlington pair, $\beta_{Dp} = 120$ as against what I got as 10 for each of the transistor. So, the major advantage I get for the Darlington pair, by making use of the Darlington pair is the current amplification factor increases tremendously.

So, base drive requirement decreases. Whenever there is an advantage, there will be corresponding disadvantage as well. One of the major disadvantages in this particular case will be both the transistors are driven into hard saturation. So, the drop will be very low, no doubt, V_{CE} is very low, that is also one of the advantages, V_{CE} will be low. But to get them out of saturation, to turn them OFF, to turn OFF it is not going to be easy. So, it will take more time.

So, we will not be able to operate this, so high-frequency operation will be difficult. So, we are going to have a problem, especially because of high-frequency operation not going to be very much possible with Darlington pair. With this we are concluding our discussion on transistors on the whole.

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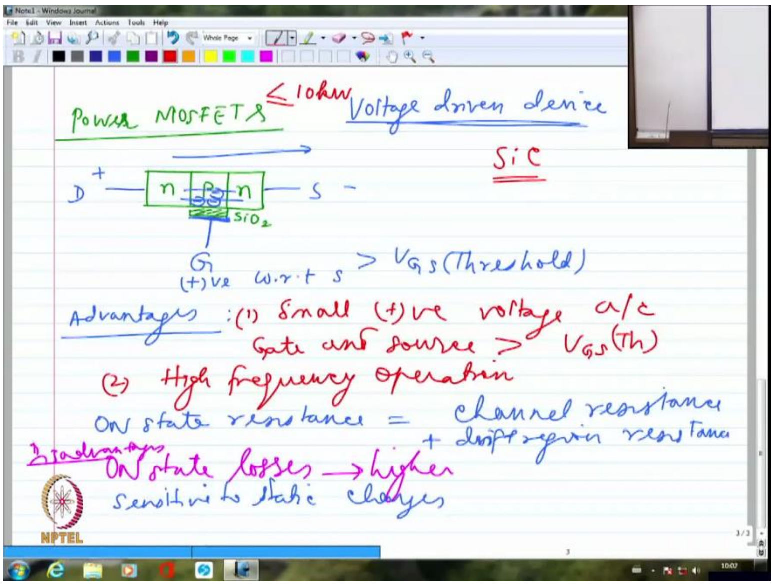

So, let us look at power MOSFETs. So power MOSFETs are very similar to the field effect transistor what are used normally in the electronic circuits. So, field effect transistors basically work on the principle of some capacitive contact. So, let me probably just show you what happens in a MOSFET. So, let us say I have an N channel MOSFET, so, I will have again, it is a 3 layered device, something like this and I am going to have here an insulating layer of metal oxide semiconductor, which is actually SiO_2.

A small SiO_2 layer is going to be put on, deposited on the P portion of the semiconductor substrate. Now, on this there will be a metallic contact. This will be a metallic contact here on this and then we are going to take out the terminal here which is generally known as the gate of the MOSFET. And then on this we are going to call one of them as drain, the other one as source, so these are the 3 terminals of a MOSFET, drain, source and gate.

Now in transistor we were directly giving the current into the base, whereas in MOSFET what we are going to do is to apply a positive voltage here, just give a positive voltage. The moment you give a positive voltage with respect to source, with respect to source you give a positive voltage, then what is going to happen is because this behaves like a capacitance, now there is a dielectric in between, on one side you have a metallic plate where you applied the positive voltage and on the other side there is a semiconductor.

So, you are going to see that there is going to be a lot of negative charge accumulation here. Because of the positive voltage which we have applied on the other side, there will be negative charge accumulation on the semiconductor side. And more the voltage is applied here, more is going to be the negative charge accumulation on the other side. So, the moment it crosses a threshold value of positive voltage, I am going to have a thoroughfare, literally, from this end to the other end.

Until now there was a barrier because P was not allowing it to conduct freely. So, I would have a thoroughfare because of accumulated negative charge, this accumulated negative charge is generally known as the channel. So, the channel opens up the moment I try to go beyond the threshold value of voltage between the gate and source. Whatever V_{GS} I am applying, voltage between the gate and source, if this goes beyond a threshold value. Then I am going to have this channel opening up in such a way that there is a thoroughfare between the current that is flowing from here, this will be plus, and this will be minus, so the current can directly flow like this.

So, MOSFET essentially starts functioning just by applying a positive voltage to the gate with respect to the source. So, this is basically a voltage driven device. This is a voltage driven device and generally the amount of voltage that could be withstood by the gate to source, that junction is pretty small, it will be anywhere between 12 to 15 volts, that is about it, nothing more than that. Which means the voltage what I am applying is also pretty small, nothing much.

So, the gate driving whatever is required, the power capacity will be really small because the voltage is small and the current is also not very large because it is only trying to induce some charge on the other side. So, this voltage driven property of the device is a major advantage over BJT. In BJT I require a large current, whereas in MOSFET I require only a small positive voltage. So, the gate driver circuit design is very simple in MOSFET.

So, we are normally seeing in MOSFET the turn ON and turn OFF happens because of the capacitive property of the junction. So, it happens much faster even than BJT normally. All you need is apply a voltage, that is a charge induced, immediately it will start conducting. So, you are going to see that power MOSFETs have the advantage, the major advantage is that I need to apply only a small positive voltage across gate and source, which should be greater than V_{GS} threshold.

If I just apply this, it is good enough to make the device conduct. And just apply the voltage immediately within a matter of nanoseconds, generally the turn ON time of thyristors will be of the order of tens or hundreds of microseconds, depending upon whether it is converter grade or inverter grade. Inverter grade may turn on in 50-60 microseconds, whereas converter grade or rectifier grade might turn on only in 200 or 300 microseconds. Whereas BJTs may take a few microseconds, whereas MOSFETs can turn on in a few nanoseconds.

So, MOSFETs are really fast, because you just need to apply the voltage and then it will create the charge and it will start conducting. So, very high frequency of operation possible in this case. It can go some of them can go until megahertz. High-frequency operation is possible. But one major disadvantages depending upon the channel length, how much is the channel length, apart from that there may be a small drift region also. That would be introduced so that I would be able to you know kind of increase the voltage level further and further. All of them put together, the ON-state resistance somewhat becomes higher.

So, ON-state resistance will be basically resistance of the channel, whatever is the channel resistance plus drift region resistance. So, normally we will see that we are going to have channel resistance added to the entire thing, because the channel is essentially a minority carrier within that P region. So, we are going to see that the resistance is somewhat higher, on-state resistance is somewhat higher in MOSFET. So, ON-state resistance, because of that you are going to see that the ON-state losses compared to thyristor, compared to BJT, it will be somewhat higher.

So, ON-state losses are higher, so the efficiency may be lower. And one more disadvantage, it is if you look at the entire device, it is working on capacitive principle. So, by chance in winter you must have seen that we also have some static that clothes stick to each other and things like that. So, if we handle the MOSFET really without grounding ourselves, if I remove the chappal and then stand on the ground, whatever is the charge it will go away.

Without that if I directly touch the MOSFET, sometimes they can get spoiled because they are very sensitive to static charges. They are generally very sensitive because the work on capacitive principle. So, the moment you touch probably unknowingly the gate terminal or something, it can accumulate the charge it can get into conduction and it can actually go through overcurrent and whatever because you are not intended to make it conduct probably.

So, it can be a problem for the device, especially if you subject it to static charges unknowingly. So, they are very sensitive to static charges. Apart from that, one more disadvantage if you may call it, as it is the on-state losses become more because of the channel resistance plus the drift region resistance. If I want to design it for larger and larger values of rating of voltage especially, I have to probably increase the length further because between the drain and source I have to have a pretty long channel basically.

Which means, I am going to increase the resistances further. So, the drop can be extremely high, that is one reason why MOSFETs are not designed beyond 1000-1200 volts normally. Most of them are rated only within 1 kilovolt or 1.2 kilovolt, generally we try not to make the MOSFET for higher ratings because at higher ratings you make the device unwieldy, very long and then in effect you are going to increase the resistance overall. So, it is not very advantageous to have a large rated MOSFET.

So, generally if I look at the different power levels of operation, MOSFETs are generally used for less than 10 kilowatt ratings, less than or equal to 10 kilowatt ratings. So, this power MOSFETs are generally used only for less than or equal to 10 kilowatt rating. One newer development has come up especially in MOSFET is silicon carbide devices, which are actually supposed to be having lower values of resistances, ON-state resistances. They are being Silicon carbide material is being used in place of silicon for making MOSFETs.

So, silicon carbide MOSFETs are really becoming popular because they are having losses almost one-tenth or one-fifteenth of whatever normally the silicon MOSFETs are having. But still silicon carbide MOSFETs have been designed only until 10 kilowatts rating, nothing more than that. Hopefully, eventually it will become higher and higher in terms of its rating because a lot of research is going on into silicon carbide devices.

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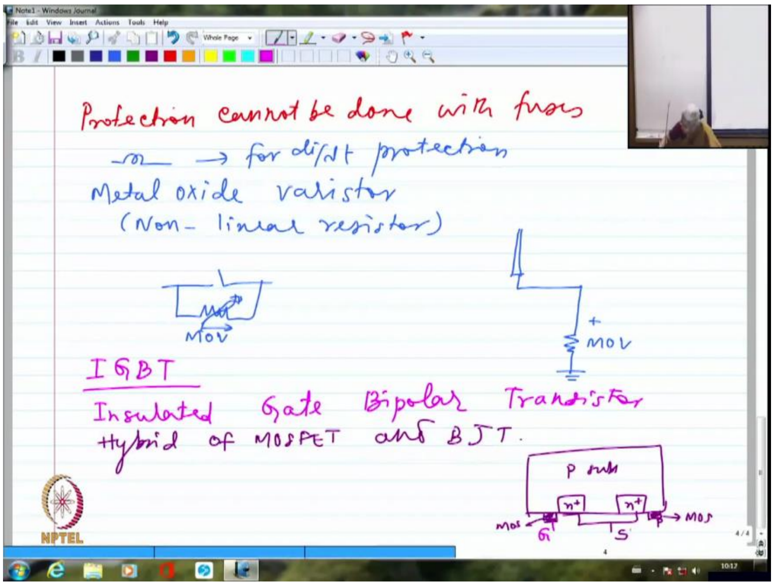

So, in this case also because the MOSFETs work very fast, protection cannot be done with fuses. So, continuously the voltage and current, both of them have to be monitored. Same as BJT, it is not really better than that in terms of protective features. Just like what we said in the case of thyristors, similarly inductance for $\frac{di}{dt}$ protection but snubbers again are not very commonly used with MOSFETs because that itself is somewhat capacitive, you do not want to intervene with the entire behaviour.

But inductances are generally used for $\frac{di}{dt}$ protection so that the current will not rise abruptly. And sometimes for overvoltage protection, something called a metal oxide varistor, MOV, this is actually a non-linear resistor. It is made up of a special material which would actually have very high resistance as long as the voltage applied across it is below its rated voltage. Let us say it is designed for 2 kilovolts, until you apply 2 kilovolts its resistance will be very very high.

But the moment you apply any voltage beyond 2 kilovolts, immediately it will breakdown, the resistance will become so low that it will essentially be taking up you know huge amount of current through itself. So, these are generally used for making sure that a very high-voltage does not come across the MOSFET. If the MOSFET is designed for let us say this is my MOSFET device and I am going to put MOV here, generally this is shown something like this, non-linear characteristics and this is MOV.

So, this MOV as long as I am applying only 2 kilovolts, it will be able to withstand that, that is not a problem. The moment you go beyond 2 kilovolts, if by chance some greater than 2 kilovolts comes across this, this will breakdown, so essentially huge current will go through that, so the overall voltage across the MOSFET also becomes very small. So, the MOSFET will not get spoiled in that case. This is very commonly used in lightning arrestors, you guys might have heard about lightning arrestors definitely.

Lightning arrestors always use non-linear resistance. What happens is as long as the lightning does not strike that will essentially have an open circuit, so we will have generally the lightning arrestor it will be something like this. You will see a very sharp tip in tall buildings and from this point it will be connected through a non-linear resistor to the ground. So, as long as no lightning strikes, this circuit is inactive, there is no problem. But if a lightning or a charged cloud comes, then immediately this is going to attract it.

This is like a corona discharge, so you are going to see in the sharp tip, the opposite charge induced, so it is going to just take away the entire charge through that and because it is taking up the entire charge of the cloud, very high-voltage will come here. So, that means very high-voltage is seen here, so this non-linear resistor will breakdown. So, you are going to have essentially this particular resistor breaking down. So, the entire voltage or in the form of current, it will be discharged to the ground, so the building and other things, whatever around will be protected.

So, this is the basic principle of lightning arrestor. It does not arrest lightning really, it is actually surge diverter, we call it as a surge diverter. It is essentially diverting the search through a non-linear resistor. So, similar principle is employed for the protection of MOSFET against over voltages.

Student: Why MOV is added in parallel across the device?

Professor: It is generally added in parallel so that the voltage across this will become very very small. So, obviously you are not going to have the device really withstanding such a large voltage, that’s way. The next one, the last device that we are going to discuss, I have essentially done very brief discussion of each of these devices, nothing more than that. So, why are we really discussing even the physics of the devices? We are really not discussing the physics; we are basically looking at how the device behaves under different conditions. So, at least we should know how to turn ON turn OFF the device, thyristor I gave it, I have still not given it for BJT, MOSFET and IGBT, what we are going to discuss next. So, we look at the firing circuits for all of them together at the end.

So, let us take a look at IGBT. It is insulated gate bipolar transistor. This is actually a hybrid between MOSFET and BJT. This device came upon as a hybrid between MOSFET and BJT. So, this has fortunately the advantages of both but in the moderated manner. You cannot say that if MOSFET goes up till 100 megahertz, this will not be able to go until 100 megahertz, it may be able to go until 100 kilohertz or maybe 1 megahertz, nothing more than that. Whereas if I am talking about $R_{DS(ON)}$, that is whatever is the on-state resistance of the MOSFET, if it is very high, this will not have as high as MOSFET, it will not have as low as BJT, it will be somewhere in between.

So, we are looking at combining the advantages of MOSFET and BJT. So, in this particular device what happens is if I am having a P substrate, this is P substrate, we are going to have N plus layers grown on this. And then these 2 are connected together to make it as a source, this is source and then we are going to actually have these as gates, these are P, so we are going to have essentially metal semiconductor deposition here and then we are going to make metal contacts here which is going to act as the gate.

So, let us say we can have it here also, in the middle also, it does not matter. So, basically we are going to have the firing done with the help of voltage, just like what we did in the case of MOSFET. So, let us say I am showing the gate here.

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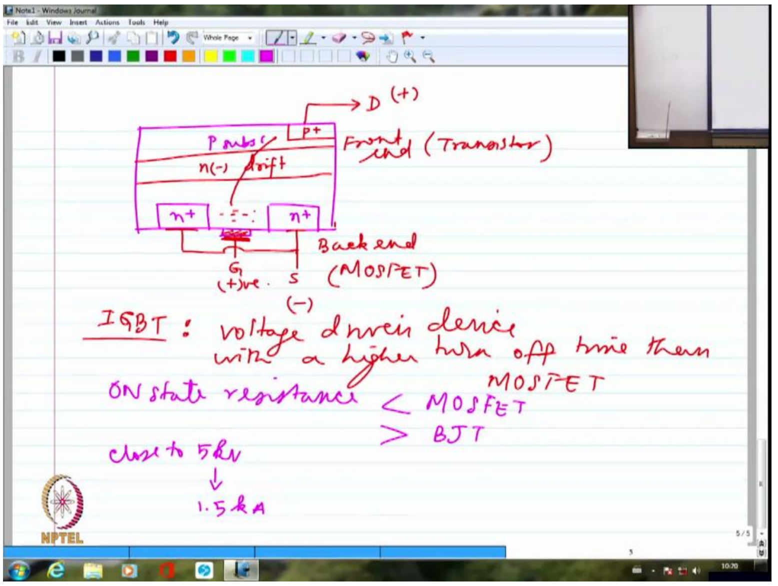

This is the P substrate, I am going to have n+ here, n+ here, let me probably show the gate in between, in the P itself. So, this is the metal oxide layer and this is going to be my gate and this is going to be the source, this is connected with this and it forms the source. In between there will be a drift region as well, so we will just have minimal deposition of n minus layer. So, this is essentially the drift region and I will have excess deposit of p+ here and which we call ultimately this as D.

So, what is going to happen is this is my source and I am going to have essentially the gate sitting in between, unless I am going to have some channel opened up here, I will not see any conduction in the MOSFET region. So, it is as good as this portion acts like a MOSFET, the lower region of the device acts like a MOSFET. So, I am going to not have any conduction possible until I apply a positive voltage here with respect to the source.

So, I will get at least some amount of negative charge induced, so because of which I will have a huge amount of negative charge accumulation here which will pass through this and go over towards the drain side. So, I am essentially going to have this portion, that is this if I say that this is the backend, this backend is similar to a MOSFET. Whereas if I talk about this as the front-end, the front-end is similar to a transistor. So, if I have plus applied here and minus applied here, initially the device is not going to be in conduction state at all, because neither the backend MOSFET will be able to conduct, nor your transistor is getting any base drive, there is nothing available. So, the entire device will be in dead state, it will not conduct. But the moment I apply a positive voltage at the gate, there will be flooding of negative charge carriers here.

So, all these things are going to merge and then we are going to have all this negative charge flooding towards the positive voltage that is being applied to the drain. So, this is actually going into the drift region and going into the P substrate and then ultimately reaching the drain. So, the entire drift of the charge carriers, negative charge carriers will be towards the drain terminal, P terminal. So, the entire conduction is started OFF because of the MOSFET that is sitting at the back end of the device.

So, if you look at the overall working of the device, the turning on happens because of MOSFET, so it is a voltage driven device. The moment I rob that positive voltage or I remove the positive voltage from the gate, the channel will be closed. If the channel is closed, we will not have any more base drive also available for the transistor that is sitting on the top. So, the transistor also goes off and you are going to have the turning OFF of the MOSFET as well.

Both of them are turned OFF one after another. First, you are going to have the MOSFET turned OFF because of which the transistor will not have any possibility of getting further based drive. So the transistor will also go off. But, definitely the time taken may be more than the MOSFET's turn off time because you have the transistor already conducting, it is probably driven into saturation already, so it is going to take a while for the charge carriers to recombine.

First, the MOSFET current has to go to 0 and then only the base drive will go to 0 for the transistor. So, you are going to have definitely more amount of time taken by the device for turning OFF even after the gate pulse is removed. So, generally IGBT is called as a voltage driven device with a higher turn off time than the MOSFET. But, because of the transistor mainly driving the major portion of the current, because MOSFET essentially plays a role in turning ON and turning OFF the device, it does not really play a role in the overall conduction, because of which we are not going to have a large ON-state resistance in this device.

So, the ON-state resistance generally comes down in this particular device. So, ON-state resistance is less than MOSFET. But however, because I have a drift region, I also have a small channel, you cannot expect it to be as low as transistor. So, ON-state resistance of IGBT will be slightly higher than BJTs. So, it is somewhere in between, it will not be as low as BJT or as high as MOSFET. But because of the fact that I have so many layers here, we would be able to make it for larger rating.

And not only that because it is a voltage driven device and it is advantageous in every way compared to either MOSFET or BJT, a lot of research is going on in this particular device and the ratings have increased tremendously in the last few years. So, the ratings that are available as of now are close to 5 kilovolts. And corresponding to 5 kilovolts, we have easily 1.5 kiloampere. But, if we try to come for lower values of voltage, that is let us say 2 or 2.5 kilovolts, we can easily get 3 kiloamperes and so on.

So, if you lower the voltage, you can go for a higher current because heat sink design is a big problem generally. So, we have at least of the order of 6 megawatts handling capacity quite easily in many of the IGBTs, single-handedly they can handle 6 megawatts. And as the research progresses in all probability we may get higher and higher rating possible.

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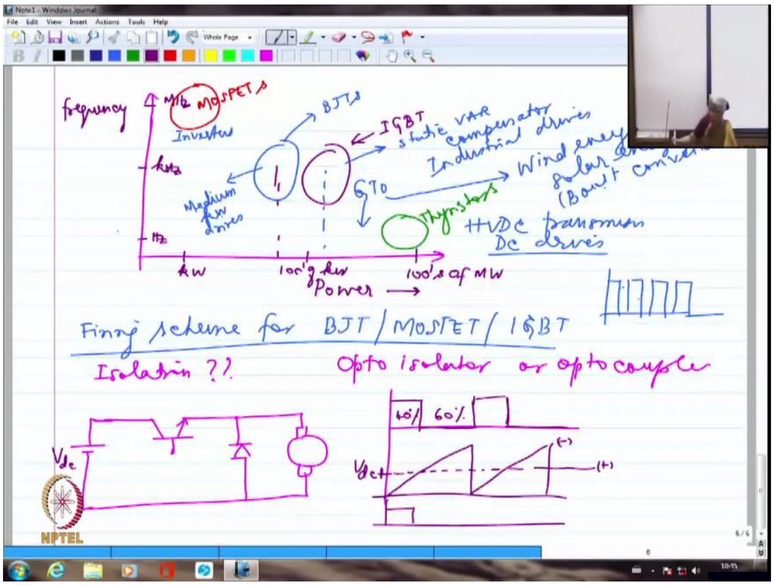

So, if we look at now the spectrum of devices, and what is the kind of applications each of them have,. So, let me write the power on this side and let me write the frequency of operation on this side. So, maybe I can say this as megahertz, somewhere here let me write kilohertz and somewhere here hertz, And similarly let me write maybe hundreds of megawatt, maybe I should say hundreds of kilowatt, this is just a few kilowatt, So, if I look at the intersection of a few kilowatts and megahertz, this is where generally we are going to have MOSFETs being employed.

And if I try to look at hundreds of megawatt and few hertz, maybe 50-60 hertz, maximum 600-700 hertz, that is where thyristors are employed. If I try to look at a little less than hundreds of megawatt, somewhere here, and a slightly higher frequency, I should say at this region approximately GTOs are used, gate turn-off thyristors can be used for slightly higher frequency than thyristors. But they can also be used at little lower power level. But if I am talking about close to a few megawatts and few tens of kilohertz, around this region is IGBT.

So, IGBTs are used in roughly those regions, whereas if I am talking about even lesser power rating than that, some there. And probably even slightly higher frequency or similar frequencies somewhere here or BJTs, IGBTs can still handle higher power than BJT because more research has gone on and more improvements have come about. It is not probably the inherent property as such but people have not put in effort basically for BJT. To be specific, in terms of applications.

Student: Is the frequency of operation of BJT and IGBT are comparable?

Professor: Frequencies are almost similar but power levels are a little lowers. Typical applications, MOSFETs are used in all inverters, household inverters, UPS, some SMPS, all the power supplies, wherever we use small capacity power supplies, most of them are MOSFETs. And MOSFETs are freely available in the market and it is not as expensive, IGBTs are expensive. And BJTs, medium kilowatt drives, industrial drives which may be of medium kilowatt capacity, most of them might use BJT but now most of them are being replaced by IGBTs.

Invariably they have been replaced by IGBT in many of them. So, these again you can say static VAR compensator, we will see what it is at the end, where we are going to probably make sure that reactive power is supplied, we can put capacitor to supply reactive power. All of you have realised that power factor can be improved by employing a capacitor. Instead of employing a capacitor which will give me fixed amount of reactive power, can I employ an inverter? And I can place the current as I feel like, the current can be put in lagging region, leading region, whichever region I want by appropriately getting the devices or firing the devices.

So, that is known as static VAR compensator, reactive power compensator. So, I can compensate for lagging as well as leading reactive power. Capacitor can compensate only for lagging reactive power; it can only provide leading reactive power. Whereas this can compensate for both lagging as well as leading reactive power. So, static VAR compensators whenever it is used generally it is IGBT and again industrial drives, many of the industrial drives, then induction heating system.

You guys have seen induction cooktop but that is all of 1 kilowatt or a few kilowatt capacity. Whereas when we use an industrial scale to melt some metal. In furnaces, in those cases against IGBTs are used invariably. When they want to control the temperature, it is always good to have a power electronic equipment. So, because of which we will be able to control effectively the voltage and current that goes into the furnace. That is the reason. GTOs generally are used in many of the wind energy and solar energy conversion systems.

Solar, what we get is DC, we have to convert that into AC if we want to feed it into grid. So, if I am getting from solar certain voltage, I might like to boost it up, so I may use a DC to DC converter, step-up converter to step up the voltage from a particular value to a higher value. If I want to step it up, then I may use a GTO based DC DC converter. Similarly in wind energy, what we get will be a variable speed; we will not be able to get the fixed speed.

So, if I have a variable speed, what I get out of the AC generator will be a variable frequency AC, I cannot feed it to the grid directly, I want 50 hertz, so I will convert that into DC. So, for AC to DC conversion I can use GTO if I want or I can again convert DC into higher voltage by using a boost converter. Depending upon the velocity of the wind I am going to have a particular frequency and particular voltage. If lower wind velocity is, the one which is being faced by the wind turbine, then I will have lower voltage as well, so I might have to boost it up.

So, boost converters invariably are designed in these things using GTO, especially for boost conversion. Thyristors, you talk about very high-capacity DC drives, maybe in steel rolling mills, paper industries if they use DC drives, generally thyristor-controlled DC drives are used. HVDC transmission, what we talked about and DC drives, these are major applications of thyristors. HVDC transmission generally cannot run without thyristor, it has been possible to have so many HVDC transmission systems all over the place only because of thyristors.

Last but not the least, firing scheme for BJT /MOSFET /IGBT. Thyristor is a little different category of firing scheme, it is having because of the fact that I do not have to give continuous pulses. If I give one pulse, it will be latched into conduction provided the current is greater than latching current and it will stay in conduction zone, unless I bring down the current below holding current and I reverse bias. So, both conditions have to be satisfied. For turning ON, I have to first of all have it forward biased, I have to give a gate pulse and the current has to be greater than latching current, only then it will stay in conduction state.

For turning OFF, I have to make sure that the current goes below holding current and I reverse bias it, only then it is going to go off. So, thyristor need not be given continuous pulses, it can be just given one pulse and it will stay on, that is not a problem at all. That is why I could use a transformer for isolation. And the transformer was called a pulse transformer and the pulse transformer was getting discontinuous DC, it was not giving, we were not giving continuous DC rather we were giving discontinuous DC like this, high-frequency ANDed pulses, that is what we were giving.

Whereas, I cannot afford to do that for a BJT or MOSFET or IGBT. If I do that, the device will conduct during this time, it will not conduct here, it will again conduct here and so on. So, I cannot definitely do that. So, I definitely need to isolate between the power and control or the gating circuit, no doubt, but I cannot do it with a transformer. So, how is the isolation provided, that is a major you know discussion point for the firing circuit for any of these devices which require continuous pulses. So, let us look at isolation, how to provide isolation?

Most of the times the isolation is provided using something called Opto-isolator or Optocoupler. And this is all electronic portion, I am not even talking about power portion, we do everything electronic and then connect it to the gate and we are done with the electronic portion. The power portion is a completely different circuit, again I have to connect it in a proper format and then I have to make sure that everything works well. The grounds will be different, that is what I am trying to say.

So let us say I have again a DC DC converter itself, maybe with a transistor, I am showing a BJT, I am going to have probably a diode, freewheeling diode, and a DC motor drive and here is my power supply. I might like to have actually this particular switch on only for maybe 40 percent of the duration, 60 percent of the duration it is going to be off and so on, maybe I want lower speed, so that is why I am going to have the requirement of having only 40 percent of the voltage as compared to whatever is this V_{dc} value.

So, this is 40 percent, and this is 60 percent. So, which means I have to make sure that this device is on only for the 40 percent of duration, how I will generate this is a matter of detail. But I can probably give you one of the schemes, normally what we do in analog electronic circuit-based implementation is we try to get a sawtooth wave generated at this particular frequency. You can definitely generate a sawtooth wave with N number of analog electronic circuits that are available.

If you just put on Google sawtooth generator, it will tell you, because CRO has a sawtooth generator within itself. So, this is a sawtooth generator at a required frequency. Let us say I want to operate this transistor at 10 kilohertz, I will get a sawtooth generator at 10 kilohertz. So, I will basically make an oscillator kind of circuit at 10 kilohertz, which is generating sawtooth. Now, I can put a comparator with Op-amp. I can compare this sawtooth output with that of some constant DC voltage.

DC voltage can be obtained from a regulator power supply, that is not a problem. So, I can compare these 2, now what I am getting as the output of the comparator will be, wherever it is high it will be actually giving me positive, provided I had given this to the positive terminal and I had given this to the negative terminal of the Op-amp, 741 for example. I can give positive terminal to the Op-amp, DC voltage to the positive terminal of the Op-amp and this particular sawtooth is the negative terminal of the Op-amp. So, I have got clearly 40 percent on time and 60 percent off time.

If I want to vary this, have to just vary the level of this V_{dc}, whatever I am giving from, let me say V_{dc1} because this is V_{dc1} have written or V control voltage, it will control basically how long it is going to be on and how long it is going to be off.

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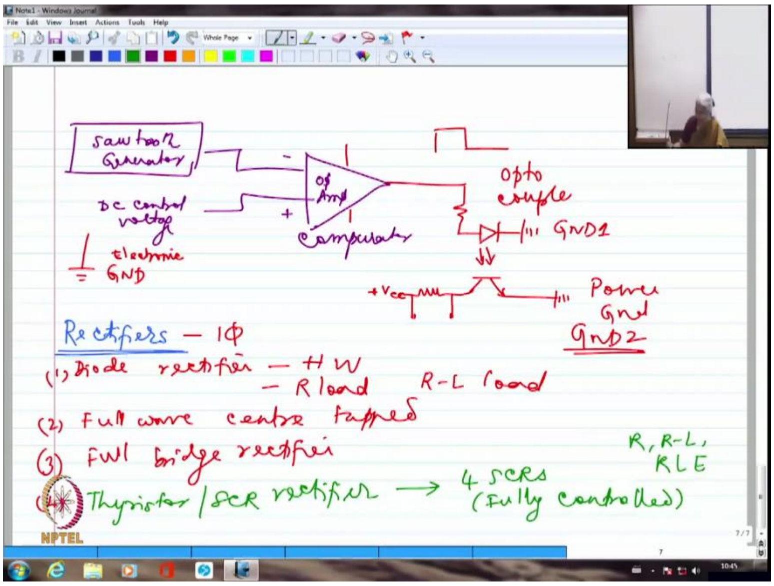

So, now let me show this in the form of a block diagram, I have a sawtooth generator, I have a DC control voltage, both of them are fed to an Op-amp comparator. So this is plus and this is minus. What I get from here, obviously will be a waveform what we wanted, depending upon how much is + V_{CC} and - V_{CC}. So, I will get correspondingly this value. Now, this I could have given directly to the transistor to turn it on, provided I did not need an isolation. But I want an isolation, so I cannot give this directly to the transistor. So, what we use in between is something called an optocoupler.

So, in an optocoupler internally there will be an LED inside an optocoupler. And there will be a photo transistor on which this light will be falling at its gate, in the photo transistor's gate, so it is a small chip, within the chip there will be an LED and there will be a photo transistor and exactly the LED's light that is being emitted will be focused on the base of the photo transistor. So, this will be connected to the ground and I am going to have here this is connected to V_{CC}.

Now I will have definitely ground here as well. I will have grounds for sawtooth generator for the regulated voltage and everything. So, if I call this as ground of electronics, whereas this will be connected to the power ground. This will be connected in all probability or if I call one as GND1, the other one is GND2, the two are not connected together.

Please understand this optocoupler is coupled to the primary side and the secondary side are coupled to each other with the help of light, it is not connected through anything else, electrically they are not connected. They are connected only because of the light that is being emitted from the LED. So, they are not conductively connected, no conductor connects both of them. So, one side of the optocoupler is connected to the LED, that ground is different, whereas this ground. So, if I may call this asGND1, this becomes GND2, other ground.

So generally, in most of, 99 percent of BJT, IGBT, MOSFET applications, we have to use optocouplers, So, this optocoupler essentially makes sure that the pulse is transmitted from one side to the other side without really having any electrical connectivity. So, the grounds become completely isolated, now whatever is available across this resistance will be exactly the same pulse, So, we should be able to get this to our gate circuit wherever we want to transmit it finally.

So, this portion is completely electronics, whereas we have to still work on the power portion, which we have not started as yet. So, so much so for the pulse generation and pulse transmission in the case of maybe BJT or IGBT or MOSFET and how the power ground and the actual electronic ground are isolated. So, we will be starting on rectifiers, let me at least give you a prelude as to how we are going to proceed today and then we will be starting on the actual rectifier portion.

I think you will require circuit theory concepts very thoroughly for this. So, if you guys have somewhat forgotten, I would request you earnestly to revise your subject theory concepts to some extent because we will be looking at RL circuit invariably, sometimes RC circuits, sometimes RLE, because battery charging for example is like RLE circuit. DC motor drive for example is like RLE, because I will have back EMF, so you should know how RL circuits behave, how RLE circuits behave, how RC circuits behave.

And whether I have R and C in parallel or R and C in series, so I want you guys to revise these portions because we are going to superpose whatever you know in circuit theory along with devices. So, it will be definitely more complex, that is the reason I want you guys to revise. And I will be concentrating extensively in waveforms, quite a lot. Power electronics is nothing without waveform, so we need to draw waveforms. Like if I apply a sinusoidal voltage, how is the output voltage going to look like, at every instant of time, what will be the voltage across the devices?

All these things we will have to look, so that is the reason we will be concentrating on waveforms extensively. And I would like you guys to practice drawing waveforms for different circuits. So, when we start, we will first start with simple diode rectifier, that too half wave. Only one diode, not 2 diodes. If 2 diodes are there antiparallel, then it will conduct all the time during forward biasing as well as reverse biasing.

So, we will look at this and this with R load RL load, we will start off with this first. Then we will go to the same rectifier, diode rectifier, maybe full wave but we will look at centre tapped rectifier. Then we will go for full bridge rectifier, then we will go for, all these are single phased of course, first, all of them are single phased. So, we are looking at single phase to DC conversion, single phase AC to DC conversion. Then we will look at thyristor or SCR rectifier.

So in SCR rectifier, again we will be looking at fully controlled, that is 4 SCRs are used in a bridge, so this is known as fully controlled rectifier. So, in fully controlled configuration, we will be looking at R load, RL load, RLE load, all 3 of them. In this we will have to derive the expressions, we will have to look at the waveforms, we will have to look at the different factors like power factor, how that is affected and we would also see how the fundamental current is, fundamental voltage is, that is 50 hertz current and 50 hertz voltage and what is the displacement between them, all those things we will look at.

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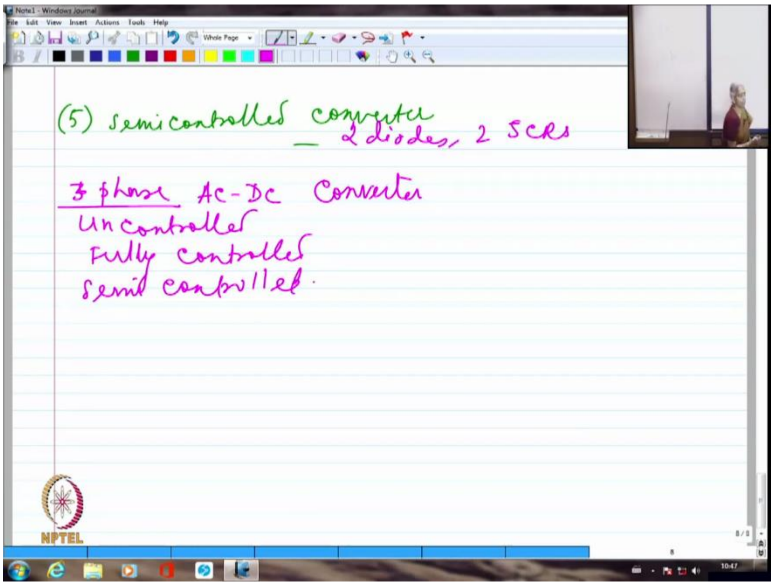

Then we will go for something called semi-controlled converter or semi-controlled rectifier. I use the terms converter and rectifier interchangeably, both of them mean basically AC to DC converters. So, in this particular case we will use 2 diodes and 2 SCRs. So, they behave differently compared to when we use only SCRs, they behave differently, so we will have to look at them. In this case also we will at least see R load and RL load. You can try to do the simulation in a very simple software called PSIM.

So, PSIM if you try to look at it, you can simply put the components and see the waveforms very very easily, even much simpler than MATLAB. So, you guys will be introduced to PSIM and Simulink MATLAB in this particular course for sure, if you have not been introduced already. Then we will go for three-phase. So, three-phase AC to DC rectifier. So, in this again there will be fully controlled, you can start off with diode, then diode converters are uncontrolled, then fully controlled is all 6 devices because three-phases I will need 6 devices, all 6 devices will be SCRs, fully controlled.

Then semi-controlled, so which means 3 diodes and 3 SCRs, so we will look at all 3 configurations, that is uncontrolled, fully controlled and semi-controlled with all different loads. So, we will look at all these configurations, so I would request you to revise the circuit theory concepts thoroughly, then we will start off on the rectifiers in the next class.