Electronics for Analog Signal Processing - I
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Lecture -10
Zener Regulator
and
Voltage Regulator

In the last class, we saw that the diode can be used in the breakdown region as a Zener diode and it can be primarily giving you secondary power sources called Zener Regulators, DC power sources.

Now today, we will discuss how to design a Zener Regulator. It is given that a DC voltage V i has been generated after it has been sort of stepped down or stepped up from the power supply using a transformer. Then, using rectifier diodes, the unipolar conversion has been achieved for the voltage and capacitive filter has been put so that the voltage is essentially at unipolar DC voltage, with very little ripple. That has been done; and that design, we have learnt how to do.

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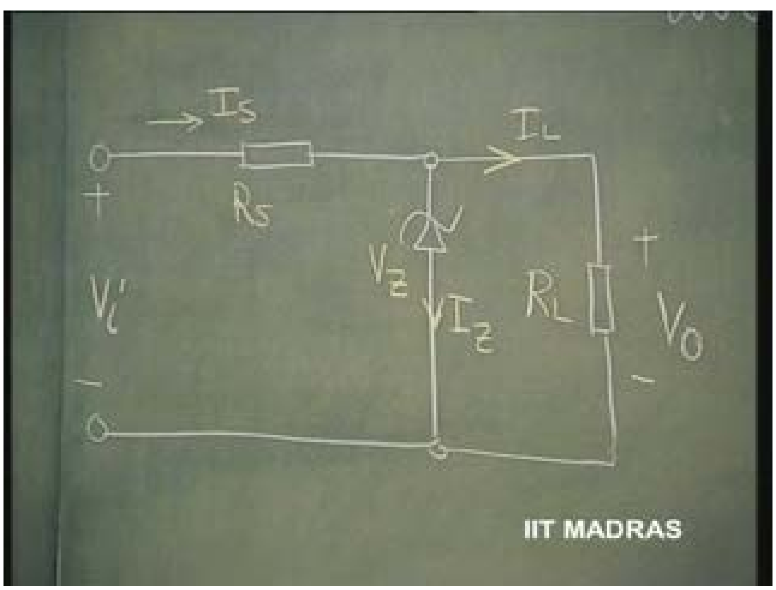

So, this is the output of such a converter, AC to DC converter, which obviously responds to input variation. If the input AC varies, the output DC will correspondingly vary; and therefore, we do not want this DC voltage to vary. We want a DC voltage which is going to remain constant so that we can use this constant voltage in biasing all our active devices later, so that we can do the design properly.

Now, such a regulator when it is required, when output DC is required to be regulated, that means, it should be remaining constant at a given value, with very little variation. One way of achieving such a thing is using this Zener Regulator. So, this unregulated voltage V i is therefore called unregulated DC. What does it mean? It is permitted to vary from V i minimum to V i maximum.

This is the variation resulting in… sort of problem for us because, we do not know where exactly we can assume the DC to be remaining constant. It does not remain constant; it keeps varying.

Suppose it varies; the operating point of all the devices will also vary correspondingly; and the design becomes difficult. So, how do we get this information about V i minimum and V i maximum? This can be got from how much your power supply varies. Let us say, it is varying from 180 volts rms to may be 280 volts rms. This kind of variation is possible; quite possible. Correspondingly, this will vary from a minimum to maximum; corresponding to 180 volts, to find out what the DC voltage is; corresponding to 280 volts, what the corresponding DC voltage is. You can then get the range of variation possible for V i.

Then, I am going to put a Zener diode. So, we know that the Zener breaks down at a specific value of voltage; then it can maintain that voltage constant. Obviously, in order to limit the current in the Zener, I will put a current limiting resistance, R s. This is essentially necessary so that our Zener is going to have a current which at most can become equal to I s.

So Zener characteristic, you know already, that it is going to be a diode characteristic, which has a break down characteristic like this.

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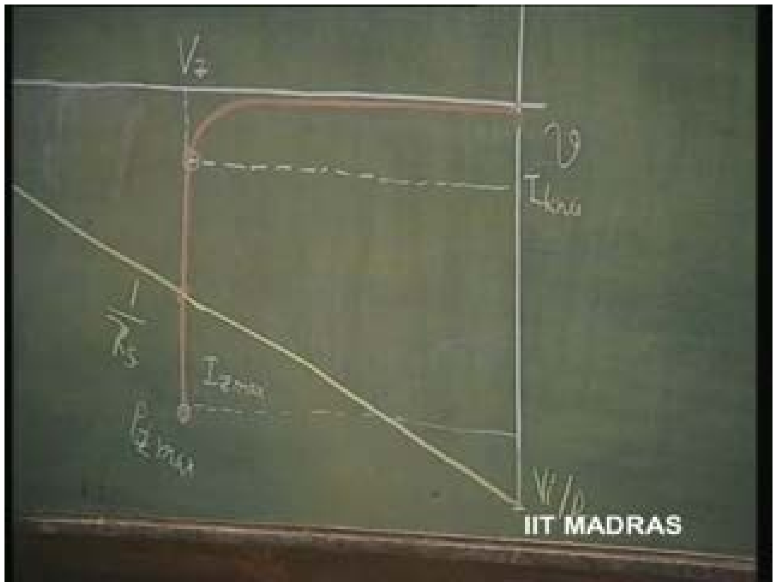

The Zener diode can operate anywhere in this range; this range of operation from the point where the voltage becomes almost constant and the current can vary to any value, this range is the region of operation for the Zener. Therefore, this point is very crucial where the diode has been reverse biased and the diode resistance is almost infinity here; and thereafter, this current increases, the leakage current increases, and it starts breaking down.

The point where it becomes constant, the voltage becomes constant; this is called a knee point. This is the knee of the curve; so, this current is the knee current. This is specified by the manufacturer. So, one should know that Zener is operated as a Zener diode only above knee current. That means, the current through the Zener should be greater than the knee current; but obviously, there is a limit on how much power this Zener diode can dissipate.

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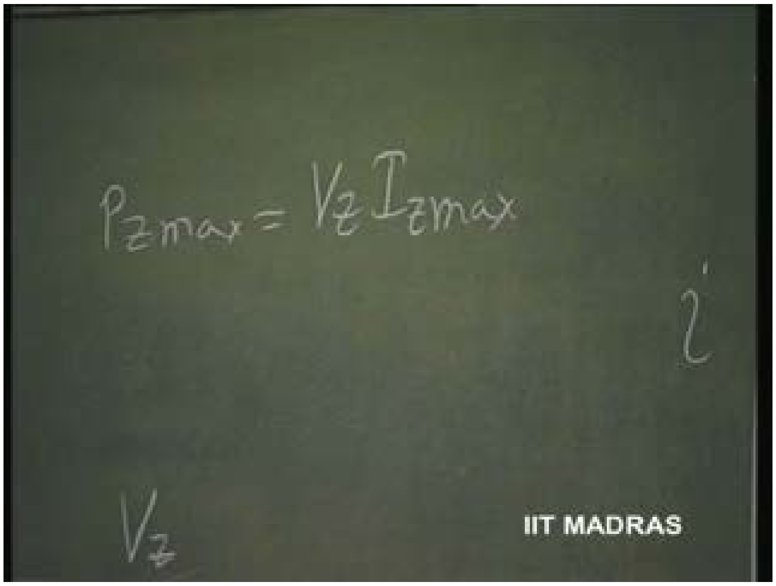

So, that means, this point here, another point, this is corresponding to P z max, the power maximum. What is the power maximum? P z max corresponds to V z into I z max. z is essentially remaining constant; and therefore, V z into I z max is the power that can be, maximum power that can be dissipated in the Zener. So, this is also given by the manufacturer.

That means, if power max is given, you will come up with the maximum current that can be permitted to flow through the Zener. So, that means, the Zener diode can be operated only within this current as a Zener diode. The current through the diode has to be always, that is, I z should be always lying within this range so that the voltage across the Zener is constant; that is the idea in this design.

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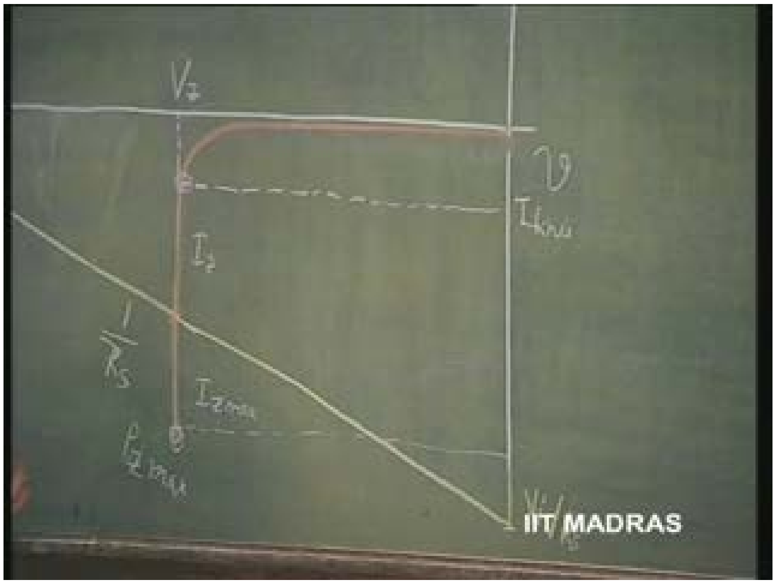

So, the idea in the design is that I z can be permitted to vary only between I knee and I z max. Now, you might wonder why it should vary. We know that V i varies from V i minimum to V i max. That means the current in this I s, which is nothing but V i, here, this voltage, minus V z by R s. So, this is V i, this voltage; this is V z; therefore, the voltage across R s is V i minus V z divided by R s.

This current now can be therefore varying because V i is changing from V i minimum to V i maximum. That means, I s is going to change from I s minimum to I s maximum. How is it found out? Because, this is changing from V i minimum minus V z by R s to V i maximum minus V z by R. This is the range of variation of this current. If this is changing from a minimum to maximum, obviously, the current in this is going to change from a minimum to maximum. Why?

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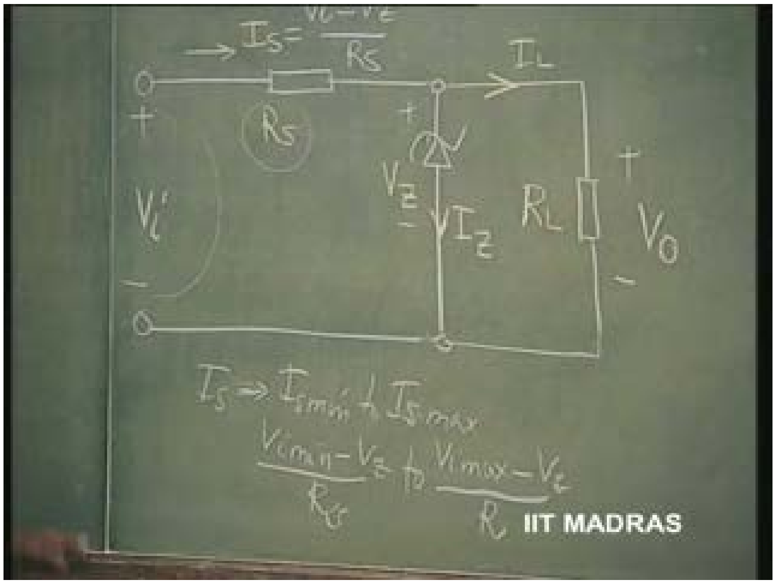

This voltage is essentially constant. That means, I L is essentially constant, if R L is constant. So, if R L is constant, then, I L is going to be constant. You are going to therefore deduct this I L from this. So, I z is equal to I s minus I L. Due to Kirchhoff's law, I z is equal to summation of this current plus this current. So, what goes in the load is removed from I s; that will be the current permitted to flow through Zener.

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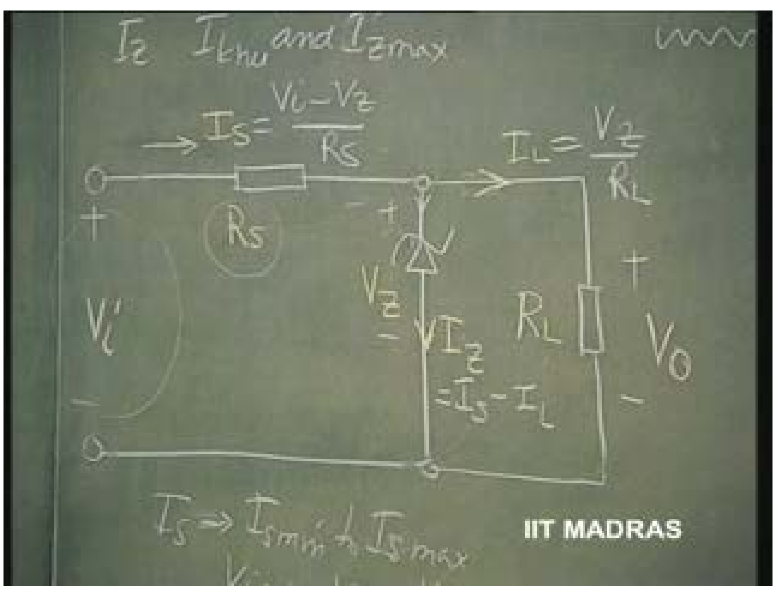

So, in order that this voltage remains constant, I should see to it that I s minus I L, which is I z, is maintained within this range at all times. If this is fulfilled, then the design is a good Zener Regulator because, then I can assume that V z is remaining constant.

So, let us therefore write down the equations necessary for doing the complete design. We know that I s is varying from minimum to maximum. Then, what is the I z minimum to maximum? I z minimum corresponds to… now, you might say, Sir, I can also have R L changing because R L… we are only designing the voltage regulator; current can be changing depending upon R L; so, I L can change. Then, we have to be careful. I z minimum is nothing but I s minimum minus maximum of I L.

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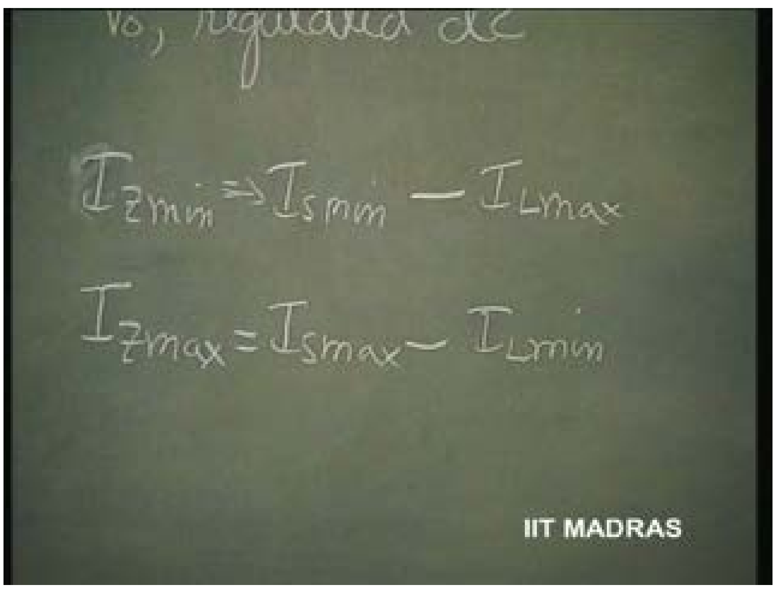

So, that is the worst case minimum for the Zener. Suppose I take the maximum from the minimum value; that is, the lowest current that can ever flow through the Zener. So, I can therefore find out if, I know the load variation, what the I L maximum is. Then I subtract, I s, I L maximum from I s minimum; that is I z minimum.

What is I z max going to be now? We will take I s max; subtract from this, the minimum possible current, load current. So, we already have I s minimum and I s maximum from this, in terms of V i minimum and V i maximum; and if we are told what I L max and I L minimum are going to be, then, I would know what I z minimum and I z maximum are.

That means, I have to select what? R L is not under your control; V z is the specified voltage to be regulated; so, it is regulated. DC voltage; it is fixed. R L minimum and R L maximum are known to me; V i minimum and V i maximum are known to me. So, the only design parameter here to be considered is, fix up R s; fix up the value of R s so that, I z minimum and I z maximum lie within this range.

I knee, we need i knee; and I z max permissible for this region. That is really the design problem. So, just after this, we will work out an example wherein we will in fact design this regulator for a specific variation in V i and a specific variation in load.

Consider Example 15 now. Design a Zener Regulator to give a regulated voltage of 6 volts. The moment that is fixed, you can fix the Zener.

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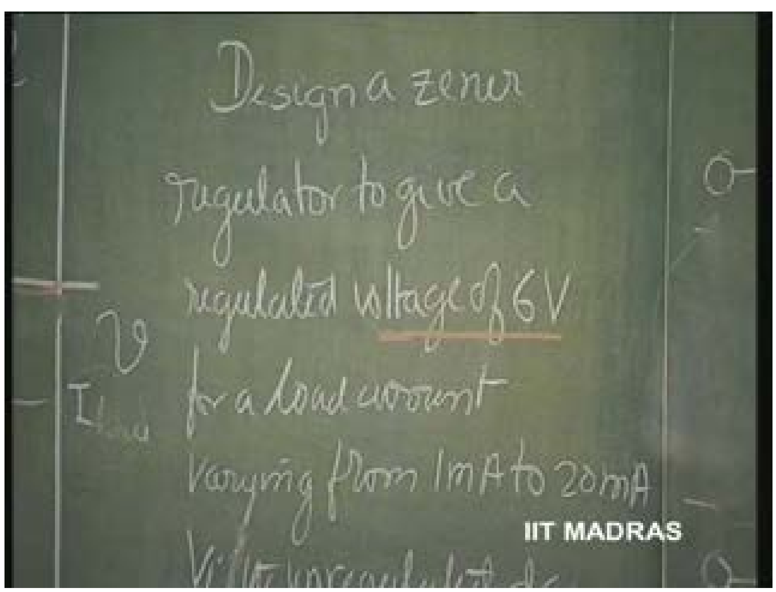

Now, the first part of the Zener, Zener voltage should be V z equal to 6 volts; that is all. One part of the design is over.

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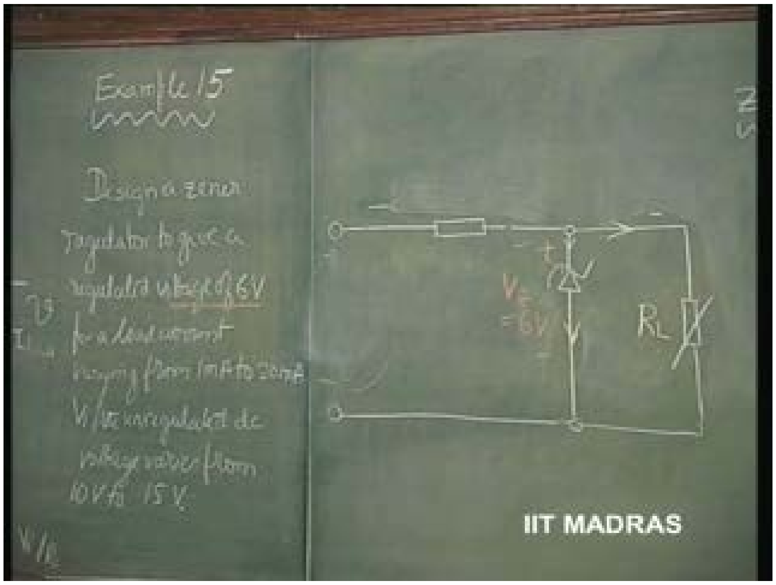

Voltage of 6 volts, for a load current varying from 1 milliampere to 20 milliamperes. This current is varying because this load is changing, say, 1 milliampere to 20 milliamperes. That can be also given in terms of load changing from 6 K to about 30 ohms; 6 K to about 300 ohms. Now, the input is supposed to vary from 10 volts to 15 volts. Fix up the value of R s.

Now, let us say, we have taken a Zener; and from the Zener diode manual, I can find out, for 6 volts Zener, what the knee current is, and what is the maximum current. Let us say, Zener chosen, this is, as I z knee equal to, let us say, point 1 milliamperes and I z max which can be got from power maximum is equal to, let us say, 50 milliamperes.

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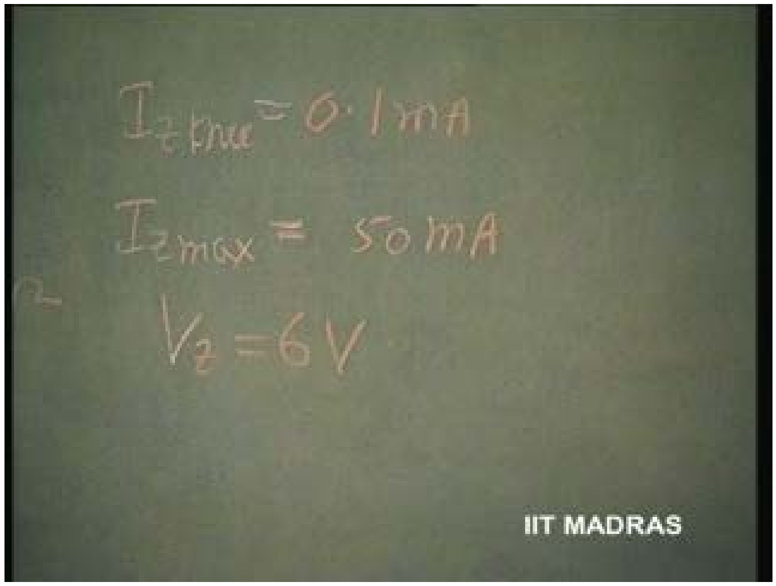

One thing we should select. How do I select this? Obviously, I z knee should be pretty low. I z max should be at least greater than the maximum current that is going to be given to the load. So here, 20 milliamperes. So, it should be greater than 20 milliamperes, so that there is some current still left for the Zener. So, let us say, it is 50 milliamperes for this Zener, which is having a V z of 6 volts.

So, how do we do the design? Let us consider when the input is 10 volts, what should happen? This is, say, input is 10 volts; Zener is breaking down at 6 volts; so, 10 minus 6 is the drop across this. So this is the drop; that is 4 volts. That divided by, this has been taken as minimum; so, the minimum current now available in R s is 10 minus 6 divided by R s.

Suppose R s is a range; I have not yet chosen R s. So I would like to know what should be the range of R s which is permissible for my design. So, 10 minus 6 is the minimum voltage available; for that, I divided by the maximum resistance possible here that will give me the minimum possible current in this circuit. So, this is the minimum current, I s minimum. That should be such that if I deduct from this, 10 minus 6 by R s max, this is the minimum current; I will take out the maximum current to be given to the load; so that is 20 milliamperes. Now, this is what is left as the minimum possible current through the Zener; and that should be greater than, this current should be still greater than, point 1 milliampere. Is this clear?

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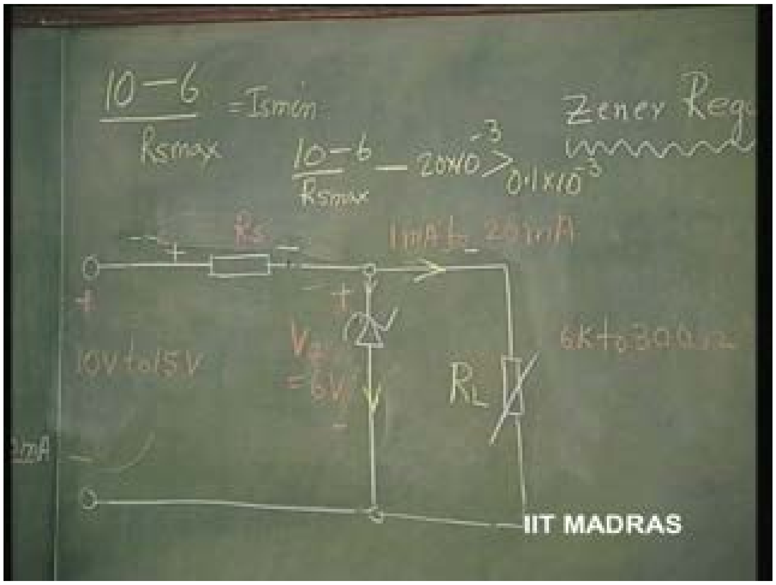

So, we have taken the minimum possible current in R s; subtracted from that, the maximum load current, arrived at the minimum possible current that can be permitted through the Zener, at which time, the Zener should still function satisfactorily. That means that current should be greater than the knee current which is point 1 milliampere. Now, this equation should give us the value of R s max.

Next, when this is 15 volts and I deduct from this the Zener voltage 6, 15 minus 6 is the maximum voltage drop here, so that is going to lead us to the maximum current I s, if R s is minimum. Under that situation, that is the possible maximum current.

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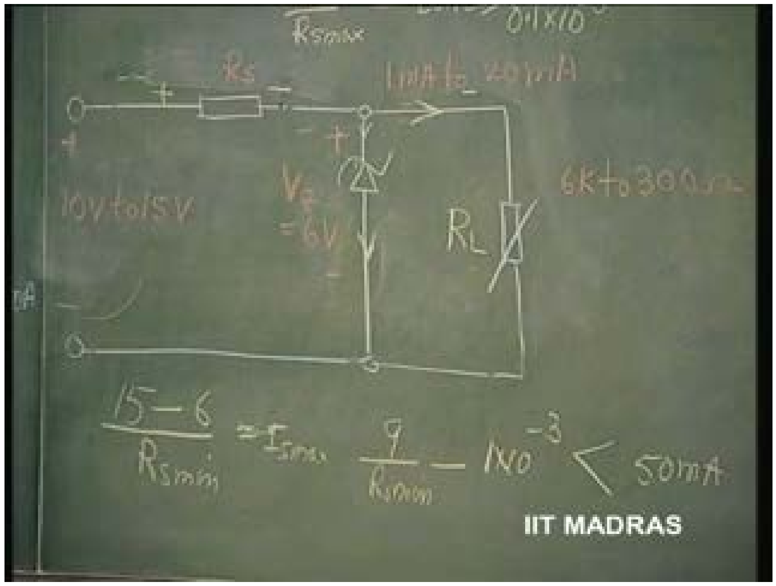

And, I deduct from this, the minimum current; this is actually I s max. From this I s max, I deduct the minimum current that will be then left with the maximum possible current through the Zener. So, this is going to be 9 by R s minimum minus, how much is it … 1 milliamperes; that is the minimum load current that should be. This is the maximum current. This should be less than the maximum possible current for the Zener, which is given as I z max, which is 50 milliamperes.

So, this equation, which is nothing but 4 by R s max minus 20 into 10 to power minus 3, should be greater than point 1 into 10 to power minus 3, which is actually speaking, 20 point 1. I am going to shift this 4 to this; so 20 point 1. So, R s max, you take it there, 4 divided by 20 point 1 milliamperes. R s max will come here; this will be 4 into 4 divided by 20 point 1 K.

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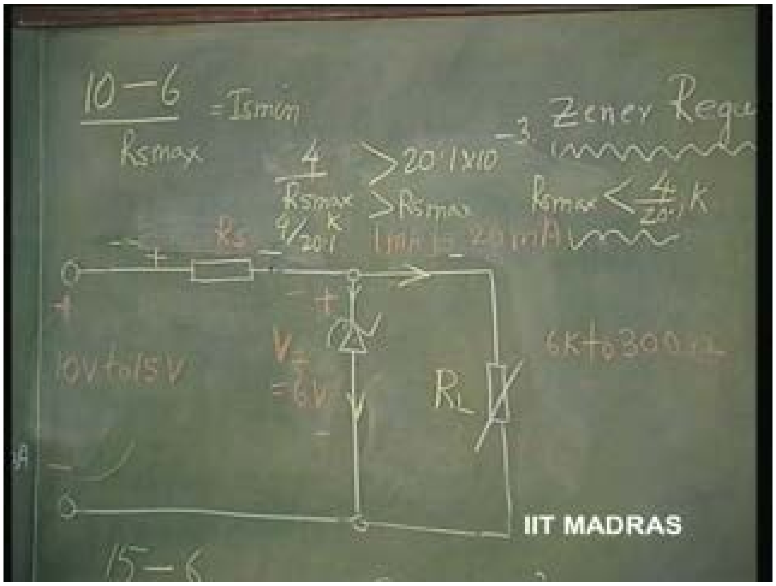

4 divided by 20 point 1 K should be greater than R s max; or, R s max should be less than 4 by 20 point 1 K. Is this clear? Now that is that equation.

Here, 9 by R s means, should be less than… this is 50 milliamperes; this is 1 milliampere; so, 51 milliamperes. So again, R s minimum is 9 by 51 milliamperes or 9 by 51 K; 9 by 51 milliamperes or 9 by 51K. Or, R s minimum should be greater than 9 by 51 K.

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So now, we have calculated these resistances. R s max is 4 by 20 point 1 K, which is 199 ohms; R s minimum is 9 by 51 K, which is 176 ohms. That means, the R s that you have to select, R s has to be such that 176 is less than R s and 199 is greater than R s. In fact, 176 is less than R s; R s is less than 199. This is the range; so the preferred value in this, we will select R s as 180 ohms. These resistances are available, to select any preferred value within this range; 180 ohms.

Now, for this resistance, we have to give specifications in terms of its wattage. So, the power dissipation in the resistance, maximum, V s max; that is, V s square divided by R s, which is the maximum drop across this is when this is 15 volts minus 6, that is, 9 square divided by 180 which is 81 by 180 which is equal to 450 millivolts. So, that means, I can select the resistance as 180 ohms Half Watt. These are standard resistances available for you to design the whole thing.

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Now, the design is complete in the sense that we know the resistance R s to be chosen, we know the Zener to be used along with this, and the Zener Regulator, if it is connected this way, it will work satisfactorily; that we know.

Now, some finer points regarding the design. I would like to mention that this Zener Regulator, I would like to see how it functions in terms of the graph. This is the theory here. Graph - let us see. This, please remember, is similar to what we did in the case of a diode and load line concept. Even here, we can bring about the load line function.

This is the diode characteristic. So, Zener diode characteristic is this; and we know that V i minus V divided by R s is another equation to be satisfied. So, this is going to be the current, I s. If the other load resistance is infinity; let us say R L is open, open circuit. That is, R L value is infinity; then, I can say that I s is same as I z. So, I s becomes same as I z.

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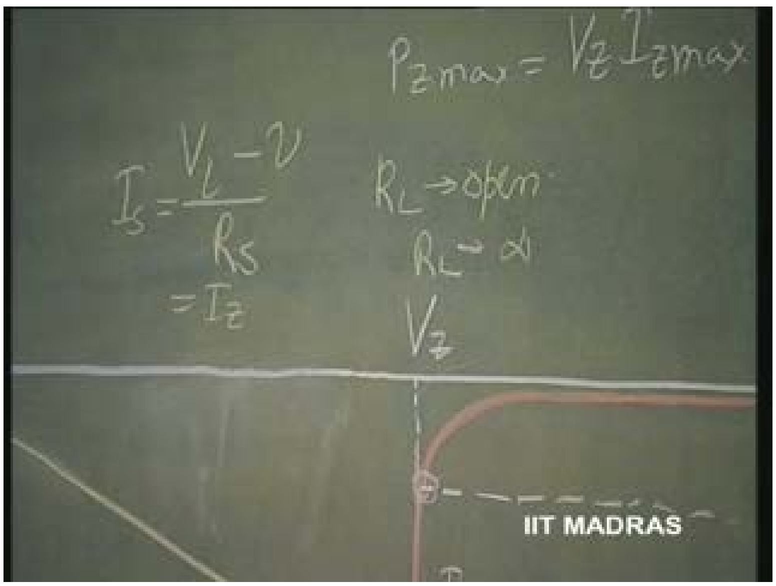

That situation, it is simple Zener diode circuit; V I, R s and a Zener. It is not complicated. And, the Zener current is same as I s. So, under that situation, we can say that, this equation is this. This is the voltage V, which is now equal to V z. So V i minus V z by R s is the current I s. So, this is the equation that is plotted here; equation of a straight line with slope equal to 1 over R s; minus 1 over R s here. Both both current and voltages are negative; so, 1 over R s. And, this is the operating point for the Zener; or, this is the Q point. This, we had deferred (Refer Slide Time: 27:36) to the diode circuit also earlier, diode Q point.

Here, the Zener Q point; the Zener is biasing at this point. So, you can see here; the Zener voltage is almost constant there. So, it is V z; and therefore, it is very simple to obtain the operating point. If V is very close to V z, then I s is nothing but, I z is equal to V i minus V z by R s. This is, as the current, this is the current of operation.

So, suppose V i varies from, let us say, 10 volts to 15 volts or whatever it is, for another voltage of V i; the slope remains the same. So, this is parallel line; so, it is shifting. So the operating point shifts here. So, what did we do in the case of diode circuit?

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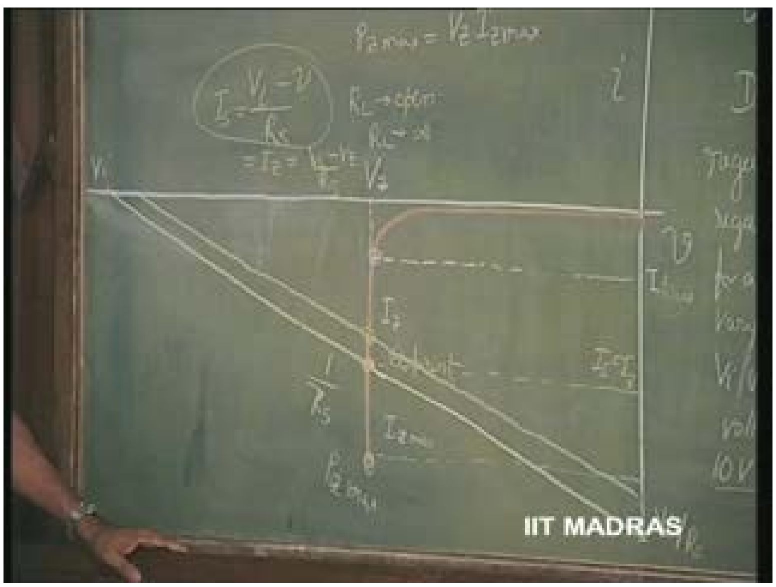

We said, this variation may be so small that this is assumed to be linear. That means, this is essentially going to remain very nearly constant at V z. Only this current is going to change now to a new value, which is, the new value of V i minus V z by R s.

Now, if this is vertical like this, there is absolutely no change in voltage; only the current changes.

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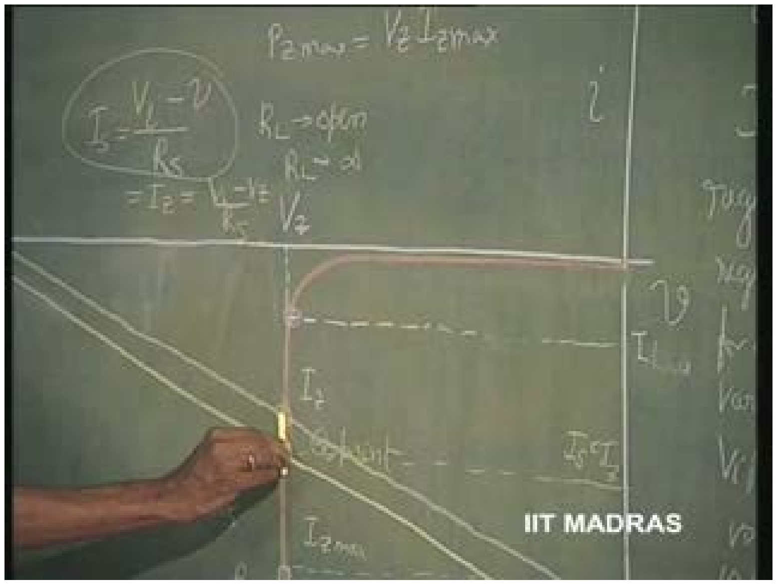

If it is not vertical, if there is a small slope, that is the case. With Zener diode, this slope, which is nothing but Delta V z divided by Delta I z around the operating point I z. That is the slope; Delta V z. Inverse of the slope is Delta V z by Delta I z; actual slope is Delta I z by Delta V z.

So, if this is vertical, this resistance, this is called the Zener small signal resistance, small signal equivalent resistance. Typically for the Zener diodes, it is of the order of tens of ohms; so tens of ohms.

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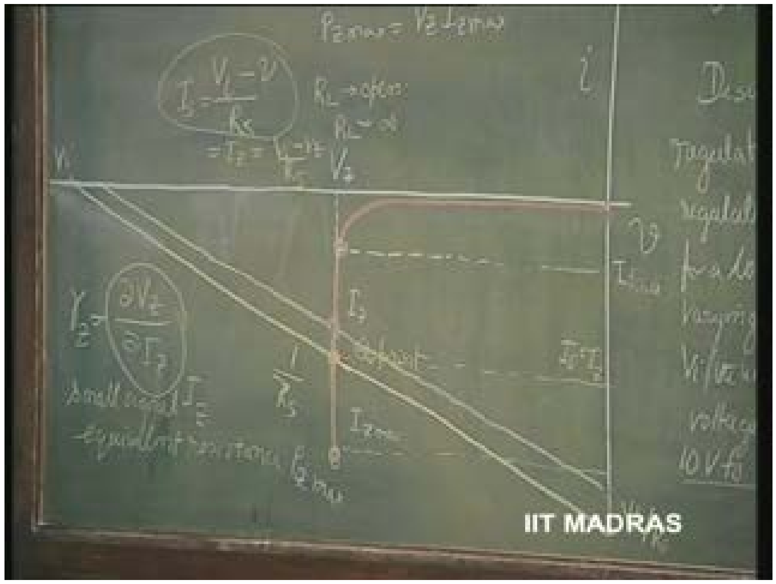

In fact, this resistance which is of the order of tens of ohms may be really negligible compared to this series resistance that you are putting here. That means, essentially, this loop is almost vertical compared to this loop; that is what it is. That means, most of the change in the current is brought about by the change in voltage here; and that will directly tell you that the change in current and the change in voltage, they are related linearly, if you were to replace this by means of a linear resistance.

Now, what is the change? If you are interested in change, I told you, you can replace the whole circuit, only for changes, in terms of the equivalent circuit. What is it? So, let us say that this is the change, Delta V i, that is occurring. Change in voltage is from 10 volts to 15 volts. So, Delta V i is 5 volts. So, for the change in voltage, this resistance is remaining as whatever R s; and the Zener diode; if it is an ideal Zener, you would have represented it as a battery with V z, simply battery.

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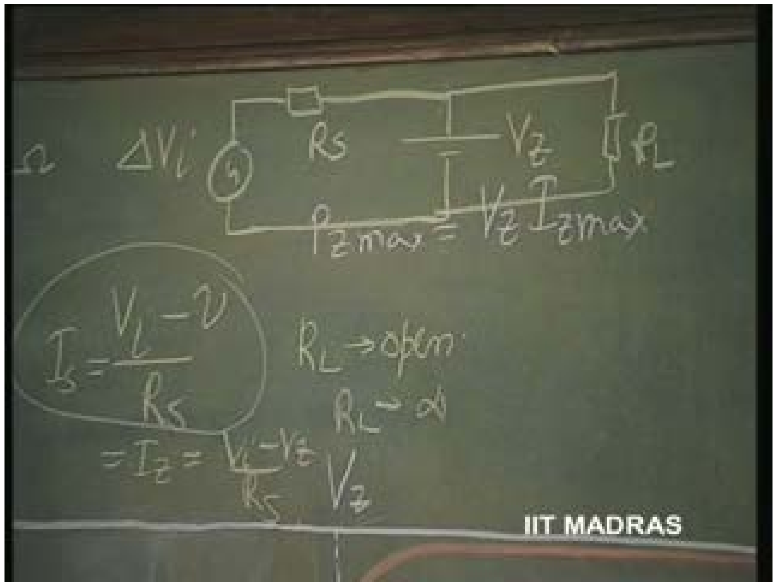

So, no change occurs here at all in the voltage of the Zener across the terminal of the Zener irrespective of the current in this. So, you can always assume this to be constant. So, you can replace it by means of a battery; and then of course, you can put down here. This is the case if this were absolutely vertical. So, there is no change in V z; so, I can replace it by means of a battery.

If it is not vertical, then I will say that there is a series resistance associated with it. So, I will replace it by means of an equivalent circuit which is R small z and a battery.
So, as far as this battery is concerned, it is of no consequence for changes; so it is a short circuit. So, equivalent circuit of a Zener diode for the whole thing is a battery in series with R z.

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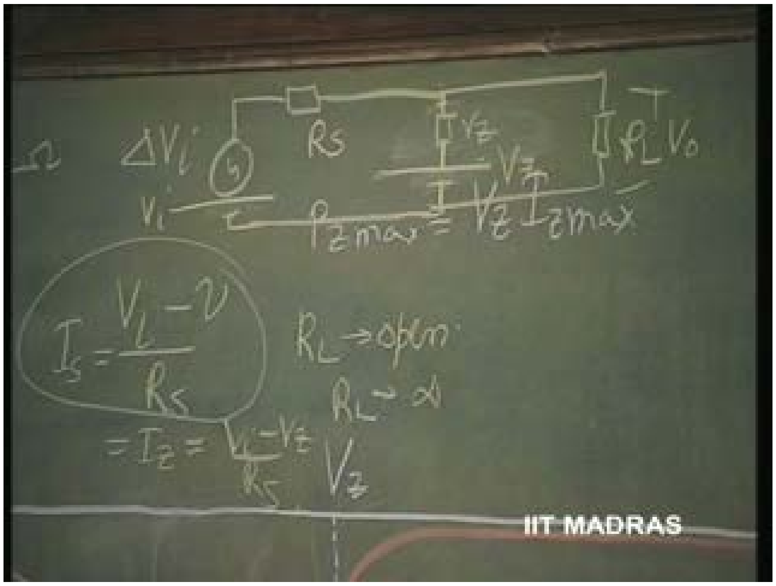

For the changes, please remember, once again let us put, if it is this V i; then, I have to put this for the whole voltage as a battery with V z. Then, this will be the V naught, total V naught. This is the complete equivalent circuit for the Zener. Now, for the changes, I can simply, since I can apply superposition now, it is a linear circuit; for this voltage, I can separately find out all the situations; and for this voltage, I can again find out the situation.

So, I would like to see, for only the changes, that means, this battery with Delta V i which is R s, r z and R L. So, this is the circuit which will give you all the changes in currents and voltages that will now occur.

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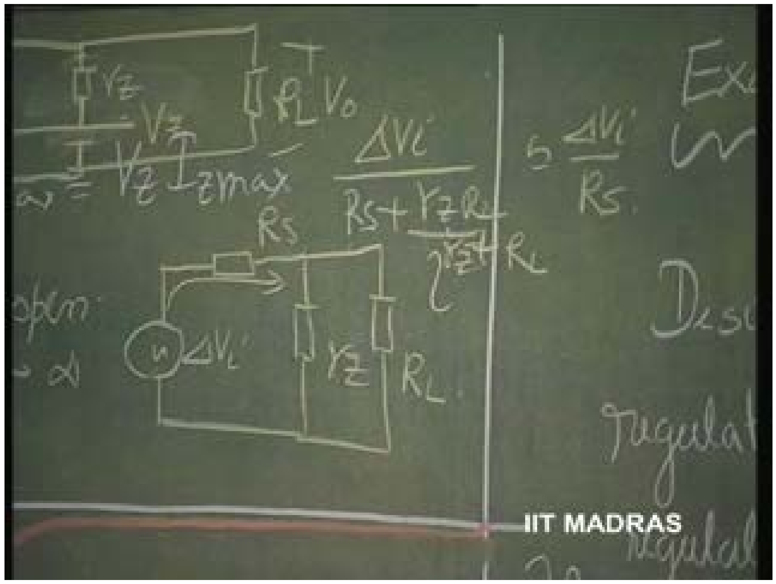

Let us use this. This is Delta V i. So, what is the change in current in the circuit? That can be easily obtained by Delta V i divided by R s, this is one resistance; plus R z parallel R L. This is essentially, R z is so small and R L may be also small; essentially, R z parallel R L is negligible compared to R s. So, it might become essentially Delta V i by R s.

This is the current limiting resistance; earlier that has been put. Typically in our example we have chosen, it is 180 ohms, we said; and this is tens of ohms and shunted by resistance of the order of 300 to 6 K. So essentially, it is R z itself; and therefore, it is essentially Delta V i by R s in this problem.

Now, what is the change in voltage at the output here, I would like to know. That can be evaluated by multiplying this current by effective resistance here; which means, this into r z R L divided by r z plus R L. So, we can say that this is Delta V i into r z R L by r z plus R L or essentially approximately equal to Delta V i by r s into r z because r z parallel R L is r z itself.

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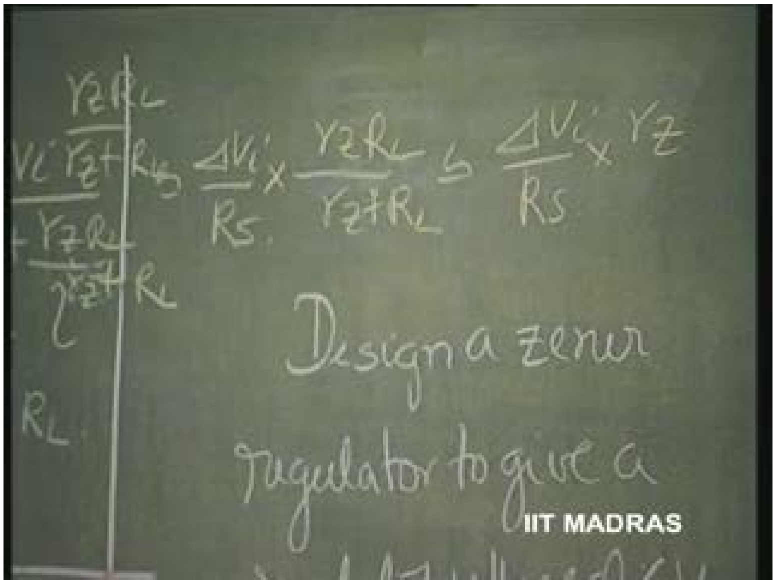

So, we can see that the change in voltage here… Typically, let us see; in this problem that we have chosen, change in voltage is 5 volts. For a for a 5 volts change in voltage, this is, let us say, r z is 10 ohms; this is what is given by the manufacturer. What is the typical value of Zener resistance? Manufacturer will tell you for this kind of Zener around the operating point. What is Zener resistance? 10 volts let us say, divided by R s; in this case is 180 ohms.

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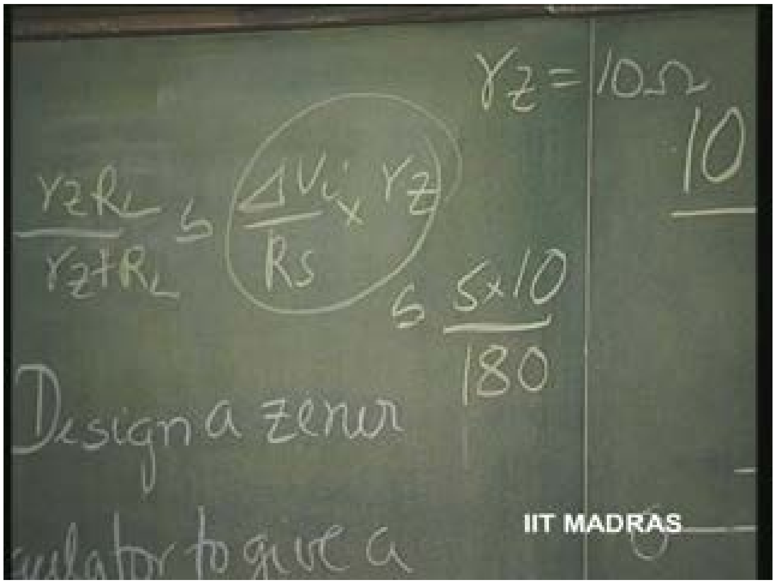

So, you can see that the voltage is simply 5 by 18 volts. So, it is much reduced. That means, change in voltage is very much reduced at this point. This we can note because this Zener diode is basically equivalent to a battery. If it is a battery, the change in voltage would have been zero. It is not a battery; it has a series resistance of R L. Because of that, when there is a change in voltage, there is going to be a small change in voltage here in the Zener; that is the Delta V z; and that we can calculate by using the equivalent circuit for the (( )) (Refer Slide Time: 37: 52).

So, if somebody says that the voltage changes by this amount here, we can always find out what the change in voltage is, which is extremely small, around the Zener voltage by using the Zener equivalent. Further, we can also do what is called as ripple reduction here, let us say. This is a different thing. At a given voltage, let us say, at 10 volts or 15 volts, the voltage, DC voltage, is not going to be just DC voltage. The DC voltage itself is changing from 10 volts to 15 volts; but along with this DC voltage, we have what is called ripple.

That, if you use a half wave rectifier, that ripple frequency is 50 Hertz; if you use a full wave rectifier, the ripple frequency is 100 Hertz. So, we know how to evaluate the peak to peak ripple. In our earlier method of evaluation of ripple, etcetera, we have understood that. So, apart from a DC voltage, there is a ripple here, peak to peak. So, it is not just a DC voltage of 10 volts; there is going to be a ripple here, something that is varying.

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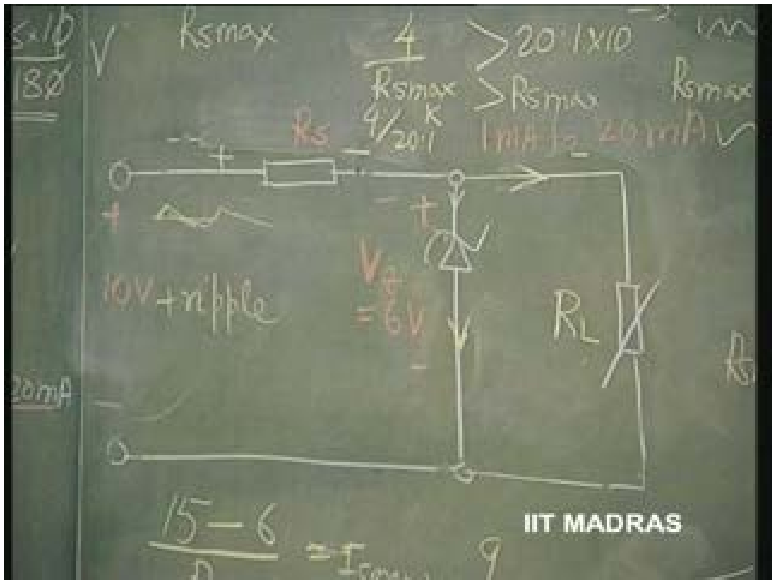

So, that ripple also gets reduced here by this factor which is R z divided by R s, because of putting… So, there is a ripple reduction; and therefore, if there is some ripple factor here, the ripple factor here is much reduced. That is an advantage of using the Zener Regulator. So, ripple reduction factor is also by the same amount.

Please understand that this is different from what I discussed previously. When the voltage itself changes from a minimum to maximum, the operating point of the Zener will change from minimum to maximum; and the Zener current will change from minimum to maximum; and then, there is a little bit of variation in the Zener voltage. So, we can no longer consider Zener is going to remain at 6 volts. It is going to vary to a certain extent; that variation can be found out from the equivalent circuit.

Apart from that, we can also find out, when there is a ripple riding over the DC voltage, how much ripple reduction occurs here. So, the 6 volts, apart from being slightly different from 6 volts, how much is the ripple that is going to be riding over the 6 volts also can be found out by using the same equivalent circuit. This equivalent circuit is more valid for ripple reduction than for this large voltage change. When there is a such a large voltage change from 10 volts to 15 volts, may be, it is not right to assume that this is linear;

whereas, definitely, the ripple itself is a small change over 10 volts. And for that small change in 10 volts, we can put down this equivalent circuit without any hesitation whatsoever.

So this kind of problem, we can discuss whenever we are confronted with obtaining an absolutely invariant DC, when AC is varying. Such Zener Regulators are quite common as secondary power sources wherein such regulation is very important so that the operating point is known to the designer beforehand; and therefore, we need not be worried about the variation that is occurring in the power supply.

Let us now consider an example which is a total design starting from the power supply 220 volts, 50 hertz. I would like to know whether the Zener Regulator that I have designed, can be fed from such a source; and how to do the design of the transformer and the capacitor. It is important. We will see the… how to fix up the value of n and how to fix up the value of C.

Now, we have known that this input voltage was assumed to be varying from 10 to 15 volts; and we will take nominally at 220 volts. The voltage is corresponding to 12 volts, we will take. Correspondingly, we can fix 10 and 15 as the maximum way and… minimum and maximum variation at the secondary of this thing.

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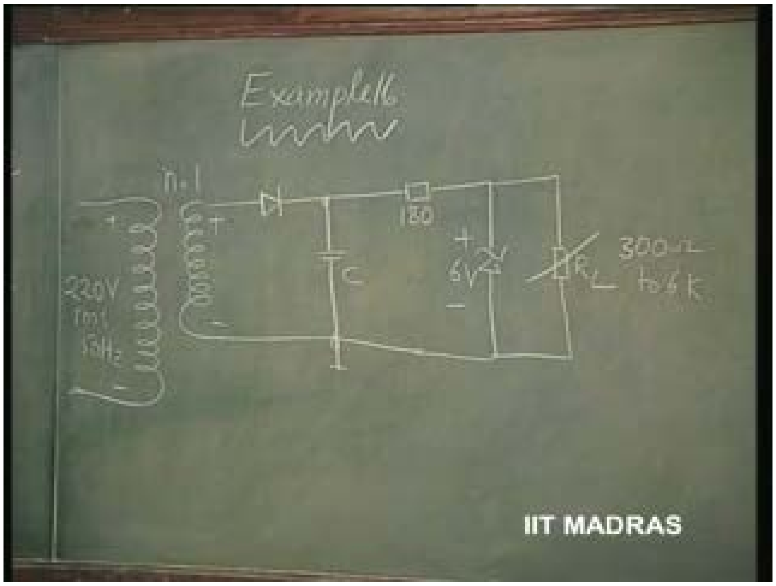

Now, for such a thing, we will design a transformer and fix up the value. How to do that? Now, the voltage here, the DC voltage, peak voltage here should be 12 volts. So, 220 root 2 divided by n is the sort of peak voltage on the secondary side; and therefore, that is to be equated to 12 volts. And n is got as 25 point 9. This is simple. This follows the same procedure that we followed in our earlier solution of different problems connected with the converter, AC to DC converter.

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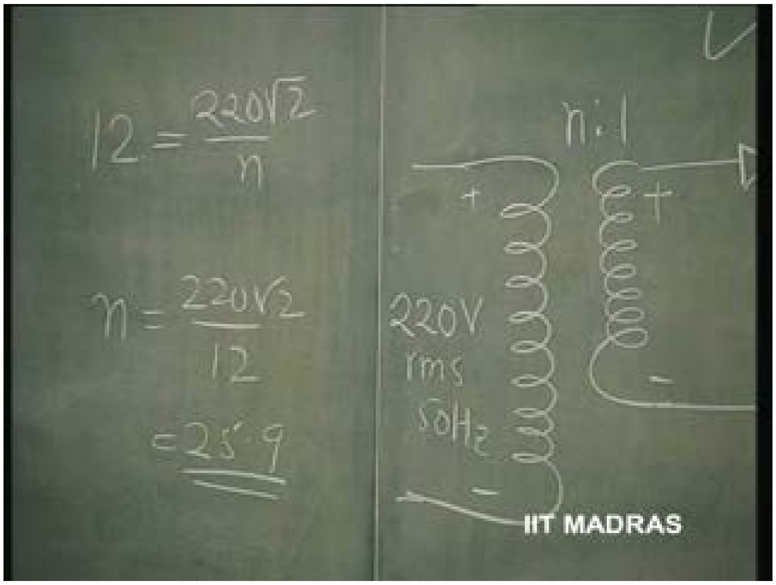

The variation comes only in this; how to select the value of the capacitor. At this juncture, the load is going to be given to you, not in terms of the resistance. 180 ohms is given as the resistance. This is not to be taken totally as the load. Load is different. Because you have connected a Zener here, if this is getting charged to 12 volts, this is 6 volts; the drop across this is now 4 volts. 12 minus 6 4 volts (Refer Slide Time: 44:00); and the current in this is fixed. 12 minus 6 is 6 volts. So, 6 volts by 180 is the current in this. 6 volts divided by 180 is the current in this; so many amperes.

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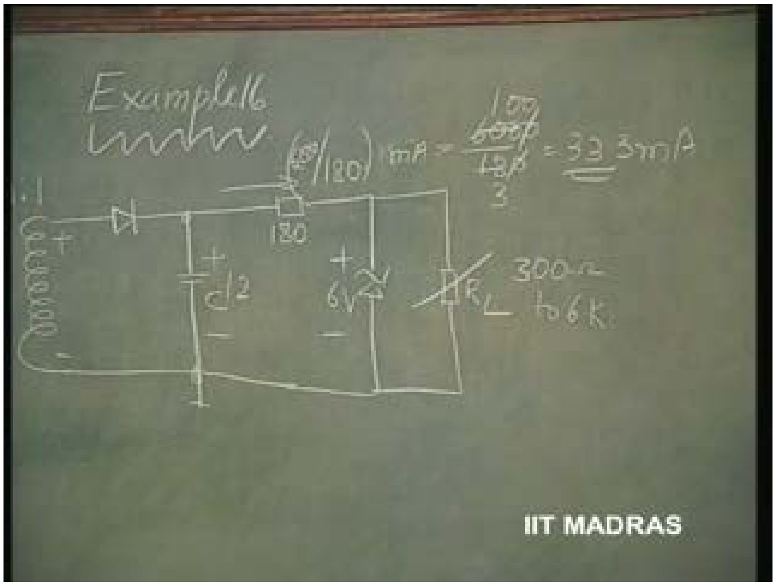

Or, this into, 6000 by 180 milliamperes; so, that is, 6000 by 180; that is, 33 point 3 milliamperes. So, that should be taken as the current constantly being drawn from the capacitor. That is, capacitor is getting discharged by a current like this. That means, let us see, if this is the current I, which is constant I dc; that divided by C is the rate at which capacitor voltage is getting reduced. That into T is the peak to peak ripple for the circuit here now.

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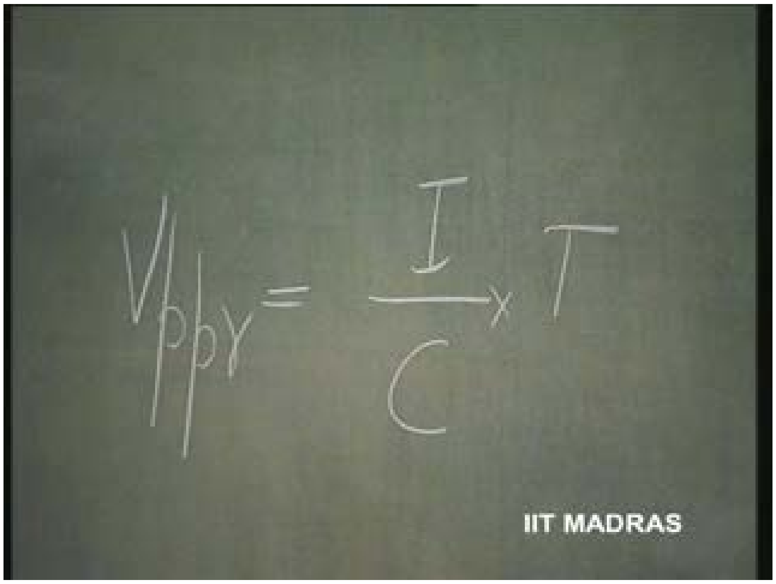

Please remember; this current has been evaluated by finding out the drop across 180, which is 12 minus the Zener drop. That divided by 180 is the current. So, this is the difference in design of a circuit with Zener Regulator as compared to circuit without any regulator. In the case of circuit without any regulator, the current is going to be voltage divided by the resistance. Here, this voltage, minus this Zener, divided by the resistance is what is going to be… And this load variation is of no consequence; the actual load variation is of no consequence as far this design is concerned. From the capacitor, the discharge current is always going to maintain constant, irrespective of the load resistance. So, this is the point that you have to bear in mind while designing such combination of circuits.

Let us complete this. This I is 33 point 3 milliamperes divided by C into T which is 20 milliseconds. So, from this, if you are specifying the peak to peak ripple, you can find out the capacitor; or, if the capacitor is known, you can find out the peak to peak ripple. So, let us say, we are fixing up the capacitor at 500 microfarad; then, the peak to peak ripple is going to be, if we select this as the this thing, then, 33 point 3 into 20 into 10 to power minus 6 divided by 500 into 10 to power minus 6. So, that is the peak to peak ripple which is going to be roughly, how much is it; so, hundred… so, this is going to be the 1 point 3, 1 point 33; so many volts is the peak to peak ripple.

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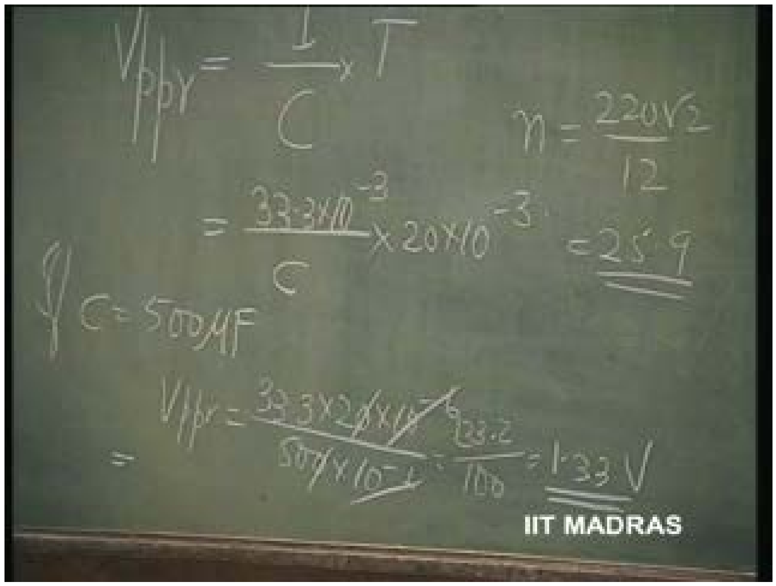

Now we have found out the peak to peak ripple at across the capacitor. So, you want the peak to peak ripple at the load. Now is the time you can, now… The peak to peak ripple at across the capacitor is 1 point 33 volts; this into r z divided by R s, as we did it in the last example, which is 1 point 33 into 10 ohms divided by 180, is the peak to peak ripple. This is across C; this will be across the load. So, you can see that there is a reduction by a factor of 18 across the load for the peak to peak ripple.

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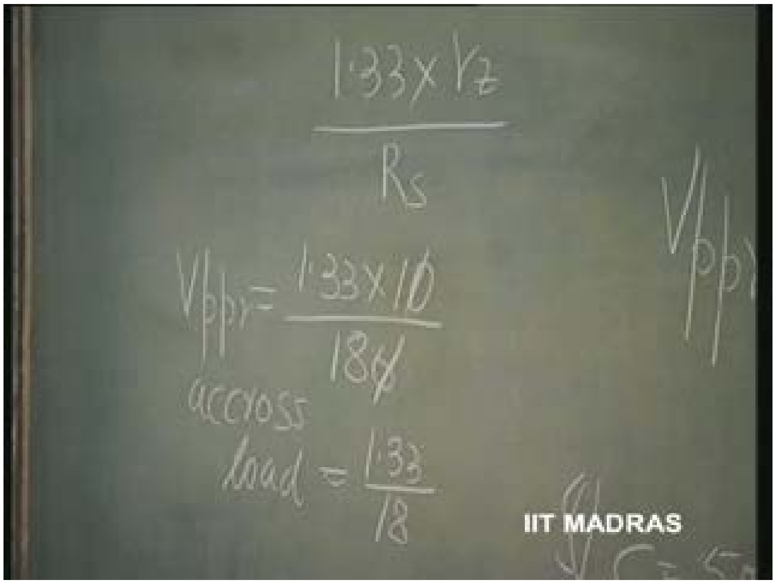

So, the design now is complete. You have made use of the small signal equivalent circuit for the Zener in order to evaluate the actual peak to peak ripple that is occurring across the load resistance. So, whether it is design or analysis, you must adopt all these procedures in the case of AC to DC converter where the DC voltage is supposed to be regulated.