Electronics for Analog Signal Processing - II
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Lecture - 26
Voltage Regulators

So, let us now understand some of the important parameters associated with voltage regulator. One of the most important parameters is called load regulation factor.

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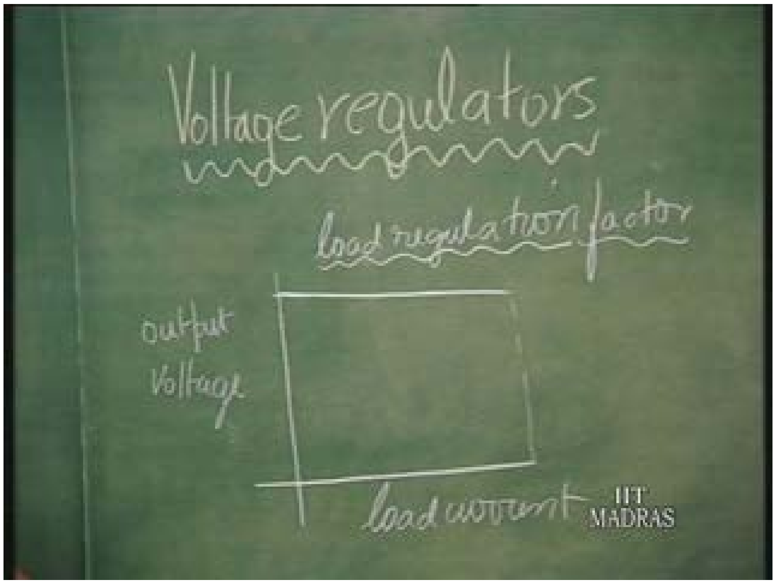

What it means is when I plot for the regulated output voltage versus load current, it should remain constant; but in most of the regulators, it will reduce slightly. If it is a good regulator, it will reduce slightly as current increases. This is because of the effect of output resistance.

So, that may not be linear for large change in current. So, I cannot represent it as a physical resistance; but there is a drop, small drop, as you increase the load current enormously. So, this is called load regulation. What is it? It tells us the percentage change in output voltage, percentage change in output voltage that will be from no load to full load.

So, when there is a large change in current from no load, that is zero, to full load, current change from no load to full load, what is the percentage change? Find out the Delta V and divide it by the nominal value and obtain it as a percentage change. That is what is called load regulation factor.

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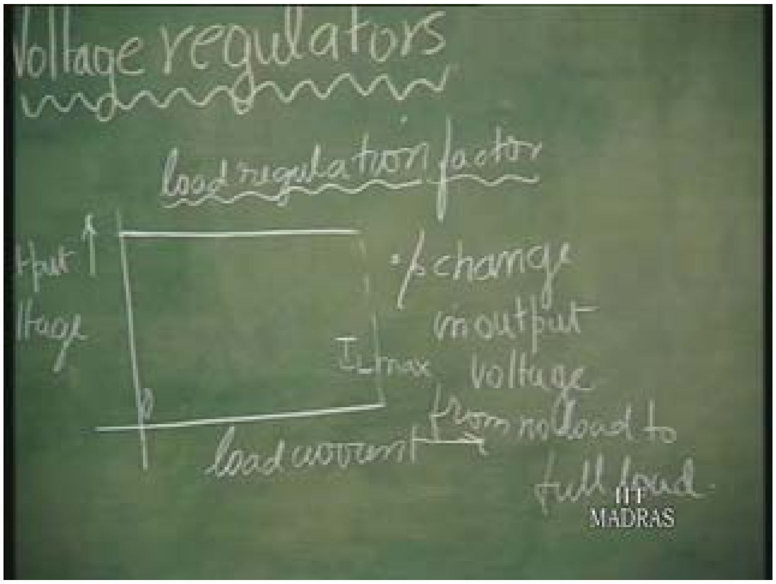

Now, apart from this, you put as you vary V i unregulated, V naught regulated. So, how does this vary? Let us say, when V i increases, there is a tendency on the part of V naught to increase, because V naught is derived from V i. So, how far this change occurs? That is again percentage change in output voltage for a change in V i from...obviously here, it cannot start from zero because we cannot get a V naught without any V i. So, it should be starting from the minimum possible V i to the maximum. We will see for this.

There is a limit, both minimum and maximum, within which the voltage regulator is supposed to act as a proper regulator.

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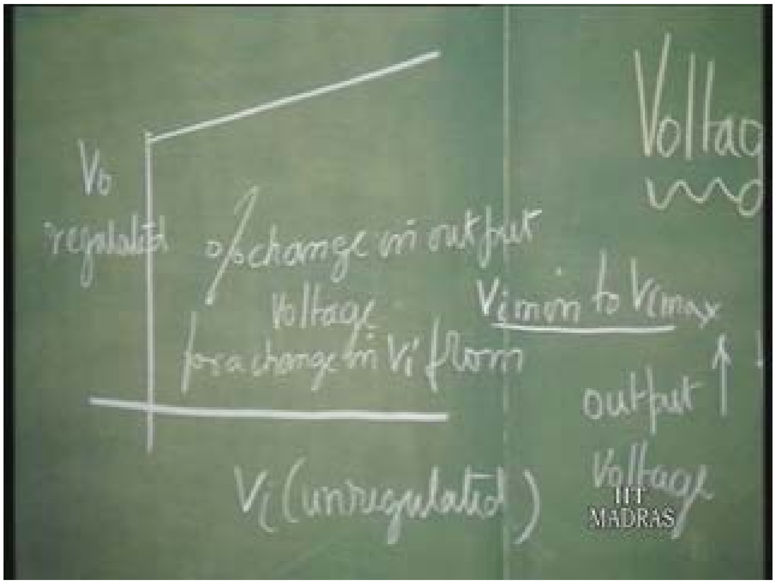

So, for this kind of change, what is the percentage change in voltage? That is called line regulation, load regulation, line regulation. Then...so, we will put this as number 1, number 2.

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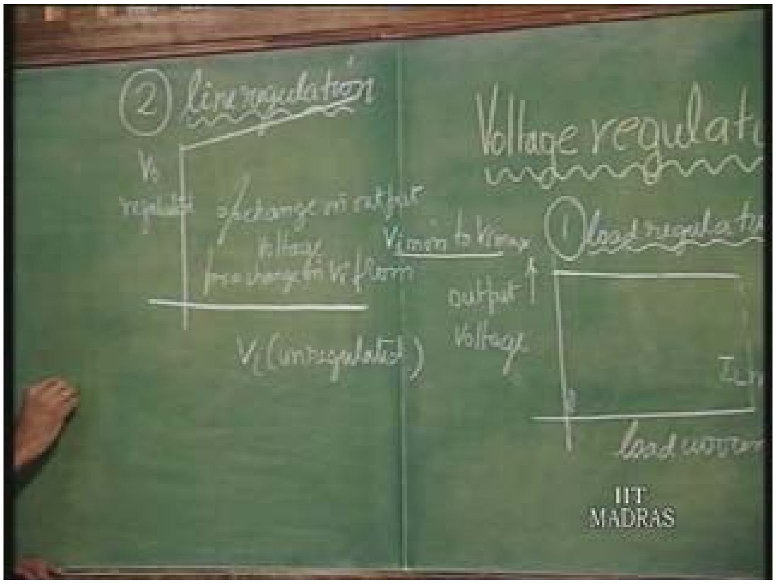

Number 3 is temperature coefficient of the output voltage, normally represented in terms of parts per million per degree centigrade rise in temperature; parts per million per degree centigrade rise in temperature.

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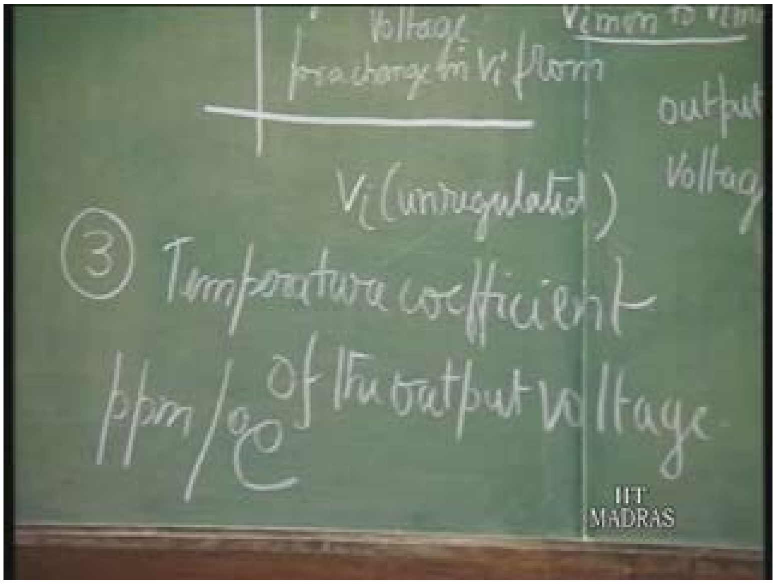

This is...since it is going to be a small value, instead of expressing in terms of percentage, it has been expressed in terms of parts per million - p p m, per degree centigrade. This primarily depends upon the temperature coefficient of voltage reference, basically. So, we tend to use voltage references which have zero temperature co-efficient here.

So, these are three important primary factors which tell you how good your voltage regulator is. Apart from this, we have other parameters which are basically called per signal parameters which are needed in trying to assess the quality of the voltage regulator in association with whatever is using that voltage regulator as its power supply.

So, these parameters are: output resistance of the voltage regulator should be very small because this should not cause interaction between one stage and other stage because there might be large number of stages which are, which are getting power from this common regulator. So, this output resistance, unless it is very low, there will be coupling between various stages. So, this is the important fact. Output resistance of the...this thing. Then, what is called as ripple rejection factor - basically tells you that input voltage unregulated is commonly derived from the line, power line, whose frequency is 50 hertz. Depending upon whether it is half wave or full wave, it will be having 50 hertz component or 100 hertz component ripple arriving over the input voltage.

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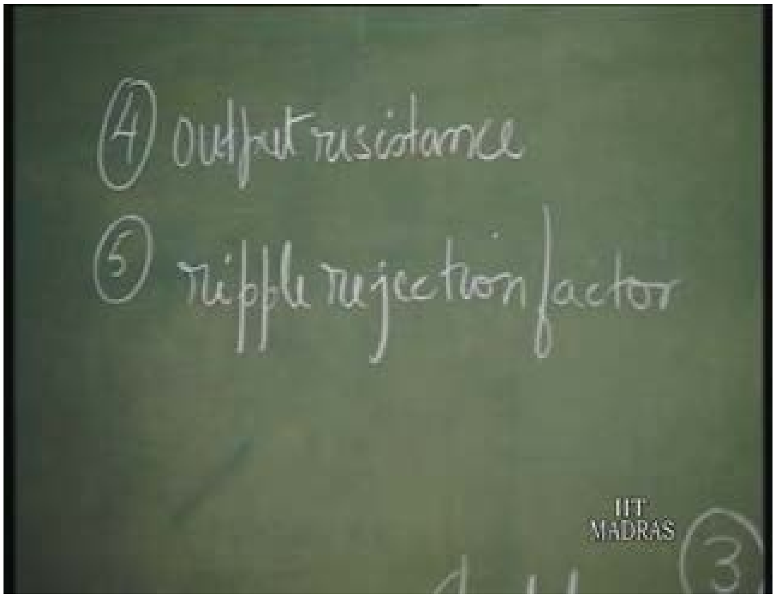

④ output resistance

⑤ ripple rejection factor

This ripple voltage is going to be very small and therefore this is also included as one of the small signal parameter. How nicely your regulator secured is able to reject the ripple at the output? So, this is ripple rejection factor. These are basically the parameters associated with this. Then, there are certain limiting factors associated with any voltage regulator.

So, these are power dissipation, maximum. This is delivering power to a certain equipment or the circuit and it is supposed to get regulated voltage as the supply. In doing so, how much power is wasted in this regulator? That is important because all the time that much power may be wasted; and therefore, an input voltage may keep on changing. So, when the input voltage is maximum, power dissipation is maximum, if the load current also is reaching a maximum.

So, at that point of time, regulator is really dissipating lot of power. So, that power is an important factor in the design. Then, efficiency. Consequent to loss of power in regulator, the output power dissipated divided by the input power is a factor in determining whether this regulator is efficient or not. So, efficiency is another measure. Then, there is what is called V i unregulated voltage maximum.

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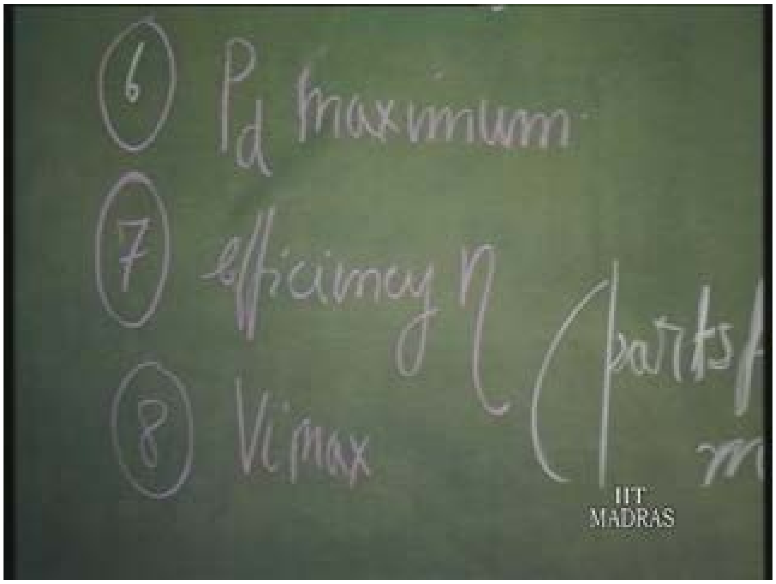

And then we have a maximum current that can flow. We are given I L maximum that can be delivered by the regulator, without any problem. And also, we have V i minus V naught, maximum, minimum. This is important because this is responsible for making it work. Again, this also causes maximum dissipation in the I C, voltage regulator.

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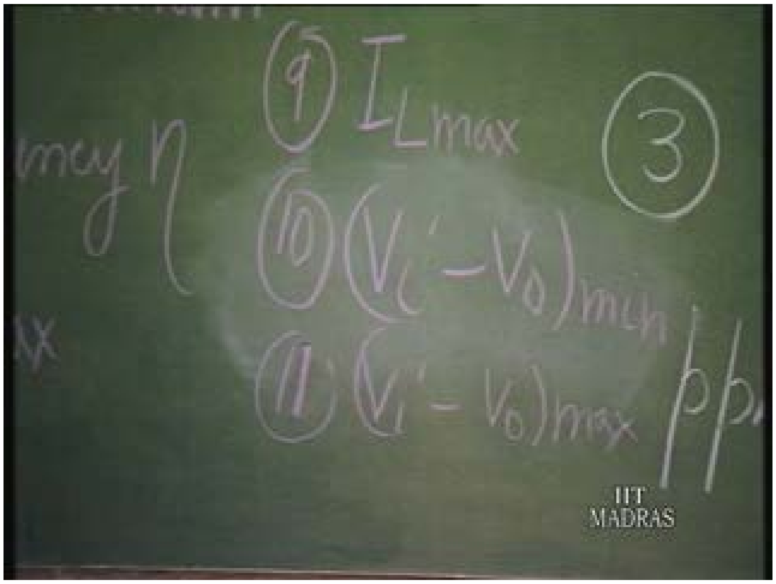

So, all these ratings are very important in assessing how good your regulator circuit is.

Let us take a simple circuit first as a voltage regulator circuit and see all about these parameters and performance factor, etcetera.

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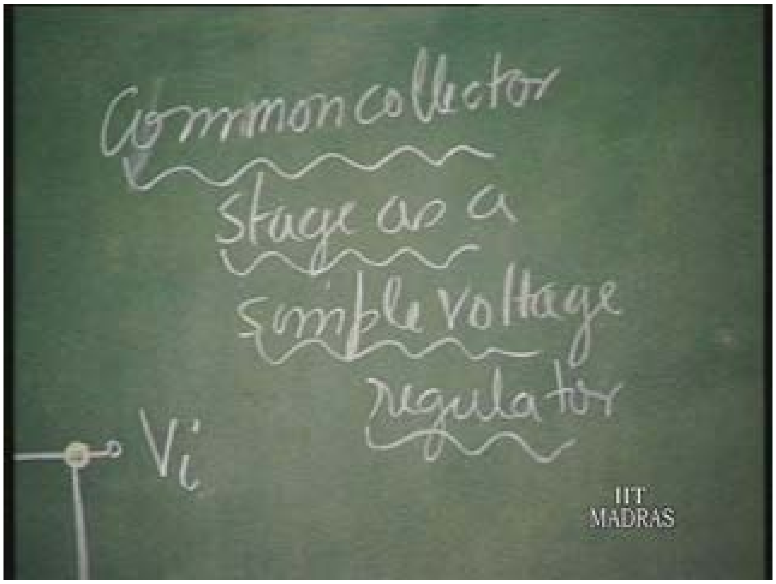

Common collector stage as a simple voltage regulator, we will take. Please remember that we had discussed Zener regulator long ago wherein the circuit was just current limiting resistor with the Zener diode output; and this can also give voltage regulated because as V i changes, only the current in this changes. And therefore, this remains fairly constant. Remember. This also slightly increases as the current here increases. That increase is not much.

So, that is a Zener regulator and we could connect a load there. So, what happens is that load would take a current of V z by R L. So, as V z by R L increases, this will get...this Zener will get less and less current from it. So, this is V i; the current in this is V i minus V z by R s. And therefore, since this current is limited, the load current should be such that it should give you a Zener diode with minimum V current still flowing through it. That means you cannot have load which is lower than a certain resistance; or, you cannot load it too much. So, we do not want the Zener to be loaded too much. So, we put a current amplifier.

This is similar to the structure that we have discussed, we have a voltage reference and we have a series pass transistor. We do not really now need a comparator. We straightaway use the output voltage and V z as the input voltage to this transistor so that the drop across the transistor is controlled.

So, this is one input voltage to the transistor and this is another voltage to the transistor. So, V z minus V naught is what is getting amplified by the transistor amplifier so as to adjust it to the required value, so that, output voltage is, V naught is equal to V z minus V Gamma. So, it is going to remain fairly constant independent of V i.

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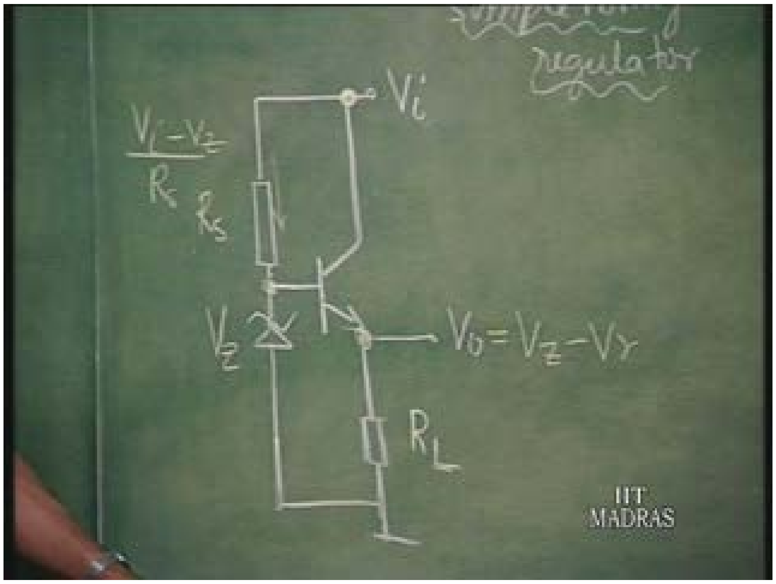

As of course this load current changes, the load current changes, the load current is going to be V naught divided by R L. What happens? As this changes, V naught by R L changes, this is going to be changing because this is what is delivering the load current. So, the base current of the transistor is V naught by R L divided by Beta plus 1. It is the emitter current. So, this is the base current.

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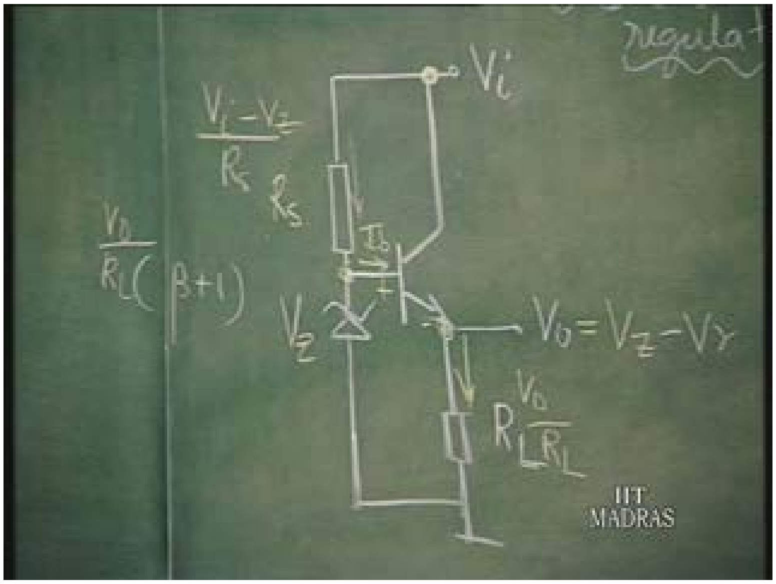

So, V i minus V z divided by R s. That is the input current to the Zener. Out of this, the base current is removed. So, this is really the Zener current.

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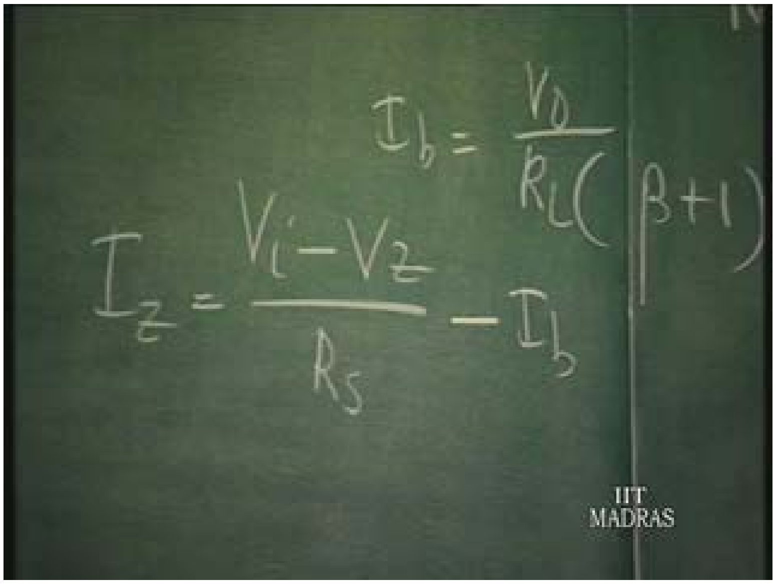

$$I_b = \frac{V_0}{R_L(\beta+1)}$$

$$I_z = \frac{V_i - V_z}{R_s} - I_b$$

So, since the base current is going to be a fraction of the output current V naught by R L, this is not going to change much. The Zener current is going to remain constant even if the load current changes because it is a fraction of... So, this voltage is going to remain fairly constant. If you permit large variation in load resistance directly across the Zener, then there will be a large variation in the Zener voltage and therefore Zener regulation gets affected. Consequently, output voltage will change.

So, please see that by putting a current amplifier like this, we have been able to get better regulation than the ordinary Zener regulator. V naught is equal to V z minus V Gamma. Now, let us investigate what happens. As V naught increases... Let us put down this. This is going to be V naught divided by R L Beta plus 1.

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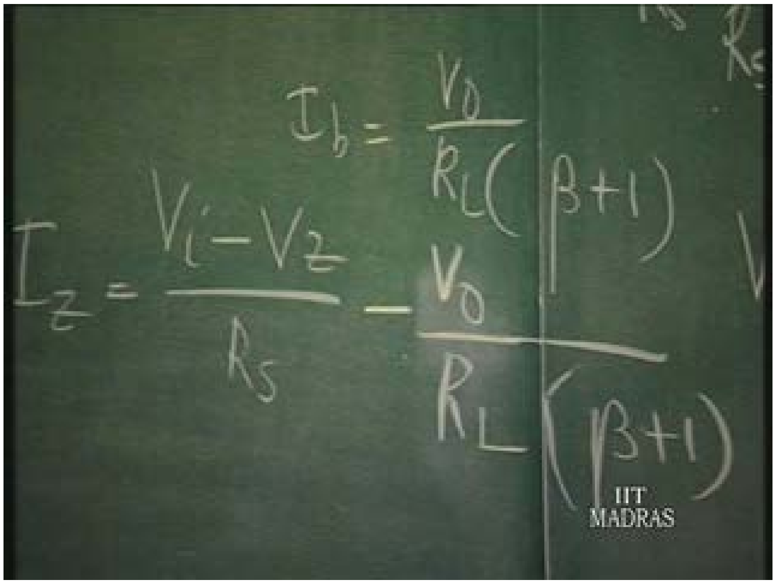

As R L decreases, this current will increase. As this current increases, this current is going to decrease. I z is going to decrease. As I z decreases, the Zener voltage is going to decrease slightly. That is one effect. Apart from that, V z is going to decrease and V Gamma; that is a cut-in voltage of this...as the current increases, V Gamma is going to increase.

So, this is going to increase in magnitude; this is going to decrease; so finally, the voltage is going to decrease. V z is going to decrease. V Gamma is going to increase. So, V naught is going to decrease as we load more and more.

So, we can see that this is what happens with I L. This is V z minus V Gamma, nominal. No load. From no load, this is going to change in the following fashion. But, that is going to be very small. That is called line...load regulation. This is...this is the load regulation. During this time, V i is maintained constant. You only change the load resistance here and plot the output voltage which is V z naught, V z minus V Gamma. That is going to vary slightly.

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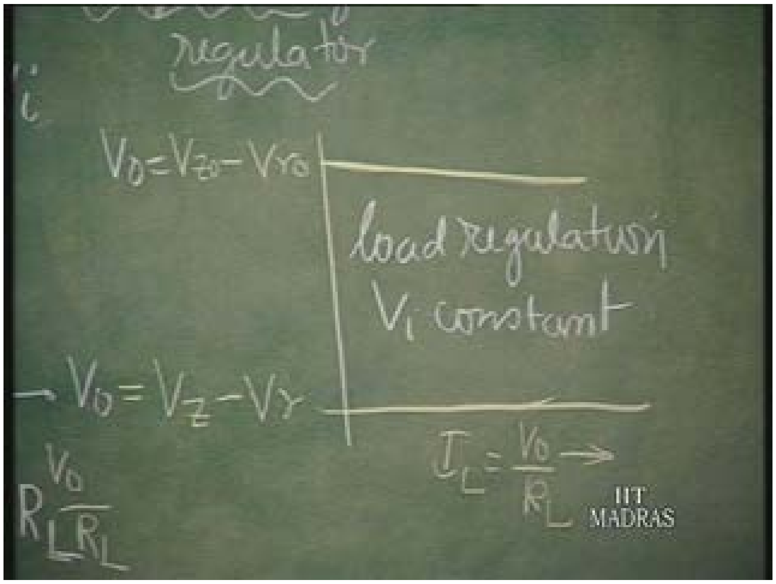

Next, what is line regulation? Now, you will vary V i. Let us see from what value to what value. As V i is decreased, this current is going to decrease. However, we see from this equation that this current cannot be made too small because this current should be such that this V i minus V z by R s minus this current should still be greater than the knee current of the Zener.

So, V i cannot fall. V i should be greater than, first of all, V z so that this breakdown occurs; this small thing. V i should be greater than V z. And V i minus V z divided by R s should be still minus I b max, maximum current you take from this, corresponding to the highest load current. That should be still greater than I knee for the Zener.

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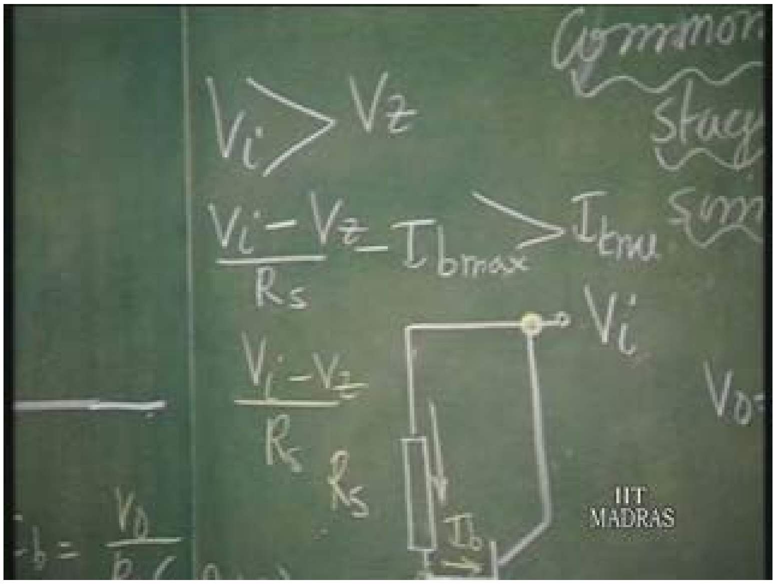

So, V i minimum comes from this fact that it should be greater than V z obviously; and then, not only that, V i minus V z by R s minus I b max should be still greater than I knee for the Zener. So, in such a situation, we will come up with certain V i minimum, lower than which we cannot go.

Then, let us say, V i starting at certain V i minimum and we can keep on increasing V i. Then, this current will keep on increasing. This current will keep on increasing. Suppose it is loaded minimum. Then, this minus I b minimum will be the maximum current that will flow through the Zener. That should not still cause too much dissipation in the Zener. So, that is a maximum current limit in the Zener.

So, we must have V i minus V z by R s minus I b minimum, should be still less than I z maximum, based on the power dissipation in this Zener; should be still less than that. Not only that, you will see that this transistor is also getting reverse biased to a greater and greater extent.

So, this voltage will keep on increasing. Then, this voltage will keep on increasing. That voltage that you apply should be such that the V i minus V z should still be greater than V c b overrating of the transistor... sorry, less than...this is the maximum limit. So, this should be less than the V C B over rating. This should not cause breakdown of the transistor. So, these are the basic limits.

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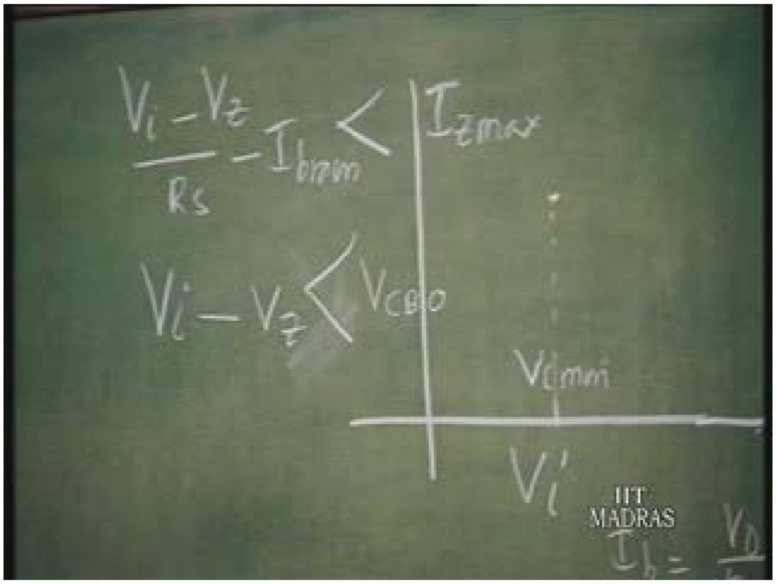

Apart from this, we have the power dissipated in the transistor. Output power is V naught square divided by R L. This is the output power. Input power is going to be V i into I i. What is I i? I i is V i into, I i is this current plus this current. So, this current is very nearly equal to V naught by R L plus this current, which is V i minus V z by R s.

So, this is the power dissipated at the input, total power dissipated. V i into the total current. This is called the bias current. This actually is the load current; this is normally very small compared to this. So essentially, you have the power dissipated which is V i into V naught by R L.

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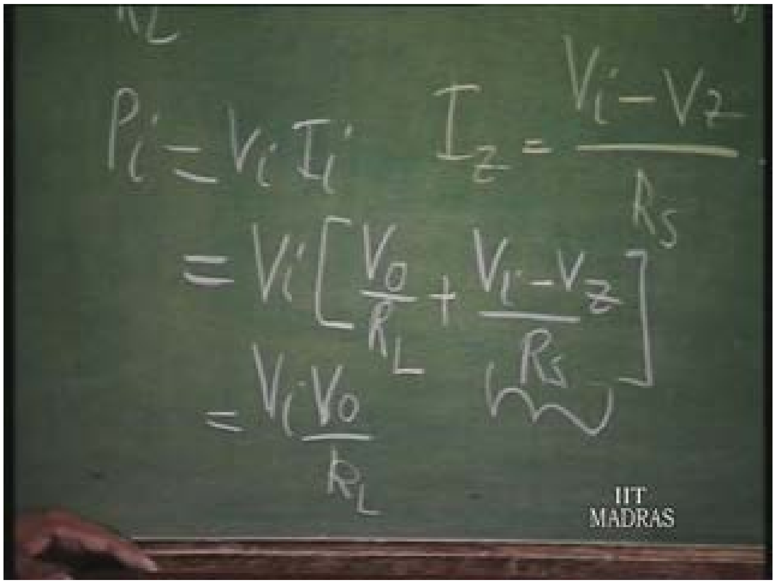

So, efficiency is going to be output power divided by input power. Output power is V naught square by R L. Input power is V i by V naught by R L. So, we get this as essentially equal to V naught by V i. Simply because we have neglected the bias current, it is essentially a ratio of output voltage by input voltage.

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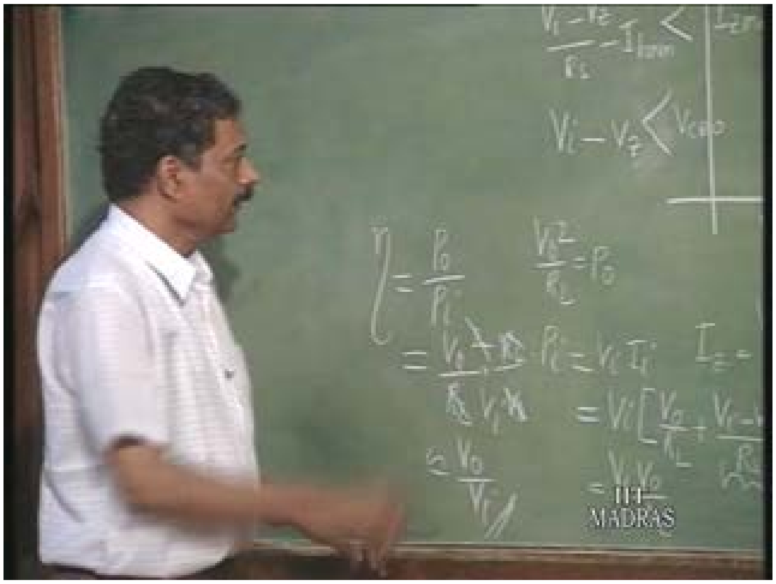

So, the higher the input voltage, lower is the efficiency. This is one factor to be borne in mind and this power dissipated in the transistor is nothing but...the V c of the transistor which is V i minus V naught. V i minus V naught into, essentially V naught by R L; if you neglect the, the...Alpha, if you assume it to be...when this current is same as this current. So, V naught by R L is the current. V i minus is the differential voltage.

So, this differential voltage is important. When this is maximum and this is also maximum, power dissipated is the highest in the transistor. So, that should be less than P d max of the transistor. So, this will also give you another value for V i max. If V naught is fixed, this will give you another value for V i max.

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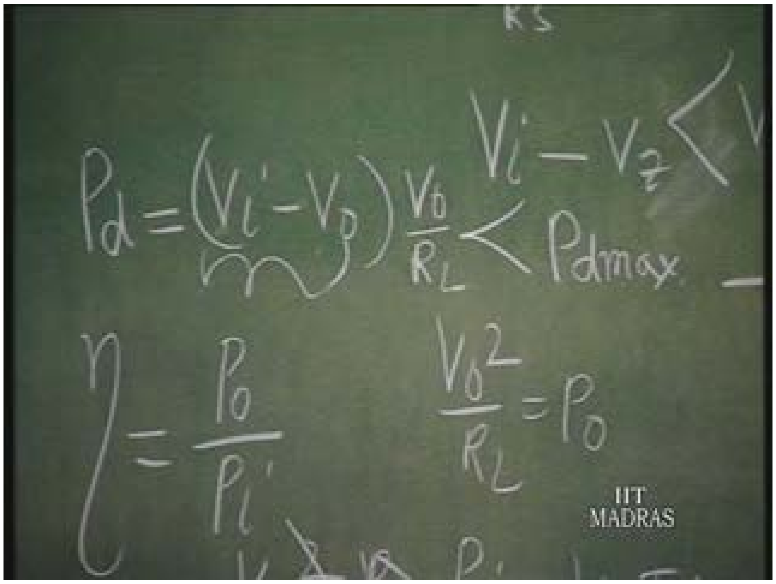

So, this information, you can plot this characteristic of V i; as it varies, how does V naught vary? Why should it vary? Let us say, if V i is increased, this current is going to increase. If this current is increased, this voltage is going to increase. If this voltage is increased, this output voltage is going to increase.

So, this is the direct effect. The load current remaining the same, V Gamma will remain the same. So, this is going to increase because Zener current is increasing and Zener voltage is increasing. So, this is increasing because Zener voltage is increasing, as V i increases. So, this is what is called line regulation.

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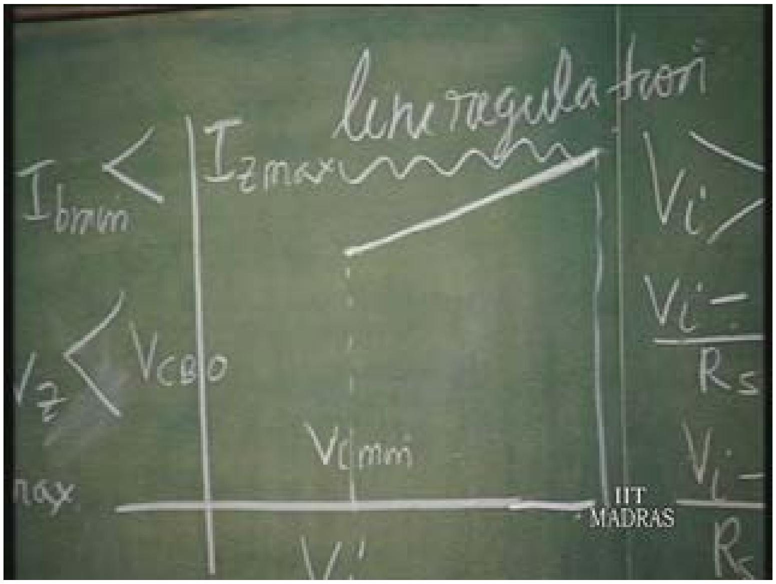

So, we have now established what the efficiency of this circuit is, what the power dissipated, maximum, for the device is, from which we can get V i max that we can go, as far as this circuit is concerned.

Now we can evaluate the temperature coefficient. Temperature coefficient of output voltage V naught which is Delta V naught by Delta T. So, Delta V naught by Delta T. This divided by V naught divided by T naught, evaluated at room temperature, expressed as what? - parts per million per degree centigrade because Delta V naught by V naught is a ratio converted into how many...how many parts per million it will change for 1 degree change in temperature.

So, this is what it is. Actually, that is the temperature. Delta V naught by Del...V naught is the parts per million change per degree centigrade. You do not have to find out the sensitivity of this. This is what is called as sensitivity of the voltage with respect to temperature. We want this ratio which is Delta V naught by V naught expressed as parts per million per degree centigrade to Delta T.

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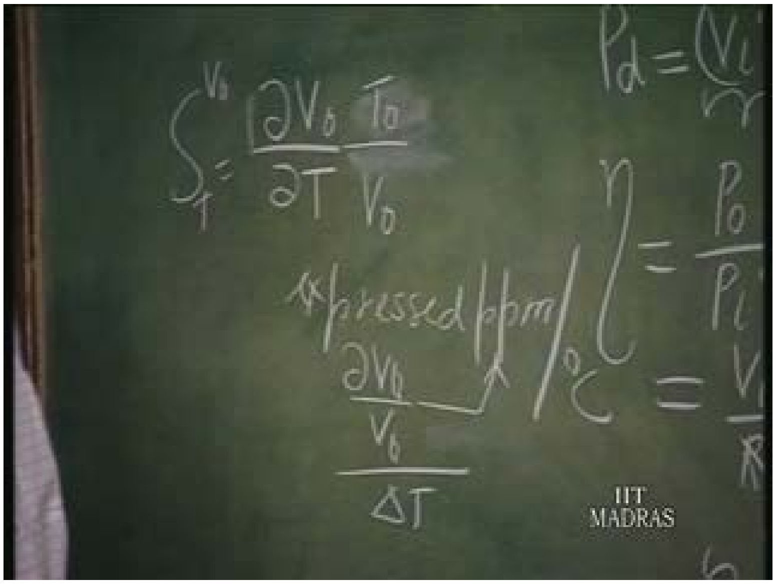

So, we can find out this by finding out Delta V naught by Delta T from that. That is equal to Delta V z by Delta T minus Delta V Gamma by Delta T, both of which will be given by the manufacturer; Delta V z by Delta T for a specific Zener diode.

If it is an avalanche diode, it will have a positive temperature coefficient. If it is a Zener diode with Zener mechanism dominant, then it will have negative temperature coefficient. So, this will have positive temperature coefficient. Typically, let us say, if it is some 7 to 10 volts Zener breakdown, then Delta V z by Delta T will be about 2 to 2 point 5 millivolts per degree centigrade. Delta V Gamma by Delta T is already known to us as about minus 2 to 2 point 5 millivolts per degree centigrade.

So effectively, this will have a positive temperature coefficient. If the Zener voltage is lower than about 5 volts or so, then the Zener mechanism dominates; and this will be negative. Then this will be, with this negative sign, will be positive. So, you can have an arrangement such that the overall coefficient is zero. That is how what are called as zero temperature coefficient voltage references are designed. So, we can therefore find out the temperature coefficient of this voltage, Delta V naught by Delta T and divide it by V naught in order to get how many parts per million per degree centigrade it changes.

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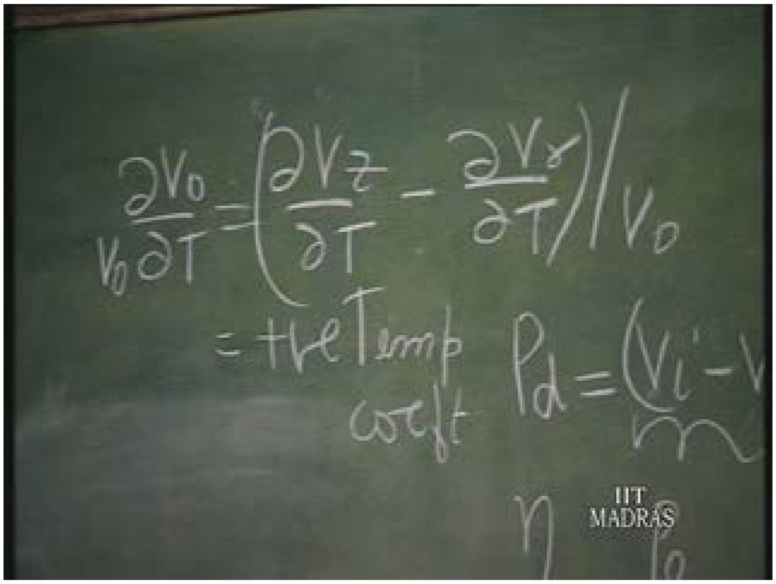

So, this forms the explanation about load regulation, line regulation and temperature coefficient and power dissipation and efficiency of this voltage regulator. Apart from this, we would like to know the output resistance which is important in telling us whether it is a very ideal battery source that we have derived.

So, if you look at this, the output resistance of this is nothing but r e plus r z effectively, divided by Beta plus 1. This we have done; common collector stage amplifier, we have done. So, very nearly equal to r e, r e plus r z divided by Beta plus 1, apart from the shunting effect of R l, which is not of consequence because this is going to be very small.

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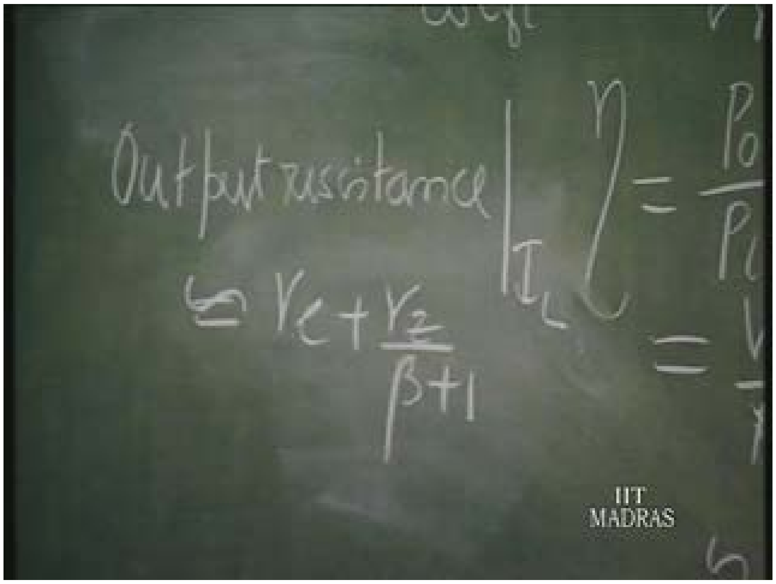

r e is going to depend upon the operating current. So, this has to be evaluated at particular load current. V t by I L is what r e is. r z is going to be of the order of 10 sub ohms. So, this is pretty low output impedance. Apart from this, we have to also discuss about ripple rejection factor.

Now, that is going to be very important here. That, if there is a ripple here, how much of it gets transmitted to the output here? So, that really depends upon H r e of this transistor here. H r b or whatever it is. That, when I am exciting it, the collector, how much gets transmitted to the emitter, if the base is grounded?

So, that gets transmitted through what is called H r b. That is, H r b is of the order 10 to power minus 4 or so. That, when I excite the collector by means of a voltage, how much it transmits to the emitter? So, you have the base resistance divided by base resistance plus the collector to base resistance. Collector to base resistance is very high. So, it is of the order of 10 to power minus 4 to minus 5. Apart from that, when I vary this, this varies because this is not really zero resistance for small segment. It is r z. So, r z divided by r z plus r s still appears as a variable voltage here which straightaway appears at the output.

So essentially speaking, the ripple depends upon the value of r z and how large r s is. So, now you can see that r s has to be pretty high in order to make the ripple rejection.

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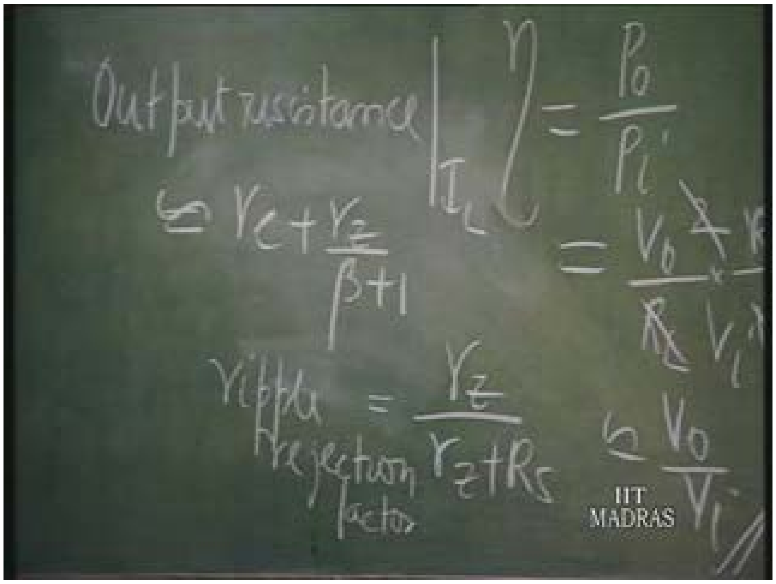

So, there are two parts to the ripple; one through the transistor, another through the Zener. Normally, it is this Zener which is higher than that through the transistor because this resistance is very high. This resistance on the other hand is not that high.

So, this is what comes into picture as ripple rejection factor. r z by r z plus r s. So, one might therefore put large valued capacitor here in series with the resistance in order to reduce it further. That will not affect the D C performance; but it will definitely improve the ripple rejection factor. The way to do it is put a resistance here and put a capacitance across this; so, that will reduce the ripple rejection factor further.

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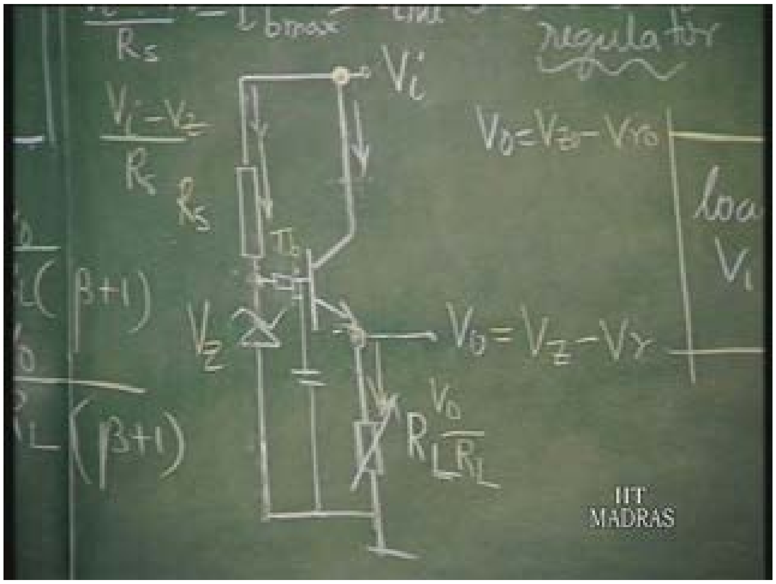

So, this is the complete design of a simple voltage regulator. We can see so many factors involved in the design that ultimately make up a good voltage regulator. Now that you understand what we have discussed so far, let us see Example 21, where the voltage regulator is designed.

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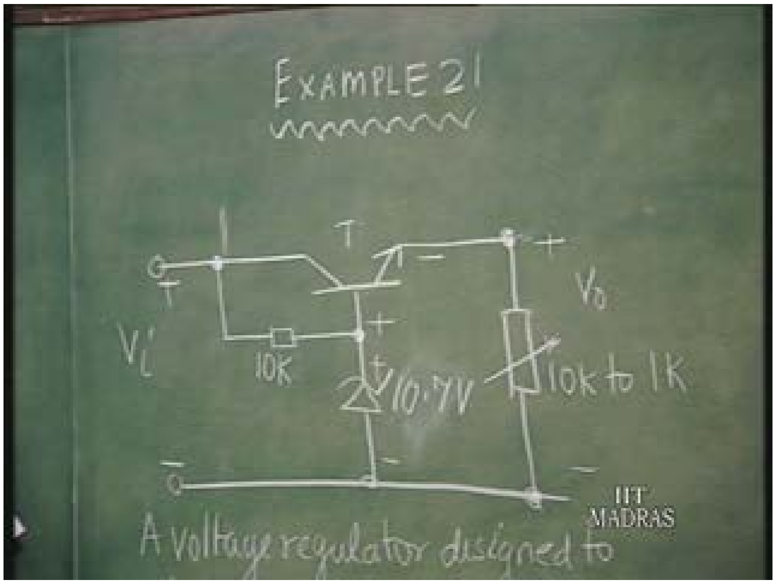

A voltage regulator designed to

A voltage regulator designed to give a regulated output of 10 volts is shown in figure. The load varies from 1 K to 10 K.

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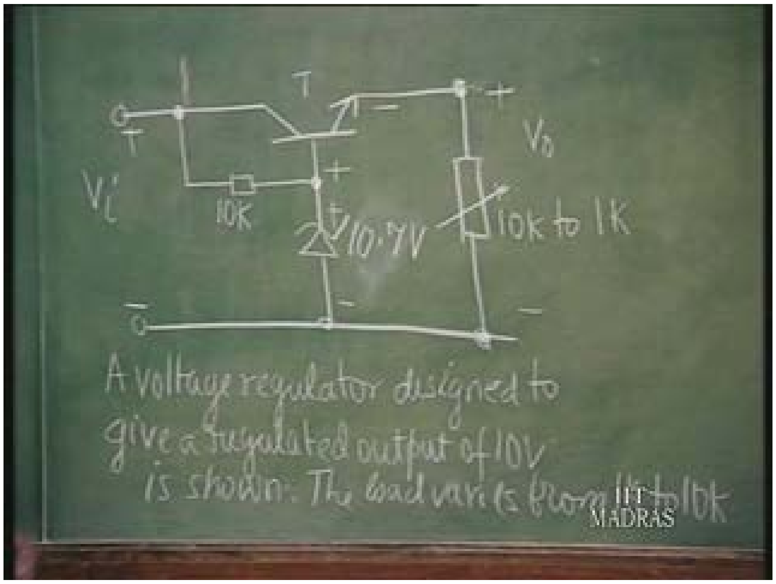

A voltage regulator designed to give a regulated output of 10V is shown. The load varies from 1k to 10k

Determine the various parameters associated with the regulator. Let us try to understand this regulator which has been made to work for a load variation of 1, 10...1 K to 10 K. I put it as 10 K to 1 K because load...it gets more loaded as the resistance decreases. So, as you can see, this is 10 point 7. Zener voltage is 10 point 7. There is a voltage of about point 7 drop here so that output voltage is 10 volts.

That means what he has assumed as diode drop is point 7. So, this is...V naught is going to be 10 volts. So, as this changes from 10 K to 1 K, the current changes from 1 milliampere...corresponding to 10 K to 10 milliamperes. It is a modest load. Now, as far as this bias current is concerned, it depends upon V i. Let us see what V i minimum should be. It is 10 point 7. So, V i should be greater than 10 point 7 by some amount because there should be some current in this.

So, if this is assumed to be, let us say, point 1 milliamperes, we will take, assuming that V current is less than point 1 milliampere. So, this 10 K into point 1 milliampere will give you a drop of 1 volt. So, 1 volt drop here, 10 point 7 plus 1. So, this should be greater than 11 point 7. So, the current is going to be greater than point 1 milliamperes. So, 11 point 7 volts.

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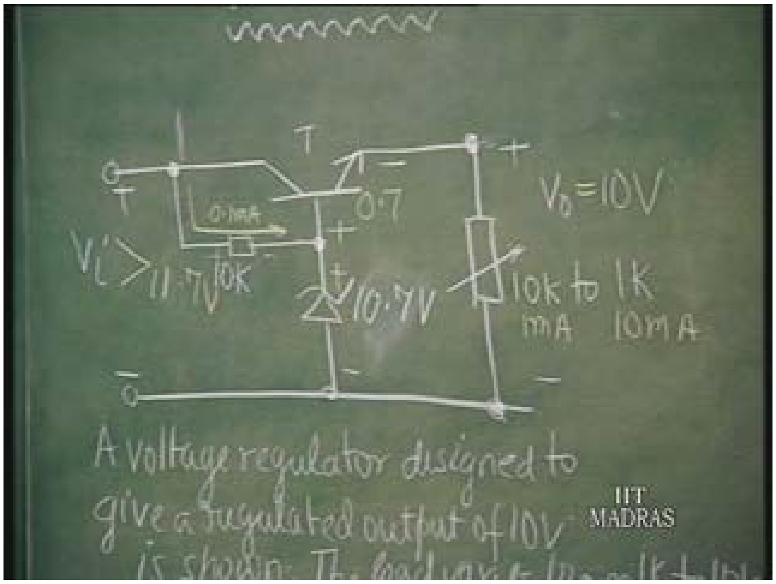

So, if that is the case, we get V i minimum as equal to 11 point 7. Look at it from another point of view. This is 10 volts. This is point 7. As far as the transistor is concerned, this can go down to 10 point 7. No problem. So, the minimum is always fixed by this in this case; Zener plus whatever current, that is minimum current that is required here, is going to fix something minimum.

Now maximum - as this gets loaded heavily, that is, when this is carrying 10 milliamperes, this current is going to be 10 milliamperes. Assuming that this is point 1 milliampere, therefore negligible; you can say 10 milliamperes into the V c e; whatever it is, is going to be the dissipation in the transistor.

So, power dissipated, maximum...if it is, let us say, given as 100 millivolts, let us say for the transistor, you have to find out really what the actual power of the transistor that you are using, that limitation is. Suppose it is 100 milliwatts. Then we have V c e; that is V i minus 10 volts. That is the V c e; into 10 milliamperes. This should be less than 100 milliwatts.

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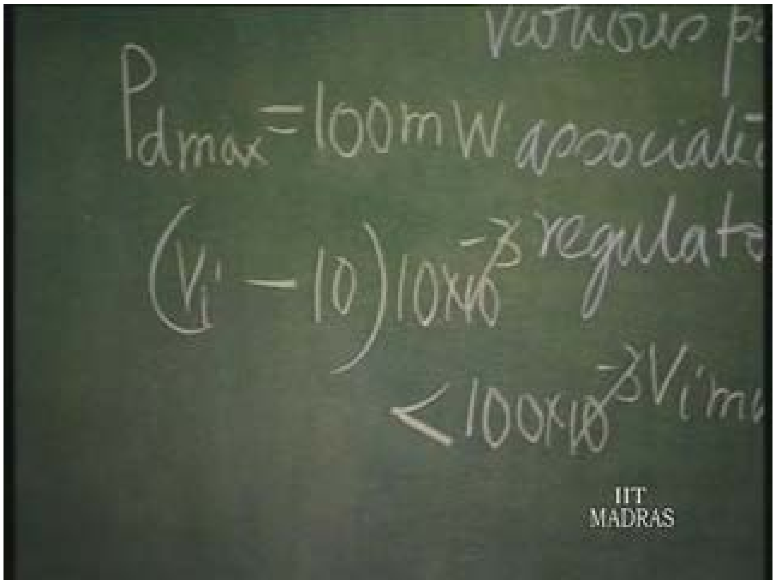

various p

$P_{dmax} = 100mW$ associati

$(V_i - 10)10\times10^{-3}$ regulato

$< 100\times10^{-3}$ $V_{i\,m}$

So, we get this as...V i should be less than...this becomes 10. So, 10 plus 10 - 20 volts. This becomes 10. So, 10 plus 10 - 20 volts. So, V i maximum should be 20.

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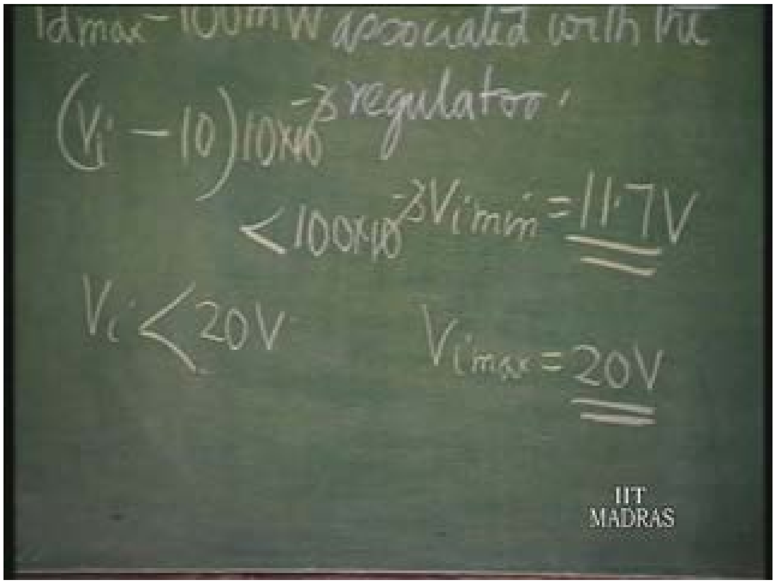

$P_{dmax} = 100mW$ associated with the

$(V_i - 10)10\times10^{-3}$ regulator.

$< 100\times10^{-3}$ $V_{i\,min} = \underline{\underline{11.7V}}$

$V_i < 20V$ $V_{i\,max} = \underline{\underline{20V}}$

At that point of time, you may...must remember, this is 20 volts, this is 10. Roughly, 1 milliampere is going to flow through this. So, 1 milliampere plus 10 milliamperes - 11 milliamperes, strictly speaking. So, 11 into... let us say, whatever voltage you are considering. That should be less than 100 millivolts, strictly. So, V i max will be slightly less than 20 volts. Please remember that.

So basically, we have to consider another iteration of the whole thing. So, V i minus 10 into 11 milliamperes is the sort of power dissipated; or actually, V i into 11 milliamperes is the power input. This is the power input. Power output is V naught, 10 volts, into 10 volts divided by...into 10 milliamperes. 10 volts into 10 milliamperes. So, this is 100 milliwatts. 100 milliwatts is the power output and for that we are using maximum dissipation transistor of 100 milliwatts. Not very efficient.

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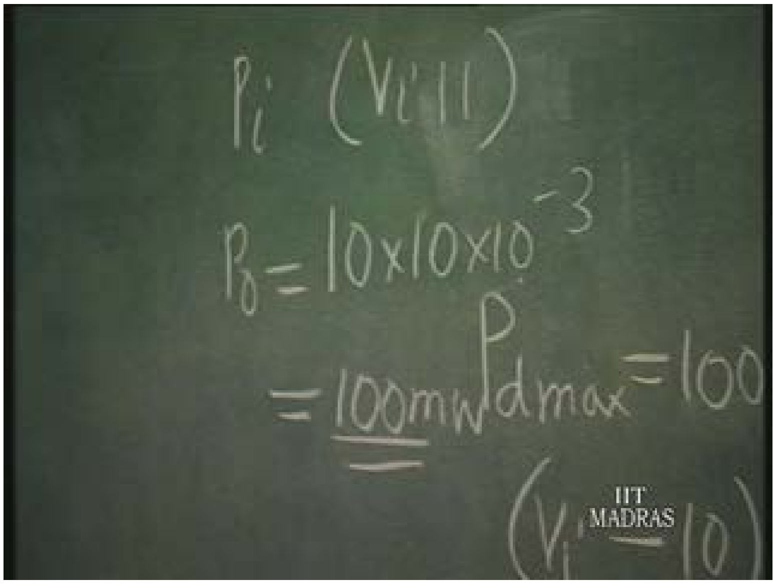

So, under the worst case, it will dissipate 100 milliwatts here and 200 milliwatts will be the input. Basically, input is...input power is V i, which is 20 into 11, which is 220 milliwatts, considering the bias current also into account. This will increase at that time to about 1 milliampere.

So, efficiency is going to be 100 divided by 220 into 100 percent, expressed as a percentage. So, 500 by 11 - about 45 percent efficiency.

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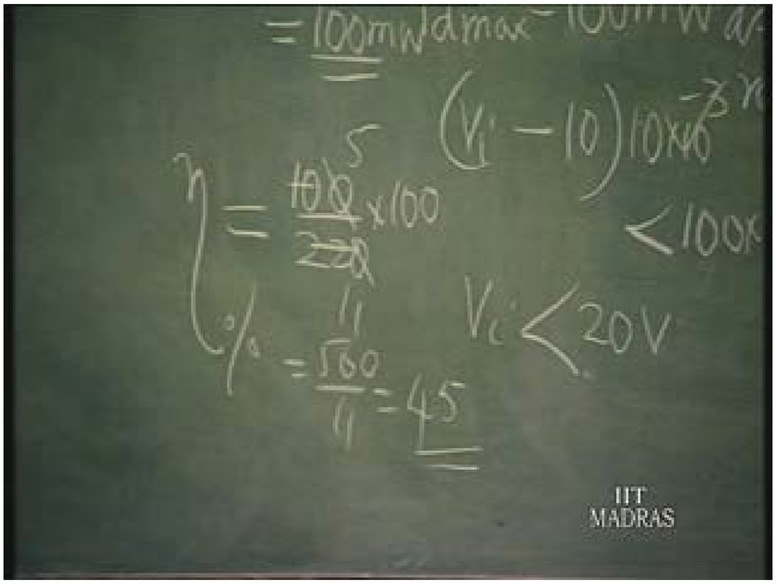

So, we have now evaluated the maximum dissipation. Given this, we have evaluated V i max. Given this, we have found out the worst case efficiency to be less than 45 percent.

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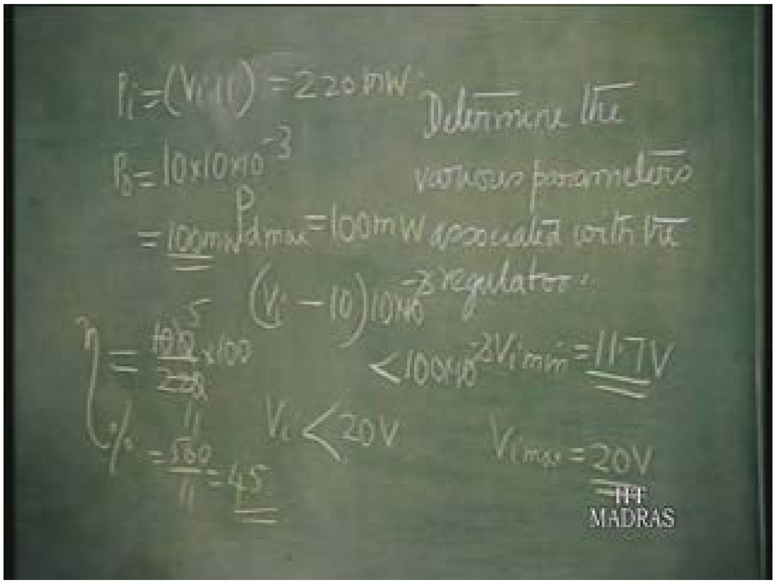

Now, apart from this, we can also evaluate, let us say, the output impedance; let us say, at 10 milliamperes current, because that is the worst case. Lower the current, higher is the output impedance. So... Sorry. 1 milliamperes. Instead of 10 milliamperes, we will evaluate it at 1 milliamperes. So, r e is going to be V t divided by 1 milliamperes. V t is 25 millivolts. So, 25 ohms plus r z is 100, you consider; and Beta is, let us say 100 we take.

So, 100 divided by 101; for 26 ohms is the output impedance, assuming Beta as 100, r z as 100 ohms. These are the typical values. So, the order of magnitude involved in the output impedance is 26 ohms.

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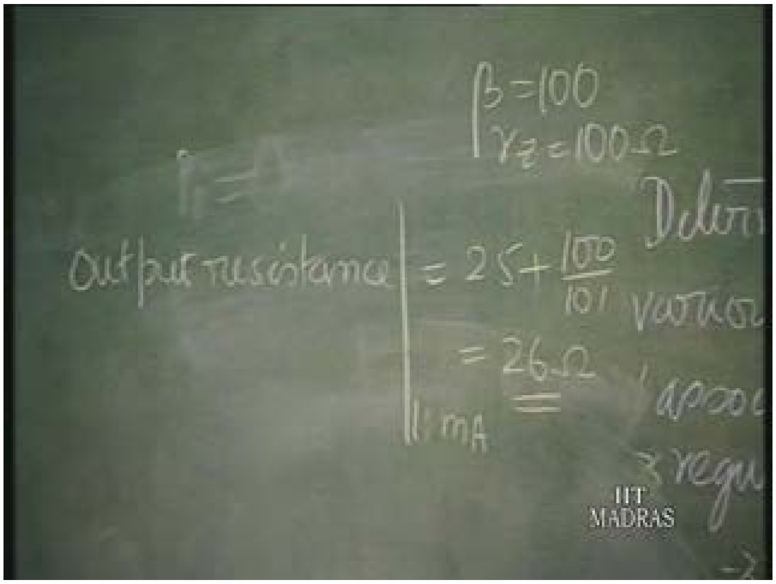

Apart from that, ripple rejection factor - this is going to be r z, 100, divided by 100 plus 10 K. So, 10 K roughly. So, this is equal to 10 to power minus 2. That is the ripple rejection factor for this circuit.

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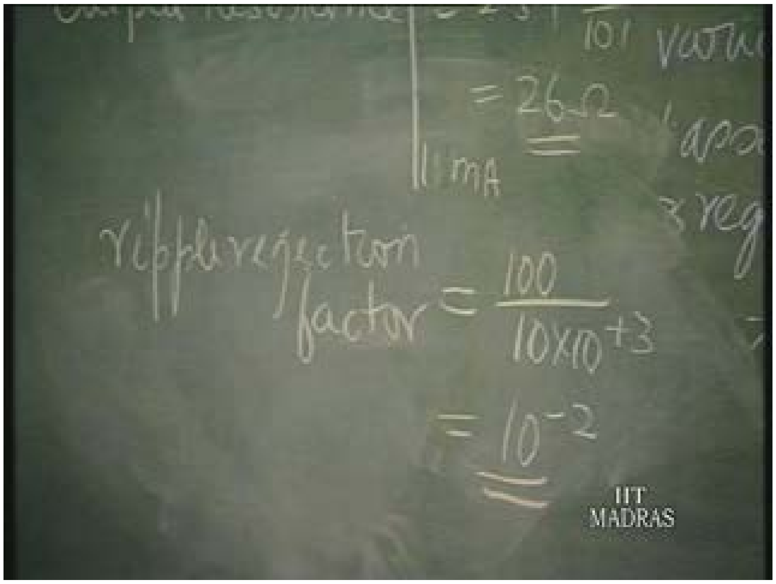

So efficiency, ripple rejection factor, output impedance and temperature coefficient. 10 point 7 - the temperature coefficient of this voltage is going to be positive; may be about say, 2 point 5 millivolts or 3 millivolts plus 2 or 2 point 5 millivolts here.

So, about 5 millivolts per degree centigrade rising temperature. That is the temperature coefficient - 5 millivolts per degree centigrade rising temperature. Now, so this is going to be 5 divided by 10 millivolts per degree centigrade rising temperature, into a million. So, this gives you 100; this is 500 parts per million per degree centigrade.

Assuming that the temperature coefficient of V z minus V Gamma is 5 millivolts per degree centigrade, since the voltage reference is 10 volts, 5 divided by 10 into 10 to power 3 millivolts into 10 to power 6 will give you so many parts per million per degree centigrade.

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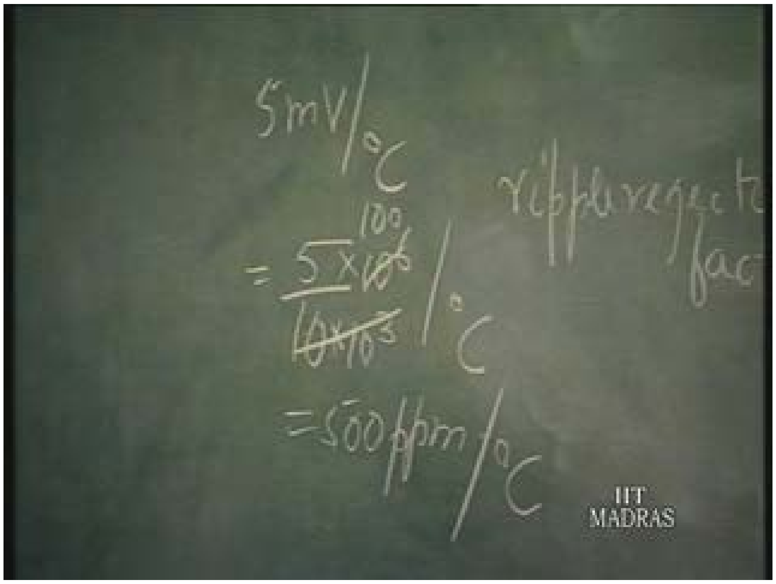

So, we have evaluated the temperature coefficient of the output voltage as 500 parts per million per degree centigrade. So, all the performance factors are available with us. As far as regulation characteristic is concerned, you can get this also from your knowledge about the Zener characteristics and the diode characteristics. You should know how much the Zener voltage is going to change as the current is going to change, because of V i changing.

So, V i let us say, changes from 11 point 7; which means current is about point 1 milliamperes, to 20 volts, which means current will be 1 milliamperes. As the Zener current changes from point 1 milliamperes to 1 milliampere, find out the change in Zener voltage. That is Delta Z, let us say. That divided by 10 is going to be the ratio change in output voltage; and the input changes from minimum to maximum. That expressed as a percentage is going to be the line regulation factor.

Next, as we change the load from 1 milliampere to 10 milliampere, this current is going to change and therefore V Gamma is going to change. V Gamma is going to be, let us say, changing from point 7 to some point 706, something like that. So, then also, base current is going to change, divided by Beta. As this base current changes, we can establish how much the Zener current is going to change and find out Delta Z.

So, that will give us the load regulation factor. Again, find out Delta V naught divided by V naught, expressed as a percentage. It will give us the load regulation factor.