Electronics for Analog Signal Processing - II
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology – Madras

Lecture - 25
Control Circuits

So, we will continue with class D power amplifiers. We mentioned that active device here is used as a switch, in which case, when it is closed, voltage across that is zero and current can be any value. When it is open, voltage can be any value and current is equal to zero. Therefore, the power dissipated in the ideal switch is equal to zero, all the time. Therefore, I can now control power using an element which does not dissipate ideally any power.

As long as I do not waste power, I can convert this power into useful power and therefore efficiency could be theoretically equal to 100 percent. We will show this...how this practically can be done.

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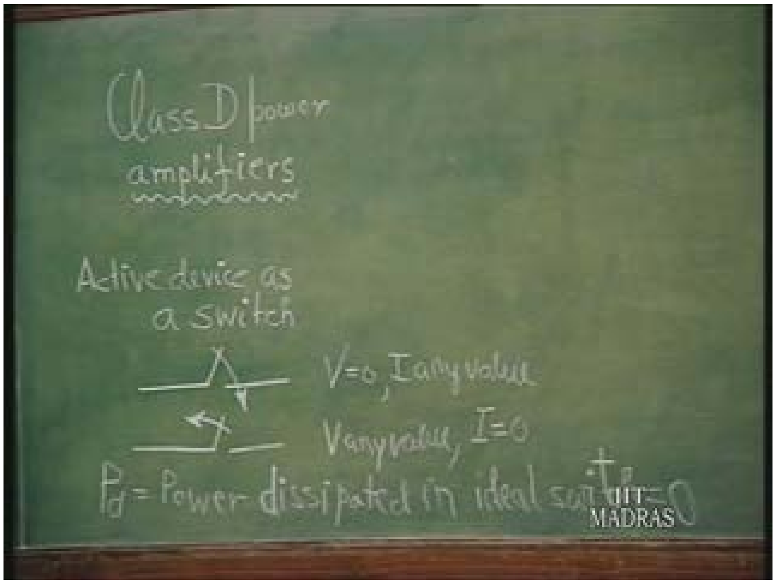

So, we have a switch here which we say is connected to, let us say, V c c and let us say it is connected to ground. When this is closed, this is open. These are complimentary switches. When this is closed, this is open; when this is open, this is closed. The wave form here V, as function of time, is going to look like...

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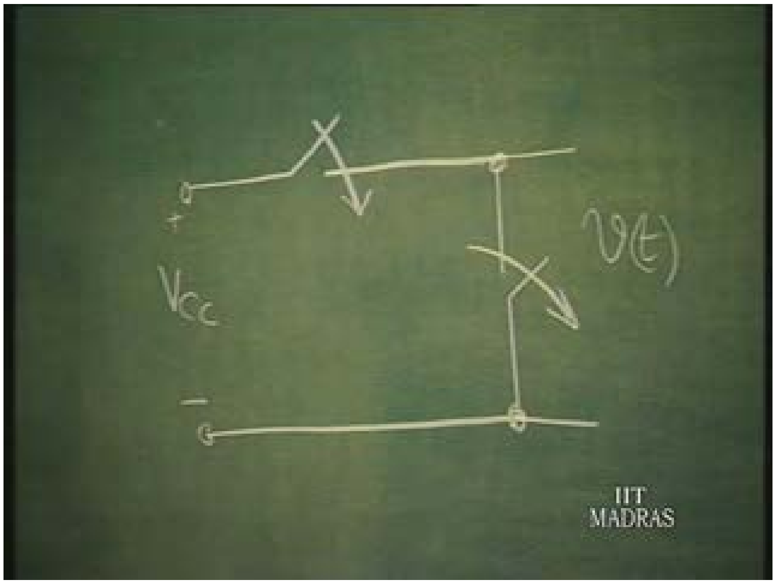

So, let us say tau is the time for which it is closed. When this switch is periodically switched with the time duration T period, then this is, let us say V c c, the average of this wave form.

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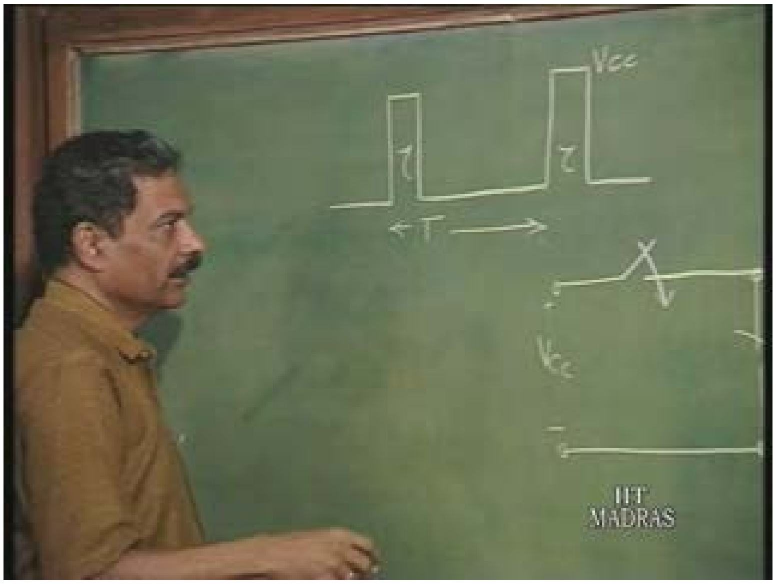

Suppose I pass it through a low pass filter. This will find out the average and that average is going to be in this case, tau by T into V c c. So, we are able to keep this on for tau; let us say therefore, this is on for tau and off for a duration T minus tau; and this is going to be off for T minus tau and...that is, off for tau and on for T minus tau.

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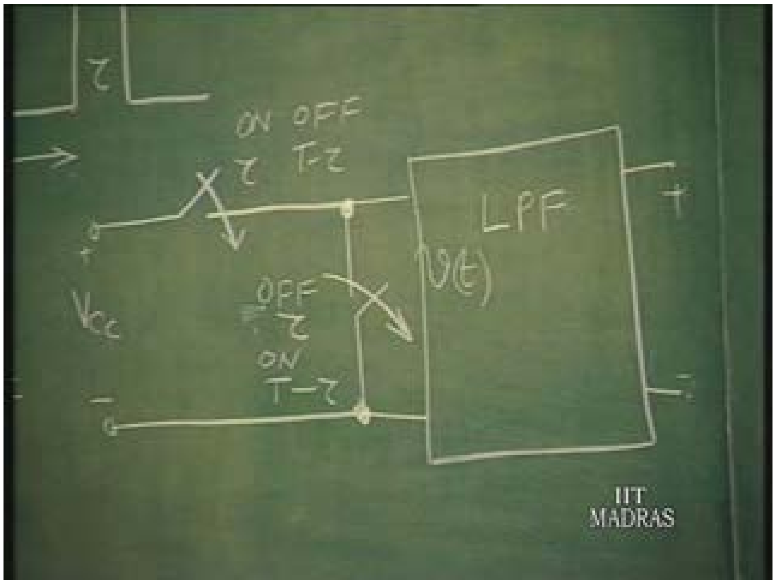

This is a complimentary switch and therefore this kind of wave form is what we expect at V t; and V average if you take here is tau T by...tau divided by T into V c c. This is amplitude; this is duty cycle. This is the amplitude and this is the duty cycle.

So, I can vary, let us say...If I can vary duty cycle according to some frequency, this gets modulated by this information and this also is modulating the amplitude. So, this is called width modulation. This is called amplitude modulation.

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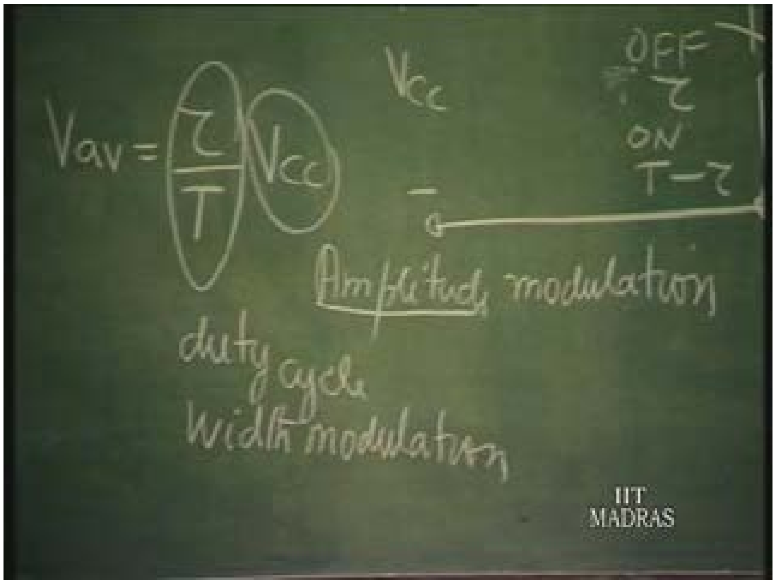

So, this scheme of things is, really speaking, called pulse width and pulse amplitude modulation. This is a type of multiplier where width of the pulse is getting multiplied by amplitude; the average of this corresponds to this. This can be very usefully used in a variety of applications for power amplifications, for also efficient converters and consequently switched mode power supplies, S M P S.

So, this idea is very important, has gained prominence, particularly because the switching can be done at fairly high frequencies. Nowadays, this...we have power switches which are available, which can operate up to 1 megahertz; and therefore the low pass filtering inductor and capacitor could be made very small in size and the modulation information can occur at low frequencies. So, this is a very good scheme for efficient power conversion from one form to another.

So, let us therefore use it for, let us say, audio power amplifications, something like that. Then, how do we have the practical scheme? Tau should be proportional to some voltage. How do we therefore get this duty cycle width or width modulation scheme? By using a voltage, I should be able to make the width of a pulse, vary.

So first, we will consider this. Next, we will consider how this average, when it is changing sign when V c c changes sign, it should also change sign, when this particular multiple can change a sign. So, that kind of operation is very necessary for sort of efficient outputting, the modulating information. So, let us see that. First, let us think of a scheme.

Assume that a wave form is available. This is a triangular wave form whose time period is T. Say, if you have a clock with this kind of period; a square wave form with this kind of period, you can convert it into a triangular wave form by integrating. So, let us say that sort of wave form has a peak value of V p and time period of T; and we put a voltage for comparison. We call this V c and let us observe this output here, V naught.

So, let us say this is plus and this is minus. This is now acting as a comparator. This is a high gain amplifier. So, the moment this voltage goes above V c, the output will go to, let us say, plus V c c and the moment this voltage goes below V c, this will go to minus V c c, saturation. These are power supplies. So, what kind of wave form do we observe on the screen?

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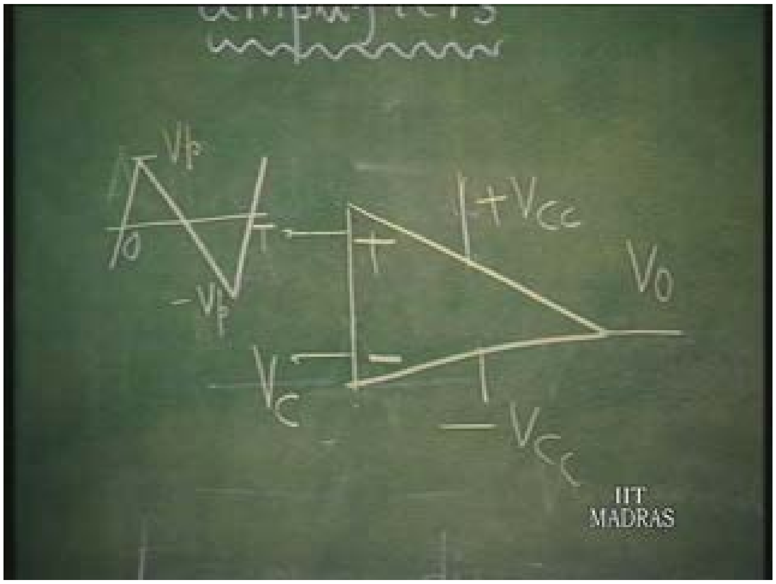

So, let us draw the triangle. So, this is V p, this is minus V p. This is time axis. This is zero. This is T by 2. This is T. And we will, just for argument sake, take this as our V c, control voltage. Then output V naught is going to plus V s the moment input voltage here goes above V c. So, and this range, the output would have gone to plus V s; and if you extend this, it would go to minus V c c, like this.

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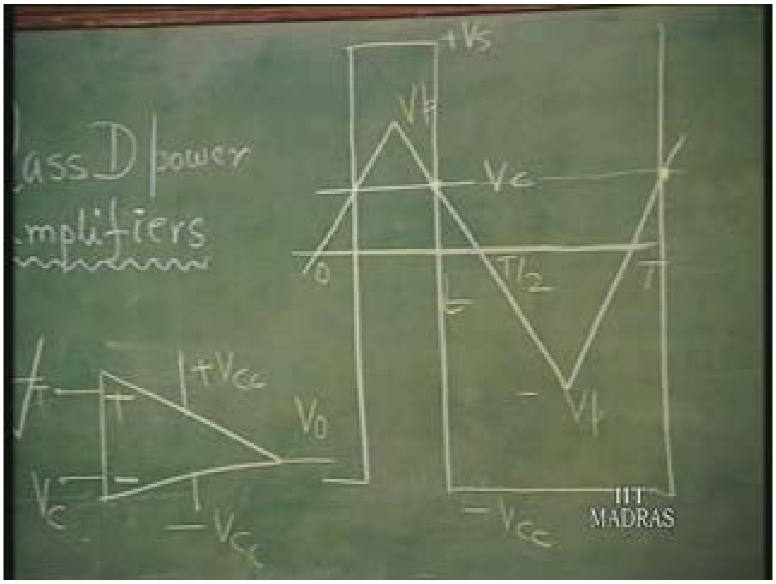

If I increase V c, the width of this is going to decrease. If I decrease V c, the width is increased. So, this is a pulse width modulator. Though...so, this circuit is nothing but pulse width modulator. Very simple circuit.

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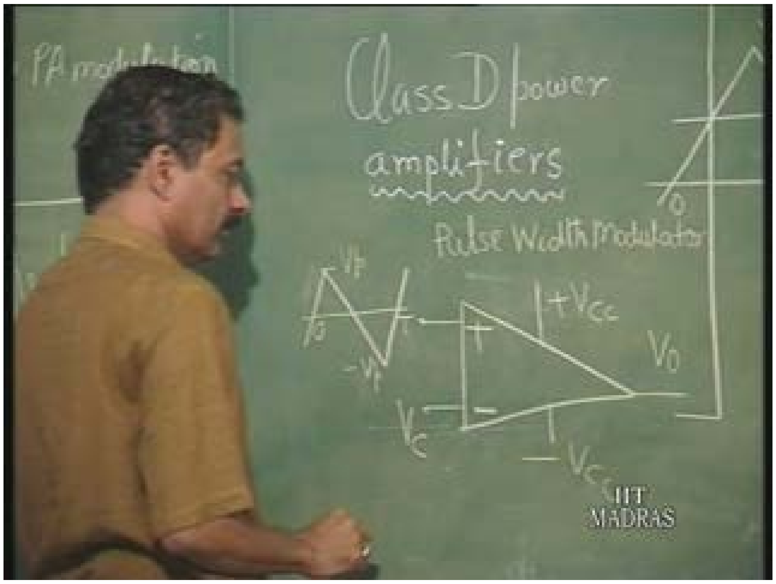

So, it uses a triangular wave form with time period T with the control voltage applied to the other terminal, output been taken here, you get a square wave. This is the output voltage here. You get a square wave which is going to plus V c c and minus V c c. Its pulse width is...or duty cycle, this is called duty cycle; tau by T is called duty cycle. That is controlled by V c. How is it controlled? Let us mathematically see.

These 2 triangles are similar triangles. The width of this is T by 2. The width of this is tau, let us say. So, tau divided by T by 2, tau divided by T by 2 is this height divided by this. So, this height is V p minus V c divided by V p. So, this is simple. Similar triangle relationship - this base divided by this base is this height divided by this height.

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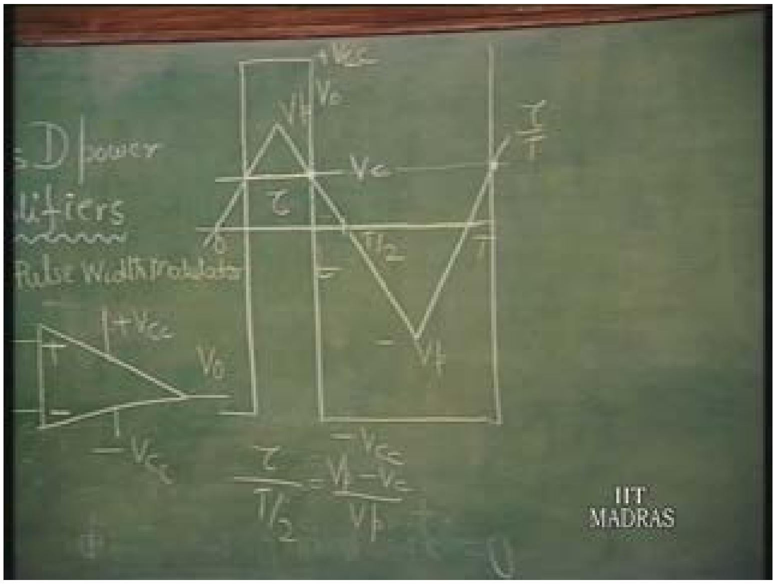

So, this will give us an equation which says tau by T, tau by T is equal to half into 1 minus V c by V p. Very important relationship. Tau by T is equal to half, 1 minus V c by V p.

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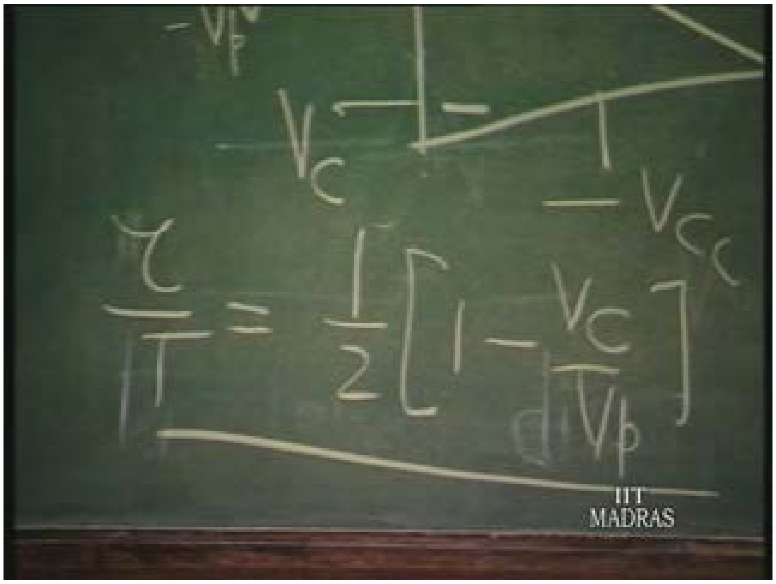

So, if I really change V c, tau will proportionately change. But I want, where...the tau by T factor to come in such a manner that the average will change in sign, when V c changes in sign. Now, the average is simply tau by T into V c c. So, average does not change sign when V c changes sign. This can be simply done by instead of connecting this to ground, this switch will connect it to minus V c c, instead of it being connected to ground.

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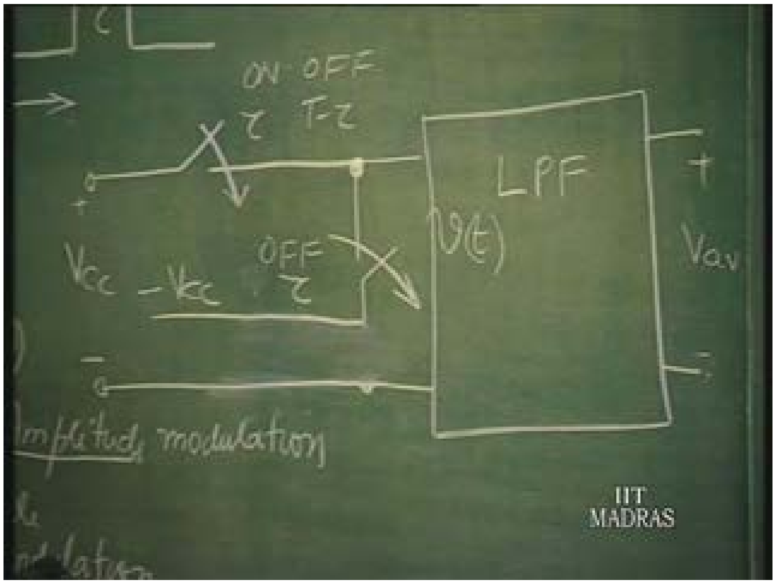

So, that means this voltage will go to minus V c c instead of being at ground. So then the average will change to tau into V c c, tau into V c c; and this is minus V c c.

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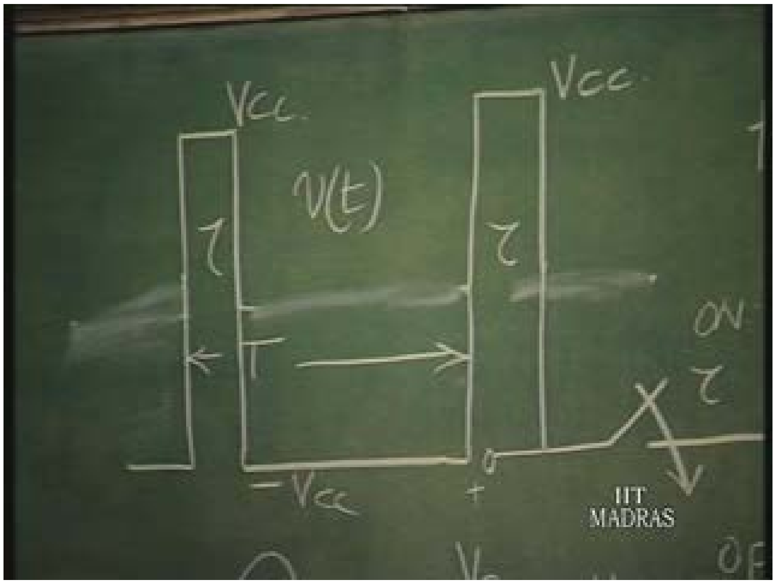

Minus V c c into T minus tau, the whole thing divided by T. That is the average. Tau into V c c, that is this area; and minus V c c into T minus tau, this is the negative area. So basically therefore, we have this, this area and this area. That is the average; that divided by T is the average.

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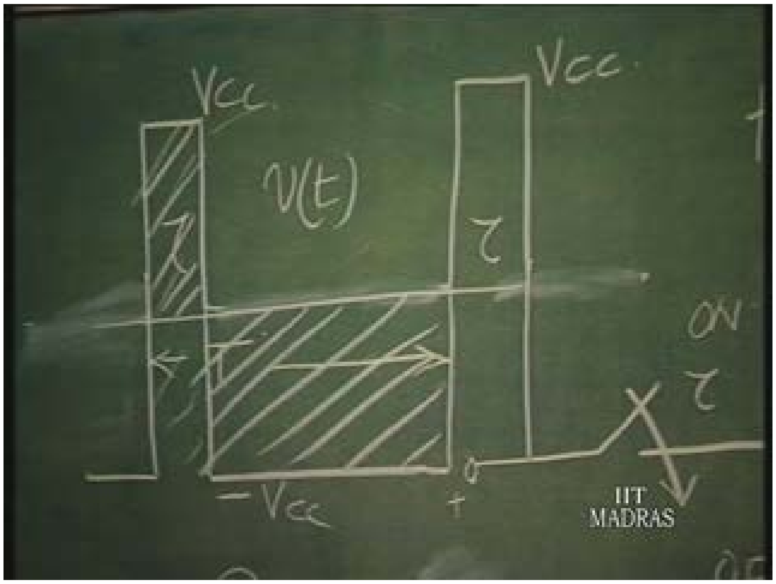

So, this comes out to be...we can take this now... V c c comes out, T also comes out, tau also comes out. So, you can say, this is 2 tau, this tau and this tau - 2 tau into 1 minus... Alright. So, this will be actually, let us say, 2 tau V c c minus V c c into T by T. So, I am taking 2 tau V c c by T out. So, 1 minus...V c c has been taken out. So actually speaking, we will leave it at that. 2 Tau minus V c c or V c c into 2 tau by T minus 1.

Now, 2 tau by T, 2 tau by T is nothing but 1 minus V c by V p. So, we will substitute that. 2 tau by T okay minus 1 is nothing but minus V c by V p into V c c.

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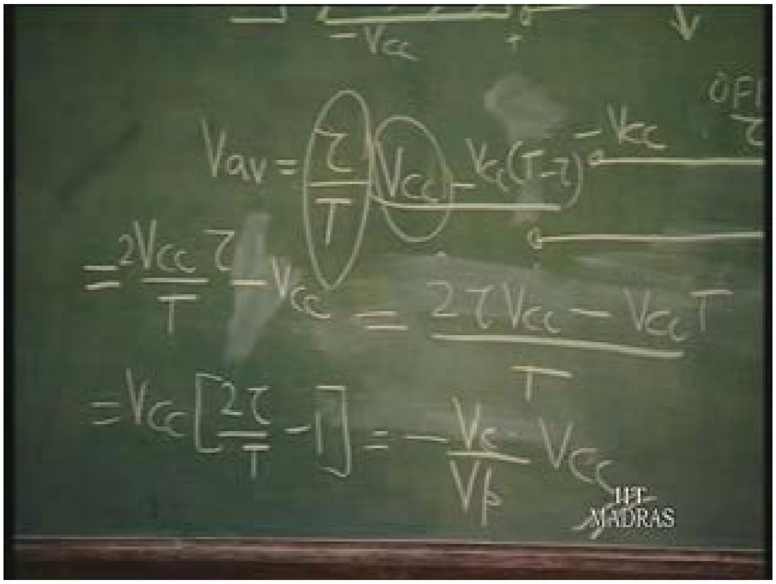

So, if I use this kind of averaging circuit here and obtain an output voltage of this type and make this control voltage control these switch positions, closing and opening is going to be controlled by this voltage here. When this is high, this is closed; when it is low, this is open. This will be open when it is high and closed when it is low.

So, such a situation, I get an output which is an average which corresponds to this. Here, V c when it changes sign, output also changes sign. So, if V c is a sine wave, output also is a sine wave. So, you can get output power, if you take the average of this wave form here. The averaging circuit therefore has to be such that it is efficient; that it should not lose any power, energy, in it.

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So, the best averaging circuit is just going to be a low pass filter combination which is going to be L and C network. So, if you are not happy with one section, you can put multiple section of such low pass filters and then across the load, we will have only the average component appearing. All the high frequency components at frequency corresponding to 1 over T will be eliminated and therefore we get very efficient power transfer, useful power transfer, on to the load.

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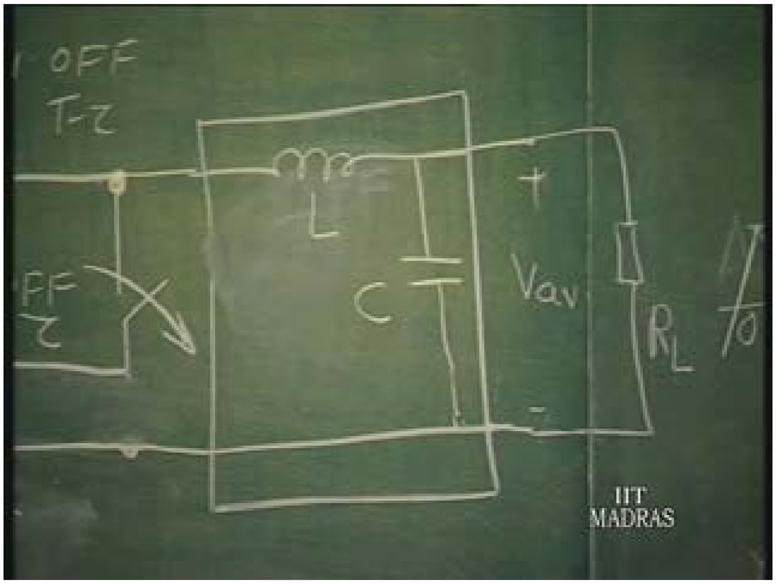

Now, consider this circuit with this...What we have assembled out of the blocks that we have just now mentioned. The triangular wave form generator gives an input to the comparator here where V c is the modulating frequency, width modulating frequency. The output of it is now directly controlling the switch. The same combination of complimentary pair we have used as class B stage; and as long as we know that this output is always going to flip from let us say, plus V c c to minus V c c, we can say that the transistor is really operating in switch mode.

So, this...when this goes to plus V c c, this will be very nearly going up to plus V c c here and when this goes to minus V c c, this will go up to minus V c c here. So this...these are two switches: one will connect it to plus V c c, another will connect it to minus V c c – complimentary.

And for protecting against any accidental opening of the transistor or in between transition during certain duration plus minus V gamma, the...both the transistors are not conducting during that period to restrict the voltage from jumping high because the inductive current will be continuous. So the...these are the clamping diodes, protective diodes, which have been put. These will not allow the voltage to go too high when the switch is getting opened in between.

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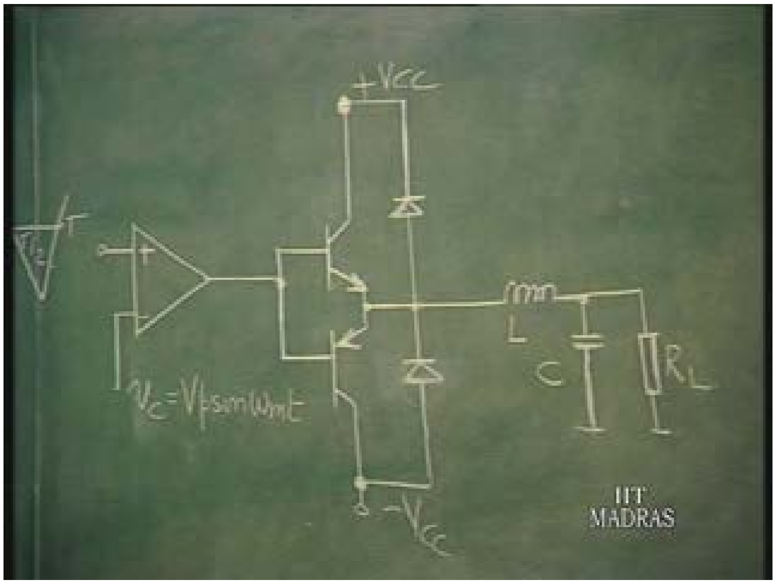

So, these...this circuit along with this low pass filter will get rid of the high frequency component, the clock frequency and generate power only at the modulating frequency. So, the...if we say that the switches do not dissipate any power, and L and C are ideal, then in this whole process of convert, obtaining this power at the power amplification here, we have not spent any energy as far as this whole circuit is concerned, assuming that all these things consume very little power at the input side, the driver circuits...We can say that the efficiency is 100 percent.

Now, what are these factors that will be responsible for bringing down the efficiency from 100 percent?

One is this. When the transistor is closed, the voltage across the transistor which is VCEsat may not be negligible. It may be of the order of, let us say, 1 volt or so for high current switching. So, this VCEsat for small signal is of the order of point 2 to point 3. It may be pretty high because some ohmic resistance drop also occur along with junction drop. Therefore, this voltage may be as high as 1 volt or so; and that is going to permit certain amount of current to flow.

So, the current that is going to flow through the inductor is going to be supplied by this transistor which is closed so that this is the power that is going to be dissipated in this transistor when it is closed. Similarly this, when it is closed during the other, other period, this is for, let us say, tau, during the other period, the other transistor is going to dissipate power which corresponds to the VCEsat of the other transistor.

And so basically, if you assume that the transistor power gets dissipated when it is closed, this will be the total power that is dissipated in the transistor when it is closed; but when it is open, the... this is the energy that is dissipated and the average power is going to be this divided by T.

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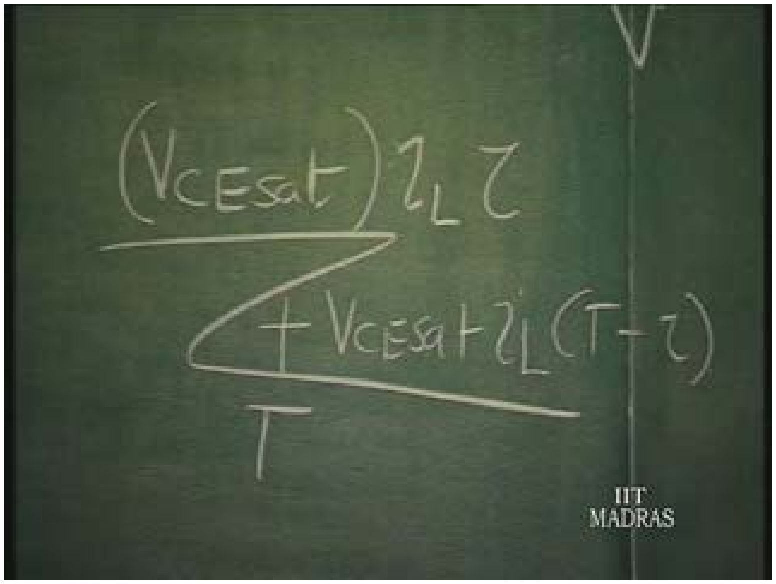

$$\frac{(V_{CEsat})\, i_L \tau + V_{CEsat}\, i_L (T-\tau)}{T}$$

When it is open also we have this going up to, let us say, this is minus V c c and this going up to plus V c c; so open, when it is open, the voltage across this is going to be twice V c c.

So, the voltage is maximum. The current is maximum, when it is closed. Voltage is maximum when it is open. So, twice V c c into the leakage current I C E naught. So, this is the power dissipated in the transistor that is supposed to be open. This leakage current, even if it is very small, the voltage may be pretty high. So, this may be becoming considerable. Again, this into tau for the transistor in one side and similarly the other transistor is going to be also dissipating; so, that divided by T.

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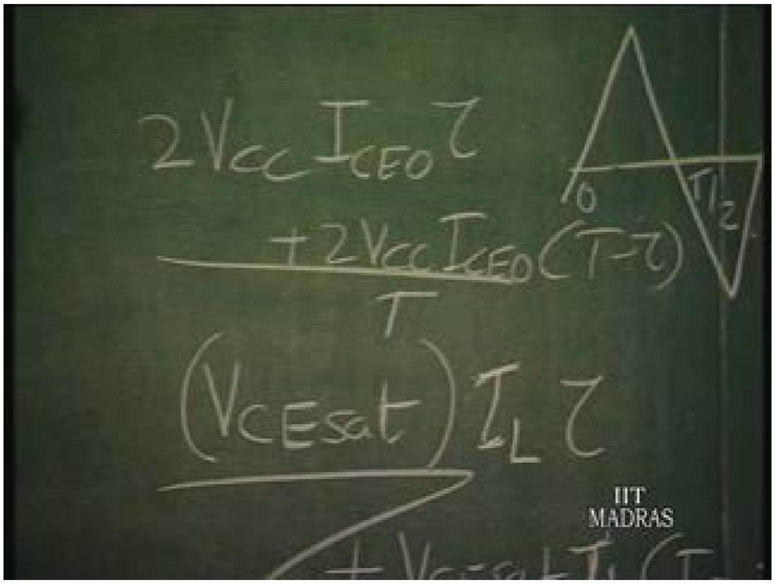

$$\frac{2V_{cc}I_{CEO}\tau + 2V_{cc}I_{CEO}(T-\tau)}{T}$$

$$(V_{CEsat})I_L\tau$$

$$+V_{CEsat}I_L(T$$

So basically, we can see that since there are two such identical transistors used, power dissipated during the entire period is going to be essentially VCEsat into I L; to what? And that dissipated during the time when it is open corresponds to twice V c c into I C E naught.

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$$V_{CEsat}I_L$$

$$+2V_{cc}I_{CEO}$$

So, this much power gets dissipated in the transistors; apart from that, we have...when the transistor is going from on to off and off to on also, some amount of power that is going to be dissipated.

This, under the assumption that, when the transistor is going from off to on, this is when it is off, voltage across it; and let us say, voltage across it is VCEsat when it is closed. This is the case of the transistor going off. Here it is on. When it is on, the current is very high and is going to zero of I C E naught, when it is off. Here it is higher. So, we have already established the power that is spent here as well as here for the transistor.

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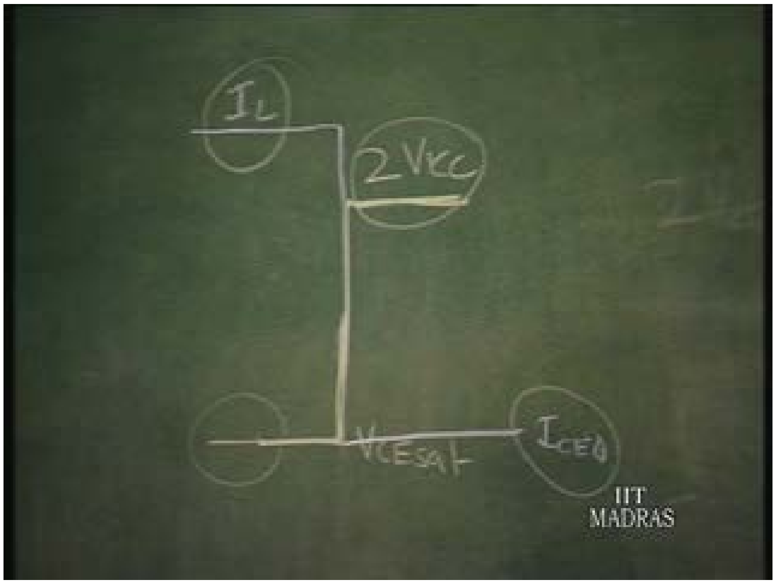

But this assumes that it takes almost zero time for it to go from off to on. But when you are working at very high frequencies, this time for it to go from off to on is not negligible.

So, this becomes comparable to the time period. In such a situation, we can assume...actually, it will not be linear like this; that it is linear. So, it is going from on to off; current is going from full to almost zero and the voltage is going from VCEsat to twice V c c and it is moving linearly.

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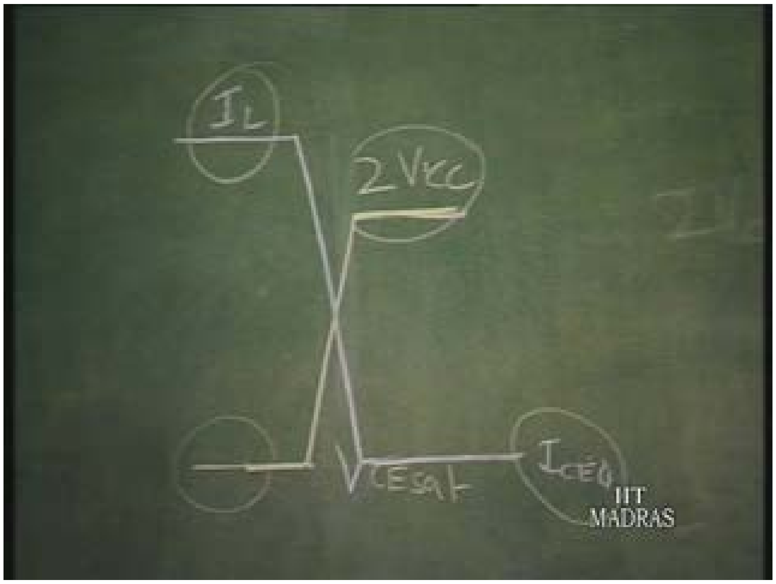

So, this is the time; this is the rise time or fall time. This happens also at the other end, it comes like this; this will go like this. So, both at the rise time and the fall time, in a time period, it happens.

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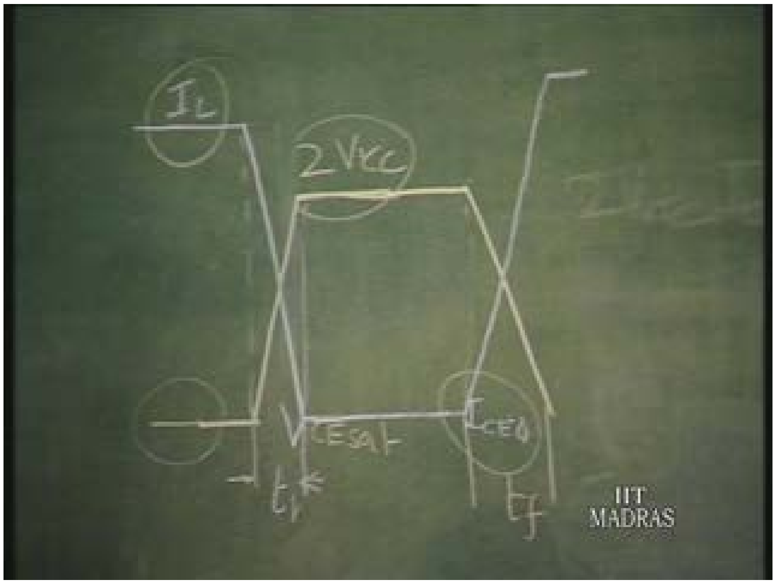

So, we can evaluate the power that gets dissipated in the transistor when it is active. Here, in this range, transistor is active; so...in both these ranges...So, if you take this kind of wave form and solve the problem in terms of finding out again the product, put down the wave form for this. This wave form, you can put down. For example, I can ignore this assuming that this is very nearly zero compared to twice V c c; this is very nearly zero compared to this. Then the voltage wave form will be something like... If you start with this as zero, V t divided by...this is twice V c c is the peak. That divided by t r is the slope into T is the equation for that. So, this is the equation for this line.

Twice V c c divided by t r is the slope, into t; whereas the other one is going to be 1 minus... So, we can put it as I L by t r. That is, this slope again; into t. I L minus I L into t by t r. At t equal to zero, it is I L; at t equal to t r, it is zero.

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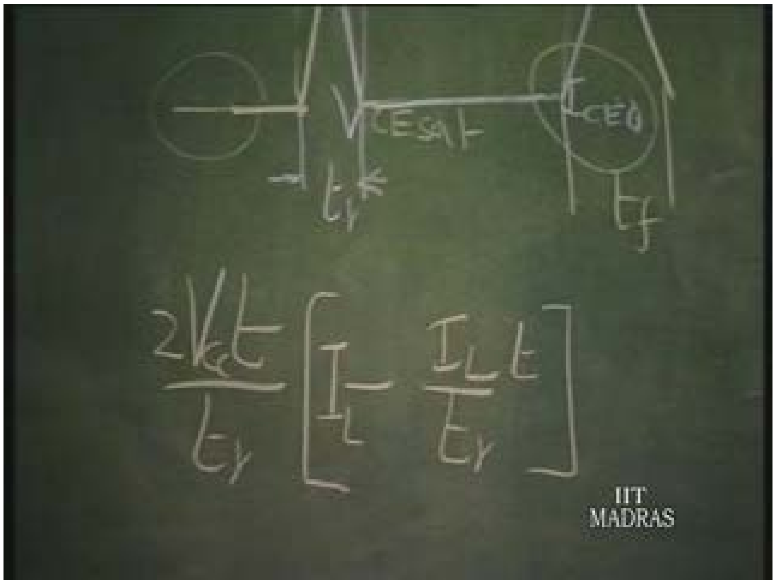

So, this is the voltage wave form; this is the current wave form. So, voltage into current is the instantaneous value of power. This into d t zero to t r is the energy and that is the energy that is what is important. That into something like 2, because it is happening over the time period twice.

So, that whole thing divided by T is the power that is dissipated for the transistor, when they are going to be in the active region during rise time and fall time.

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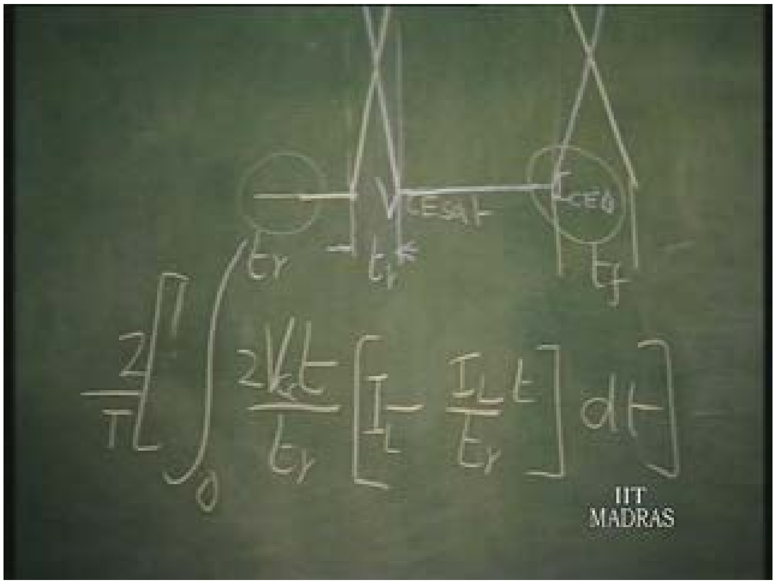

So, this can be evaluated. I am going to leave this as an exercise. This is an integral which we will solve and this is the power that is dissipated in the transistors, when the transistors are going to be in the active region during rise time and fall time.

So, all these powers must be added in order to evaluate the total power that is dissipated in the transistor. Apart from these, we have the power that is dissipated in the resistance of the coil; power that may be dissipated in the capacitor, resistance loss. All these things will bring down the efficiency and it is typically something between let us say, 80 to 85. That normally is good enough efficiency for Class D power amplifiers.

We have understood a large number of circuits: amplifiers, power amplifiers, oscillators, sinusoidal oscillators, non-sinusoidal oscillators, etcetera. Now we are ready to build systems and the important system in circuits, negative feedback system or control system; that we would call. Control circuit - under this category, one of the most useful circuit system is what is called voltage regulator. It may be...or D C voltage regulator you can call it.

You can have A C voltage regulation which we will call it as automatic gain control system or automatic volume control system. So, when we say voltage regulator, normally, we mean D C. We can also build A C voltage regulators in our electronic system; that is amplitude stabilization of oscillators. Then, let us say, A G C systems, A V C systems, these are all A C voltage regulators.

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Control Circuits

Voltage regulators

Basic building blocks

1 Voltage reference

2 Comparator (voltage)

3 Series pass transistor

So, we will discuss how to build these control circuits where something is required to be maintained constant; in this case voltage – D C voltage or A C voltage. It could be current also. Then they will become current regulators, alright? So, all these control circuits are pretty simple in the sense you want something to be maintained constant. In a voltage regulator, you want output voltage to be maintained constant. In a current regulator, you want current to be maintained constant. In an A C regulator, you want amplitude of the A C voltage to be maintained constant. In speed regulation, you want to maintain the speed of a motor, constant.

So, these are all control circuits; position - you want to maintain the position of a system at a particular point - position control; servo controller, these are called. So, we will discuss such systems that can be built using circuits. Basic building blocks of this voltage regulator, for example, is going to be a voltage reference. Now, that is the characteristic of any control circuit.

If it is A C voltage regulation also, we need a voltage reference. That is normally a D C voltage reference. Even if it is speed, we need a reference that can be a frequency or a D C voltage, depending upon the system. So, a reference forms an important aspect of the basic building blocks of these controllers.

In this case, since it is a D C voltage regulator, we would like to have a D C voltage reference with which we are comparing and seeing whether whatever we want to maintain constant is remaining constant. We have to know, compare and know whether it is changing. So, this comparison is done by what is called a comparator. It is a voltage comparator. It tells you when the...what you want to maintain as output voltage is changing with reference to the reference voltage.

So, it gives an indication. Correspondingly, I can control something. In the case of maintaining output voltage constant, there will be something coming in series. This is the active device; in this case, a transistor. This is called series pass transistor. This is coming between output and input in series; and this series pass transistor is the one that will have its voltage controlled by this comparator output in such a way that output voltage is maintained constant.

So, these three things form basic components of the so-called voltage regulator which is one of the largest volume sales as far as circuits are concerned. Integrated circuits are available now as fixed voltage regulators or variable voltage regulators. Fixed voltage regulators may be primarily meant for your P Cs and other things. These are called three terminal voltage regulators where the output voltage is fixed and variable voltage regulator which is five terminal voltage regulator I C, wherein you can design the circuit such a way that voltage output can be anything from some value to some other value. So, let us therefore understand how we can maintain the output voltage constant; the basic scheme.

So assume that this is the black box and this is the output voltage, D C output voltage, and this gets an input voltage which is unregulated; unregulated input voltage. So, output regulated. In between, we have to put something. So, let us assume that there is a common terminal. This is the common terminal between the input and output; and I put the series pass transistor in series. So, this is, I mean I am assuming that I am using a n p n transistor.

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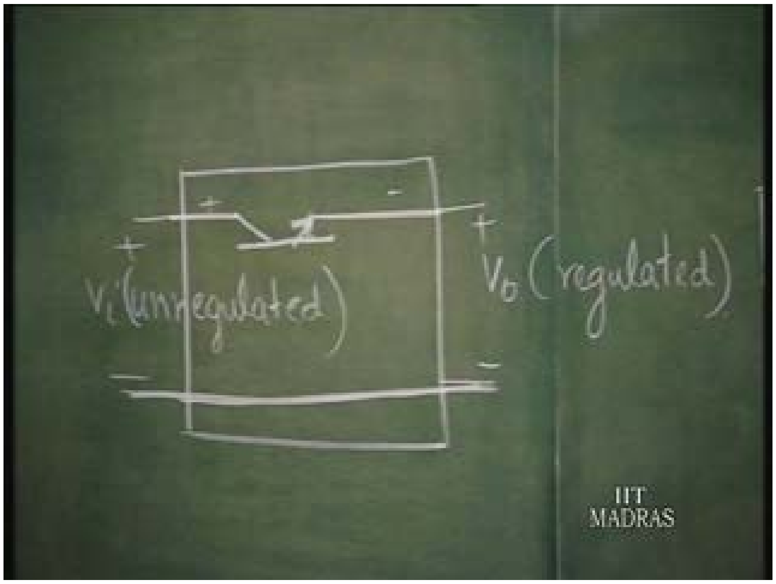

So obviously, input voltage minus the drop here is the output voltage. So, if I want the output voltage to be maintained at let us say, 10 volts, I should have something which tells me that it is going to exceed 10 volts or so. So, I want a reference. For the reference, I can use what is called a Zener diode. This, we have already earlier seen, a Zener diode.

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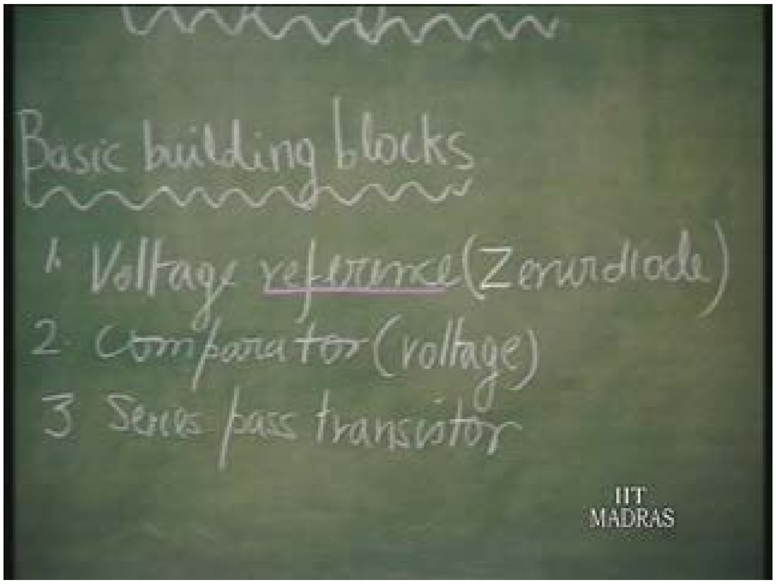

Basic building blocks

1. Voltage reference (Zener diode)
2. Comparator (voltage)
3 Series pass transistor

So, we know about Zener diodes. We have discussed this earlier in the first part of the course. If a Zener diode gets, let us say, this V i unregulated, this voltage, and I put a current limiting resistance here so that the current in the Zener is above the minimum value but below the maximum value, then the voltage across the Zener is a constant, V Z. Depending upon the requirement, I can select whatever V Z I want.

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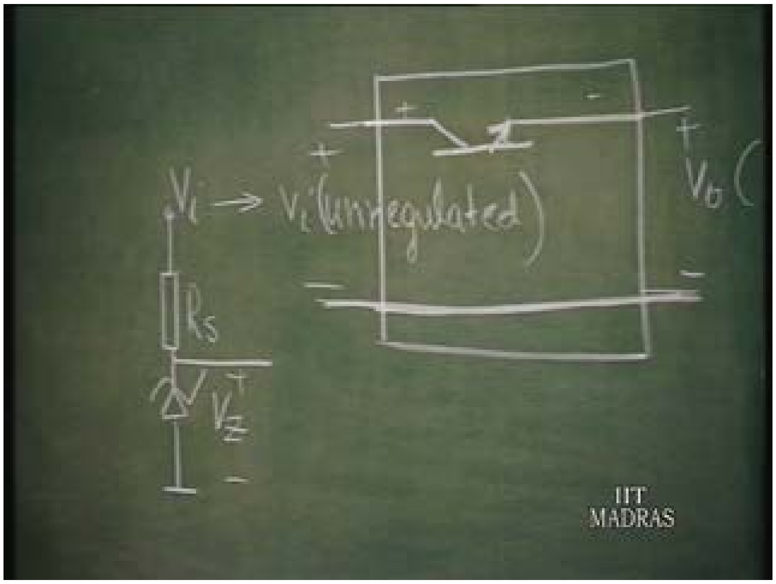

So, I am going to put this at the input, let us say. So, this is V Z. This I will select depending upon, let us say, the output voltage I want to maintain as constant. So simply, I can now compare it with portion of the output voltage. I take a sample of the output voltage. So, what will be the voltage here? R 1 by R 1 plus R 2 times V naught.

I compare this voltage with this. This is V Z. This is R 1 by R 1 plus R 2 into V naught. So...and the output of this, I connected to this, so that the base current of this is going to control the drop across this in such a manner that if this is a negative feedback circuit now, this is an op-amp. The output is somehow coming back to the input. So, if this is a negative feedback circuit as it is shown, then this voltage should be same as this voltage. This is a nullor. This voltage is zero. So, that means this comparator will work. This is the comparator here.

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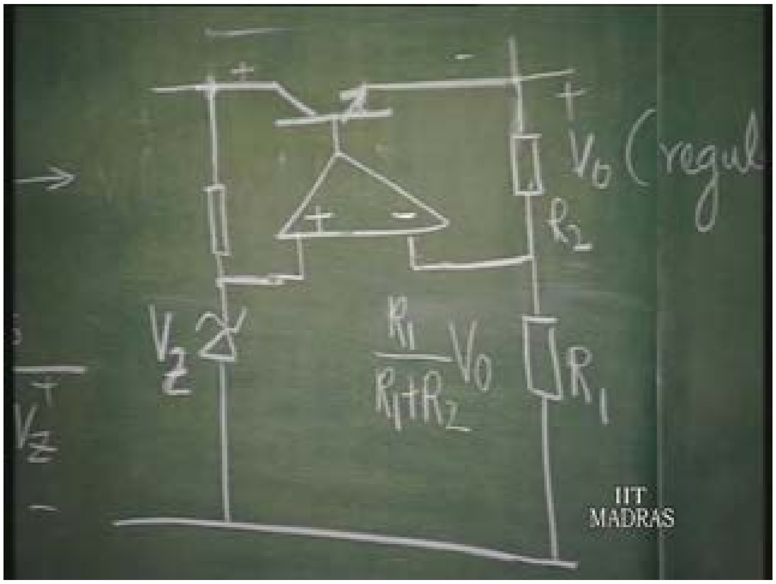

The op-amp piece being used as a comparator but in such a manner as to adjust this voltage so that the output voltage V naught into R 1 by R 1 plus R 2 equals V Z. So, V naught is 1 plus R 2 by R 1. So, this is a nice voltage regulator for you.

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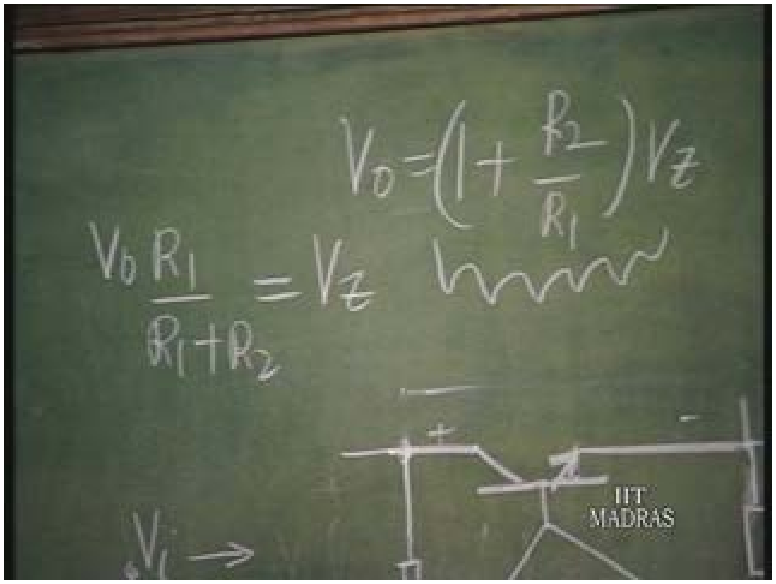

Output voltage is independent of the input. So obviously, this op-amp has to be biased. So, how do you get... This is a higher potential and this lower potential is grounded. So here, the op-amp piece being used with input voltage as the higher potential connected to normally a place where V c c is connected; minus V c c point is connected to ground. So, this is a self-contained unit.

So, this is connected to V i. This is connected to ground. And the output of the op-amp is going to be much above ground because V naught is 1 plus R 2 over R 1 into V Z. So, this is what is called operating the operation amplifier with single supply. So, this circuit is going to be exactly same as what we had earlier given.

Let me draw the circuit the other way. So, this is really my op-amp because we can consider this as the op-amp same; supply voltage as the input. Collector is connected together. Only thing is here we are giving V i and then deriving from V i...the input which is given to the plus terminal and output of this is getting feedback from this output of the op-amp... So, if you consider this as an op-amp, this whole circuit is nothing but an op-amp circuit working with single supply and negative feedback to an extent of R 1 by R 1 plus R 2 times V naught. The load is connected here.

So, this is nothing but a non-inverting amplifier because now the input to the non-inverting amplifier is V Z. So obviously, V Z is amplified as V Z into 1 plus R 2 over R 1. This is nothing but what we have earlier discussed as a non-inverting amplifier. Only thing is the current handling ability of the op-amp may not be that high. We could have as well used the op-amp itself for this regulator. So, instead of that, the current handling ability of the circuit is enhanced by using a current amplifier.

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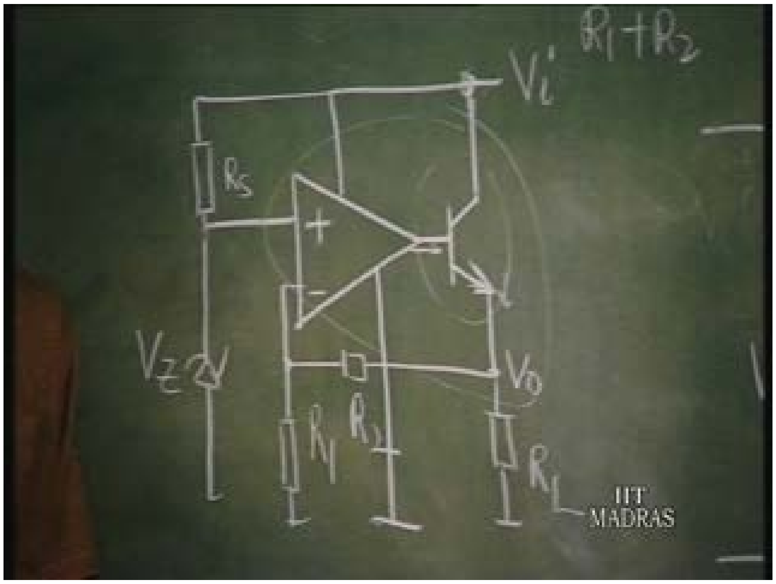

This is the op-amp output current. This current is Beta plus 1 times higher. So, by using these transistors along with op-amp, we can build any regulator suitable for any large amount of current. So, if you think that this maximum current of the op-amp is 20 milliamperes and Beta of the transistor is 50, 20 into 50 - that is 1 ampere regulator you can build by using a transistor whose current rating is greater than 1 ampere.

If you think that the transistor rating is not greater than 1 ampere, then you will connect another transistor. This transistor is not adequate. So, I want higher current rating. You will connect these transistors in Darlington pair to boost up the rating of the regulator. So, these are all current amplifiers. So, you will see a pyramid like structure here for boosting up the current of the regulator. The emitter of this is connected to the base of this; emitter forms the output. So, this kind of arrangement is always resorted to while building regulators.

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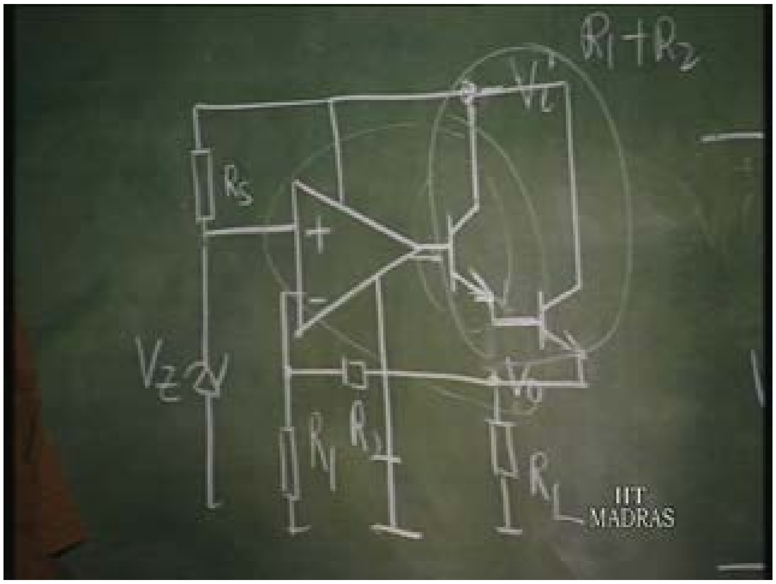

So, the series pass transistor which is this, is coming between input and output and this can be put in Darlington pair in order to boost up the current rating of the regulator. And the design of the regulator is going to be flexible here because V Z, if it is given, you can find out - 1 plus R 2 over R 1 to suit your application. Let us say, V Z is 5 volts and V naught you want is 10 volts. Then, this has to be a factor of 2. So, if V Z is given to you, then you can always find out 1 plus R 2 over R 1 required from obtaining the desired output voltage as the constant output voltage. It is fairly independent of input variations.

Now, is it really true that this circuit is going to function satisfactorily without giving any variation at the output when V i varies? Up to what extent is it valid? All these are factors that we have to determine. That means how do we assess the performance factor of a regulator? So, these are the factors that have to be understood in understanding regulators. So, let us see what are the basic definitions.

If I plot V naught of this as a function of I L...I L is the load that I am going to connect across this. This is the load. This may be a radio receiver or a television receiver or something; so, which needs the regulated supply. So, that is the load.

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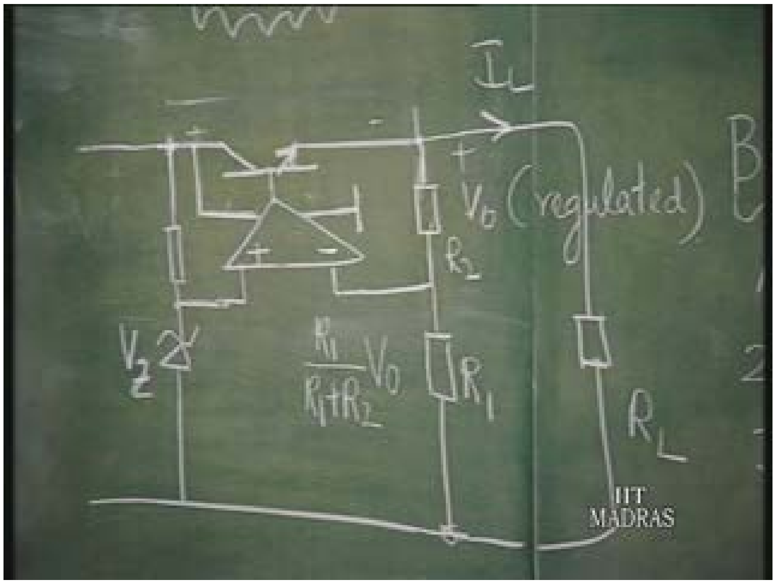

If I plot V naught versus I L, this should be constant. This is, really speaking, V Z into 1 plus R 2. This characteristic is called regulation characteristic.

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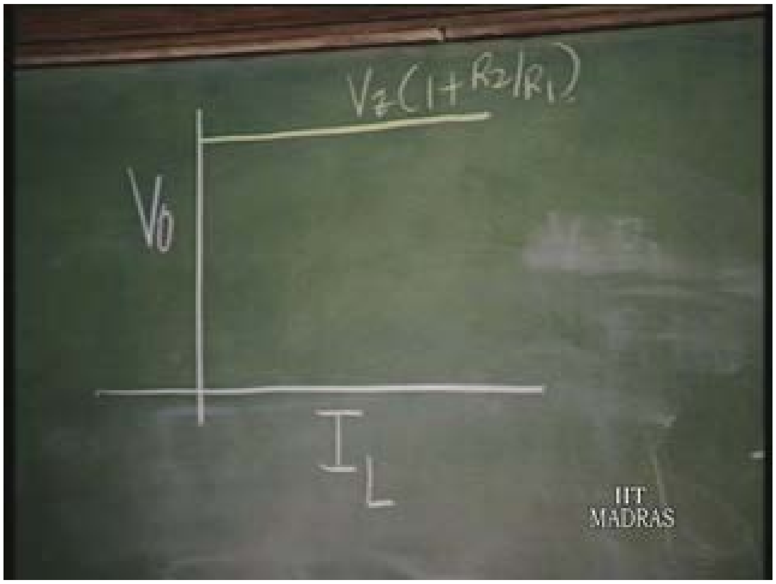

Strictly speaking, this will not be constant. This will have some kind of slope downwards. So, that is what we want to find out - the regulation characteristic of this. Up to what extent can I go on? There must be some maximum limit, I L max, up to which I can go on because this is going to dissipate power.

Input power is nothing but V input... That is, input power is nothing but input voltage into input current. Input current is here. Input voltage is this. Output power is obviously output voltage into output current. Obviously, output power is less than input power because input voltage is here, something is dropped here and rest of it is appearing here. Therefore, efficiency is going to be V naught I naught by V i I i.

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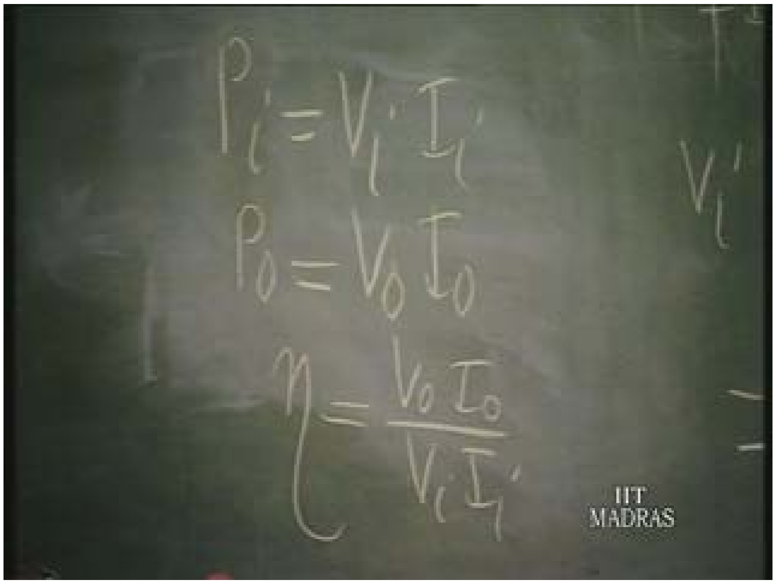

$$P_i = V_i I_i$$

$$P_0 = V_0 I_0$$

$$\eta = \frac{V_0 I_0}{V_i I_i}$$

Efficiency of a regulator is an important part because normally these regulators may supply current to large number of circuits and therefore the current of operation may be of the order of amps. Therefore, I naught is going to be of the order of amps. I i is also going to be of the order of amps because I L is the major part of current which is going to flow through this. Rest of the current is only for biasing purposes and therefore I...in a good design, I naught is very nearly equal to I i, in a good design.

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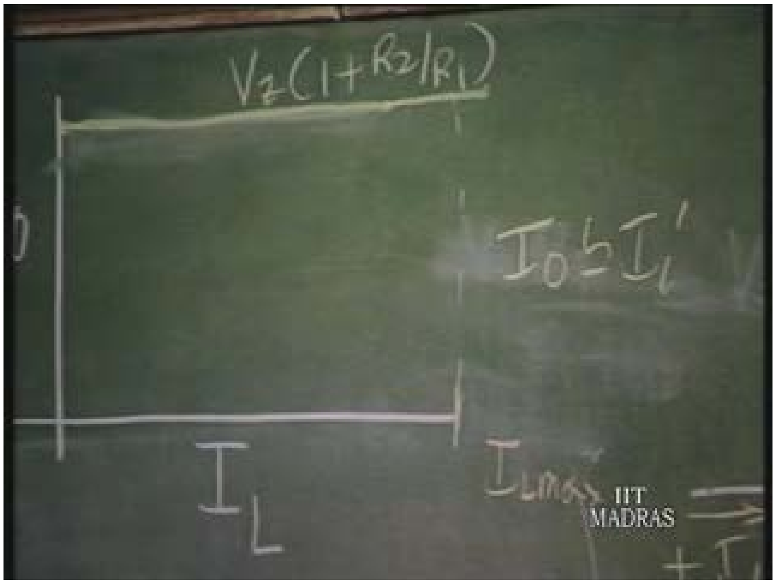

So, efficiency is going to be very nearly equal to V naught by V i.

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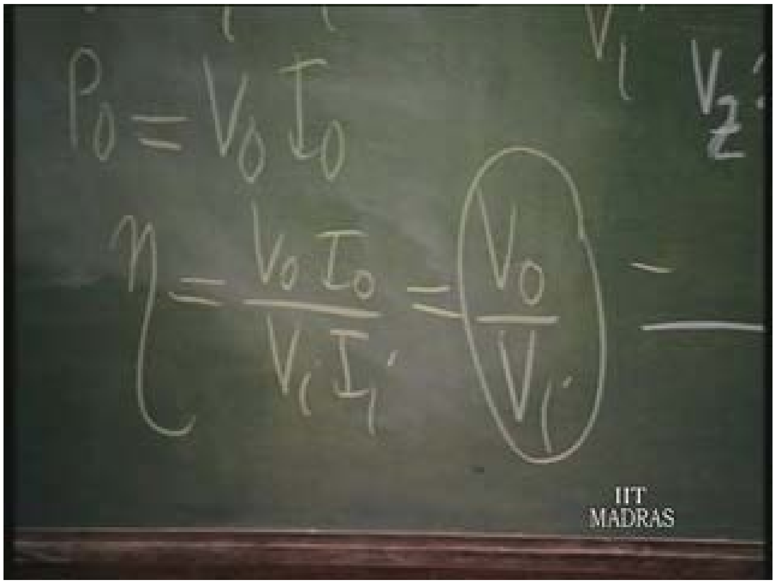

So, if I want to regulate a voltage where the input is changing from, let us say, 5 to 10 volts, I want the output to be 4 volts. Output voltage has to be always less than the minimum voltage at the input. So, input is changing from 5 to 10 volts. Output has to be

4 volts; maintain constant. At any given time, input voltage has to be greater than output voltage. So, the best efficiency I get is 4 by 5; and the worst efficiency I get is 4 by 10.

So, it might just get stuck at V i equal to 10 and I will be operating only at the worst efficiency situation of about 40 percent. Rest of it is dissipated in the transistor. So, this kind of regulator is not a very efficient scheme because output voltage is always less than the input voltage, number one; and output voltage should be made less than the least value of input voltage. That means when the input voltage is very high, efficiency is very poor. So, we will discuss more about the performance factor associated with this regulator in the next class.