Analog ICs

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Lecture - 13

Protection Circuitry for Voltage Regulator and Switched Mode Regulator (DC to DC converter)

In the last class we discussed short circuit protection for the voltage regulator and we saw a crude way of doing some short circuit protection wherein we sensed the current through the load using a resistance R sense and made use of this voltage across the R sense to divert the drive into the pass transistor. This is the method of short circuit protection adopted in most of the power ICs. Whether it is a voltage regulator IC transistor or power IC transistor whatever it is this is the common method of short circuit protection adopted universally in all integrated circuits.

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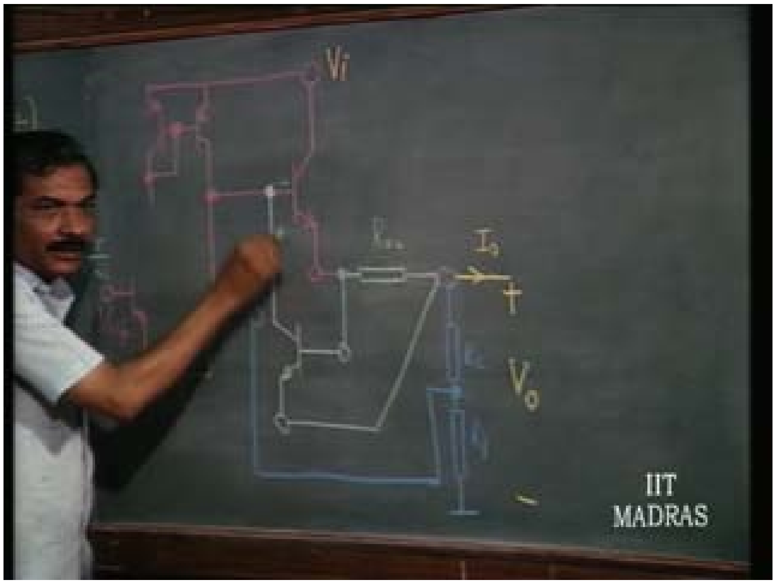

Once again the drive otherwise would have increased the current through the power transistor is diverted on to another transistor which is getting proper biasing because of the current increase. Now, that kind of short circuit protection results in the voltage source being converted into a current source thereafter. Therefore the current is going to remain constant. If on that the power dissipation under that situation in the IC is lowest at this point but highest at this point. So gradually it is increasing from this point to this point. And nobody can guarantee us as to what exactly is going to be our circuit situation. Therefore this kind of situation is not a good thing for the IC.

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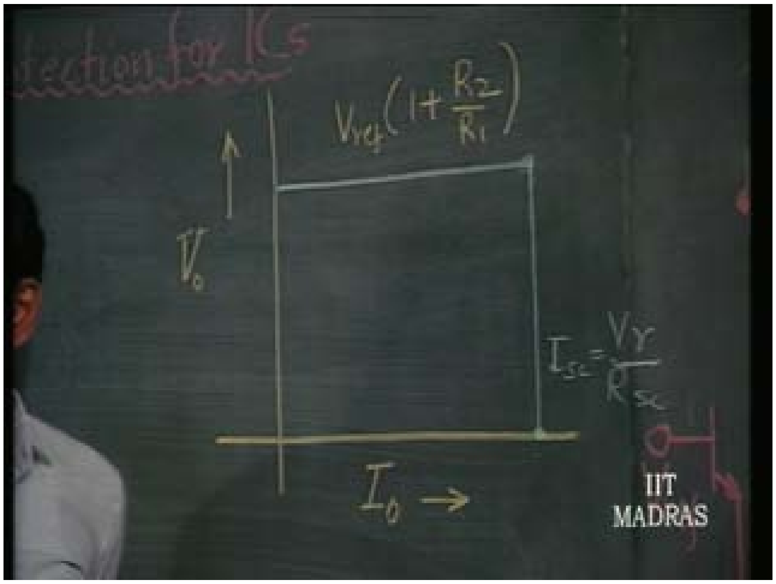

Therefore we would like to immediately sense the load and find out that the load is in excess of what is correct and thereafter we want to have our own dissipation in the IC which is as low as possible until somebody comes and rectifies the current. We have to sense both current as well as voltage for that purpose because we should know what is the voltage and what current I should sustain in order to sustain that voltage which can be anywhere between this and this.

In such a situation that particular protection scheme is going to result in what is called a fold back short circuit protection scheme. But this is what we want so the characteristic of the voltage regulator will be having a knee at this point which we will call as I knee which is the same as the earlier short circuit current and we will have this as what is called as I hold. So these are the two points between which we have to have a line. That means this is again a straight line with V_0 as y axis and I_0 as x axis so it will be just an equation of a line. We have to obtain this kind of line using the hardware there.

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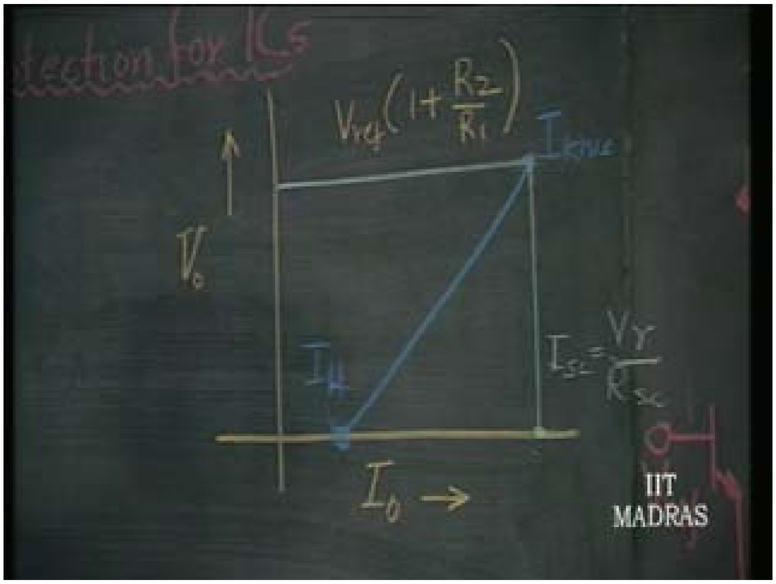

So how do we do this? Let us now therefore discuss the new scheme and we will remove the old scheme. So the same transistor is now going to be used to divert. That basis of diversion of excess current into the series pass transistor is still followed but the method adopted is now different.

How do we do it?
We know that if this is V_0 the voltage at this point is going to be V_0 plus I_0 R_s if you ignore the current in this. The voltage at this point is going to be both dependent upon output voltage and output current but this might be a huge value of voltage whereas we require only about 0.7V to be derived out of this. So obviously this has to be attenuated, that is one way of getting another variable. You have to have two points to be located in a line. That means you have to have two independent variables to fix up the equation.

So I now generate from this a voltage which is going to be low enough so let us say we will put here another attenuator as R_a and R_b and take portion of that voltage, what will that voltage be at this point now?
This voltage is going to be this into V_0 plus I_0 R_{sc} into R_a by R_a plus R_b which we will be calling it as a single variable alpha. R_a and R_b should be large. Just as we select R_1 and R_2 we are also going to be taking care not to take away too much of current from the load. So alpha is nothing but R_a by R_a plus R_b. That is a small enough voltage which we can use and that voltage has to be used to bias the transistor in such a manner that the 0.7V is still [… 08:09]

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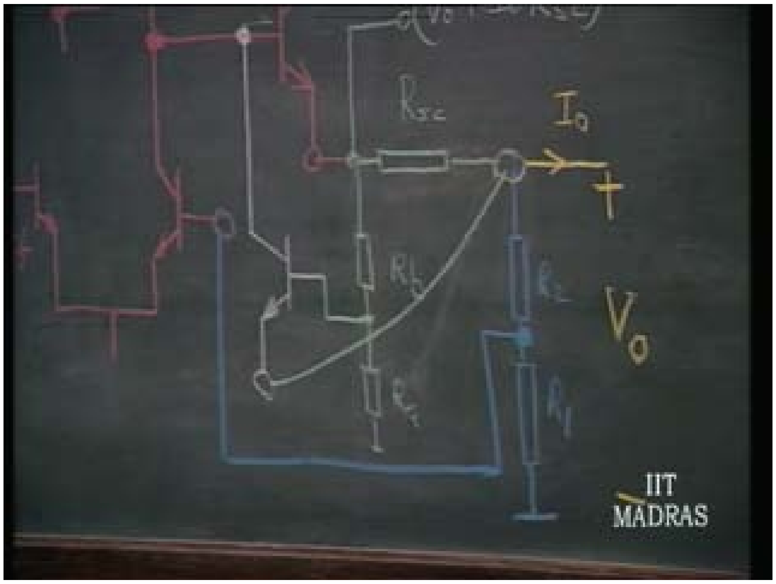

You can see the connection now, this voltage minus V_0 the other end is connected to V_0 so it is now made very small by having an attenuator as well as subtracting a huge voltage from it that should be made minus V_{gamma} that is nothing but V_{be}.

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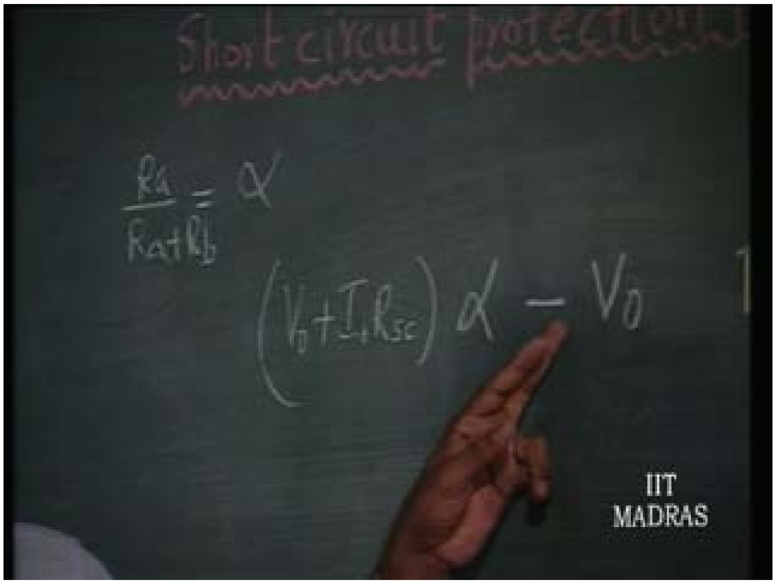

Short circuit protection

$$\frac{R_a}{R_a+R_b} = \alpha$$

$$(V_0+I_0R_{sc})\alpha - V_0$$

R_a by R_a plus R_b of V_0 into I_0 R_{sc} is the voltage here which is alpha times V_0 plus I_0 R_{sc} minus V_0. If you make alpha is equal to 1 it will be our old scheme. This will be connected to this and this will automatically connected to that. The only thing that we are now done is we have sensed a voltage which is dependent upon the output voltage as well as output current by introducing an attenuator.

What is this going to be now?

This is nothing but V_{gamma} is equal to V_0 into alpha minus 1 plus I_0 R_{sc} alpha. Once again we can check this, when V_0 is equal to 0 we still must have a voltage which is minus V_{gamma} to sustain this in whatever position it is that is why it is called the hold current. When V_0 is equal to 0 the I_0 the other variable should be able to still hold the transistor which is diverting the current in operation and that is why that current is called the hold current. Now this is nothing but the equation of that line. At one point V_0 is equal to V reference into 1 plus R_2 by R_1 and the value of I_0 is I_b whatever be the maximum current that you are letting through this system earlier called the short circuit current that is the knee current.

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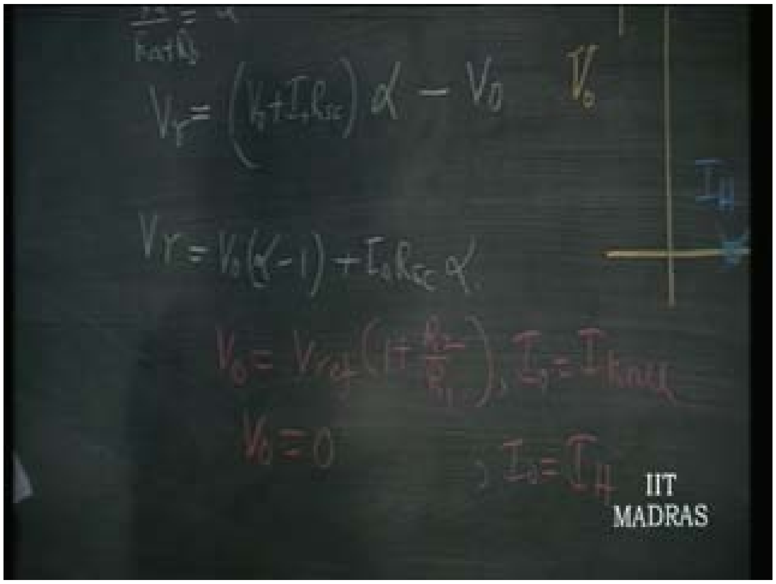

This voltage is known and this current is known. The other point is, V_0 is equal to 0 and I_0 is equal to I hold.

What would you like to have I hold as?

May be 0 but we know it cannot be 0 simply because we have to hold. That is why there is a need for I hold to be non zero. But then I would like to have it as small as possible.

The question is, can you make it very small? What is it that is going to cause problem?

One thing that you have to see is alpha has to be less than 1. In solving this equation you must have alpha less than 1. So actually when I_0 is equal to 0 it should intersect at the negative value which is magnitude of V_0 into 1 minus alpha which is that point. So now my problem is, let us take a typical example. Let us say V_{ref} into 1 plus R_2 by R_1 is equal to 10V. Unless I give you the idea the problem here will not able to appreciate this 10V. Then we will take I knee as 0.5 amperes. So I knee is known as 0.5 amperes let us have I hold equal to 0.2 ampere, we are not sure whether this is the value or not but let us see what the trouble is going to be.

Can you now find out the alpha and R_{sc}?
These are the two unknowns in this equation. All the points are given here for you to find out the value of alpha and R_{sc}. Then we will know what the trouble is regarding this.

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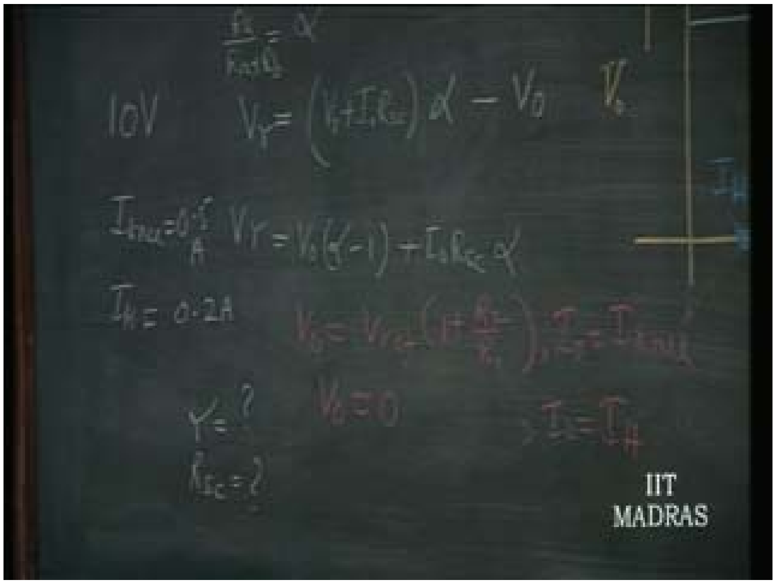

So V_{gamma} is equal to 0.7 and V_0 is equal to 10V alpha minus 1 plus I_0 is equal to 0.5 amperes R_{sc} alpha and then V_0 is equal to 0 again 0.7 is equal to I_0 is equal to I hold which is 0.2 amperes and then R_{sc}.

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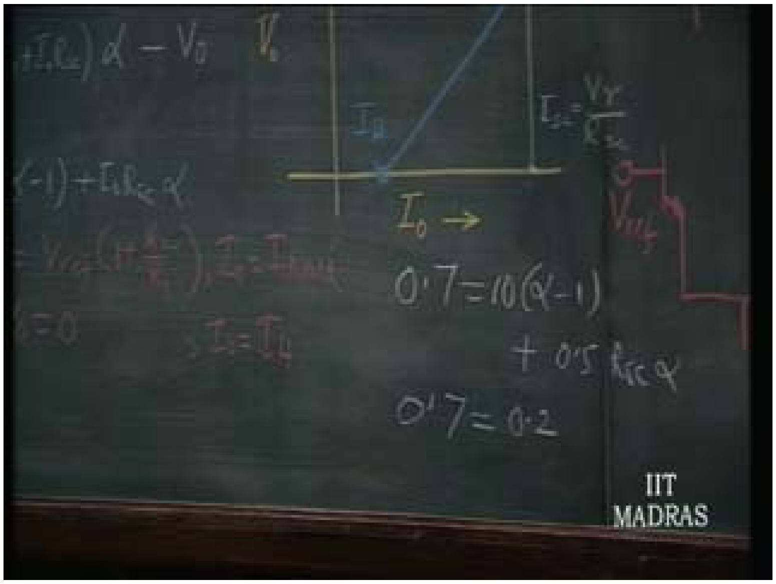

So from this you will get R_{sc} into alpha as 3.5 Ohms. So you know R_{sc} into alpha as 3.5 Ohms so 0.7 is equal to 10 into alpha minus 1 plus 3.5 into 0.5.

So what is the value of alpha?
It is 0.895.

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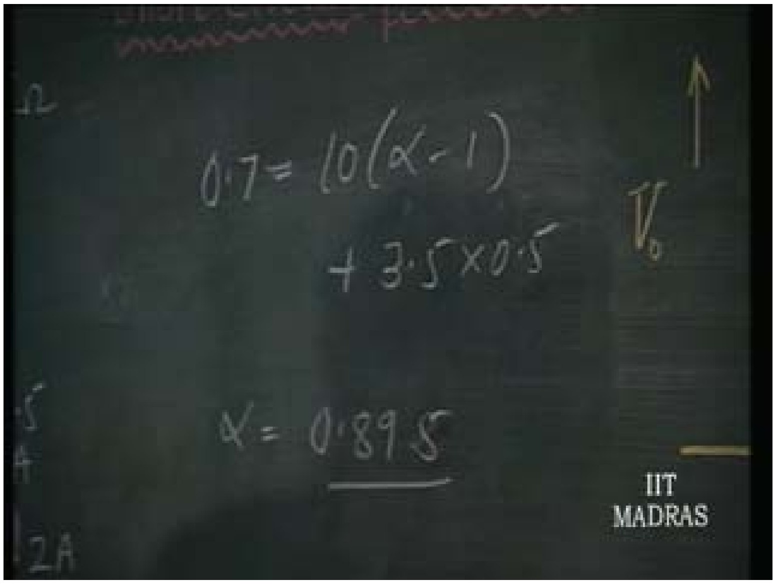

Obviously if I hold current as 0.1 this would have increased to 7 Ohms and you would have had problems with the alpha. Alpha has to be less than 1 and positive. You cannot make alpha smaller than a certain value, this is one thing that limits alpha. That means I will take that alpha which is going to be such that this particular current is as small as possible but even that may be a dangerous thing. Already we have seen that suppose I have this kind of short circuit protection at 0.5 amperes so I want R_{sc} is equal to 0.7 by 0.5 and if I want this kind of short circuit protection the R_{sc} is going to be 0.7 by 0.5 which is 1.4.

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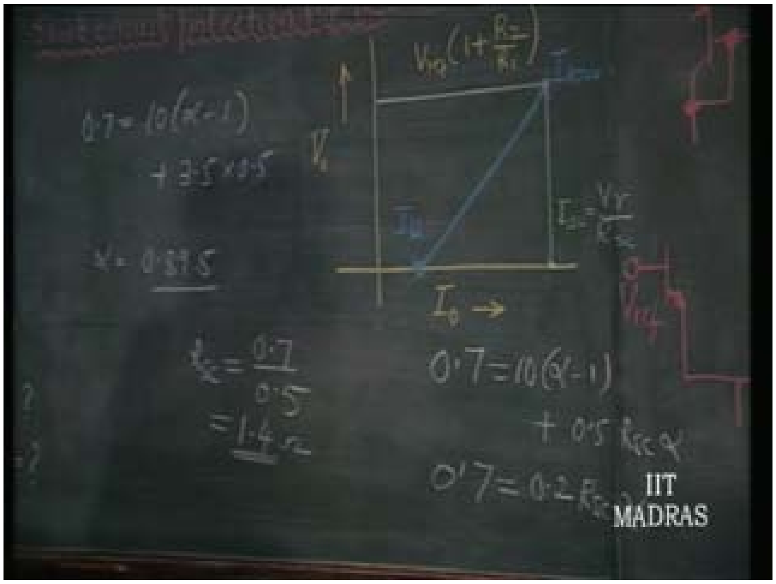

If you are adopting this kind of a situation R_{sc} is going to be 1.4 whereas suppose I would say that it is not a very efficient way. I am going to have 0.5 as the knee current and 0.2 as the whole current then the scheme gives R sense as 4 Ohms as we have already evaluated. So it is greater than what we earlier, so it matters a lot.

We are talking of the currents of the order of 0.5 flowing through now not only pass transistor but also the series resistance which is this. Therefore this will add as an additional drop between V_i and V_{out}.

What is the drop in this situation?
In this situation it is 4 into 0.5 and 2V drop is already here when it is working satisfactorily. So 2V drops here and then 0.7 and then 0.7 that means V_i minus V_0 requirement that differential requirement is increasing. This is how things are going to result in. Therefore, if you try to go for smaller and smaller hole current which is going to be only an eventuality when a short circuit occurs which is also suppose to be quite a rare phenomena then there is no point in loosing when it is in operation its functionality for a large variation in input voltage. This is something that is normally ignored in the laboratory.

They try to make the I hold as small as possible and get at R_{sc} of the order of few Ohms and then see that it is not working as a regulator simply because we have retain the input voltage at the same value but now the input minimum required is going to be higher than before. This is a common error in the laboratory that occurs while testing out this fold back short circuit protection invariably because in your enthusiasm to make I hold very small you will come up with R_{sc} which is going to be very large wherein large amount of series voltage drop is going to occur and requiring a V_i minimum which is going to be very high.

Here, apart from this the output impedance as he points out is invariably going to have, again these are all things which are going to spoil our normal functioning just in order to take care of a short circuit protection. The output impedance without feedback is going to be involved in R_{sc} straight away. Now what happens in the output impedance normally is R_{sc} plus re of this transistor. But if the transistor is operating at higher current that small re is going to be negligible. So R_{se} is what is going to fix up the basic output resistance without feedback and then the output impedance of these current sources is divided by beta. So the output impedance without feedback is going to be fixed primarily only by the output impedance here divided by beta rather than any of these resistors.

Even when this is pretty high this is not going to fix up the output impedance because we are going to make the this particular thing very high that divided by beta is the output impedance without feedback and with feedback it is going to be reduced by the loop gain of this stage anyway. So, that output impedance is going to be low because of the fact that there is negative feedback here. So when you evaluate output impedance without feedback please note that even though this comes into picture this point is at high impedance point and that divided by beta is the one that normally fixes up the output impedance without feedback.

We would like to have this as a passive structure. Any protection circuit you have to make it purely passive as much of it as possible. Obviously this is the only part which is active here. Rest of the things is all passive, that is the reason. It is like negative feedback being used for improving the performance or desensitizing the performance factors from the active parameter. We do not want our protection circuitry to depend upon any active parameter.

Now we will be just considering the fact that most of the problems we are facing when designing these regulators and what we will have to do with protection, power dissipation, etc. Now, if you are trying to protect the transistors or IC we are having problem with increase power dissipation and that is what we saw here. Now, why does the power dissipation occur here? That is mainly because this is a control circuit where the pass transistor is working in the active region.

The technique of maintaining output voltage across a load constant involved in something like putting an active resistance which is nothing but the transistor and varying the drop across this in the active region. Therefore output voltage remains constant when input voltage was varying.

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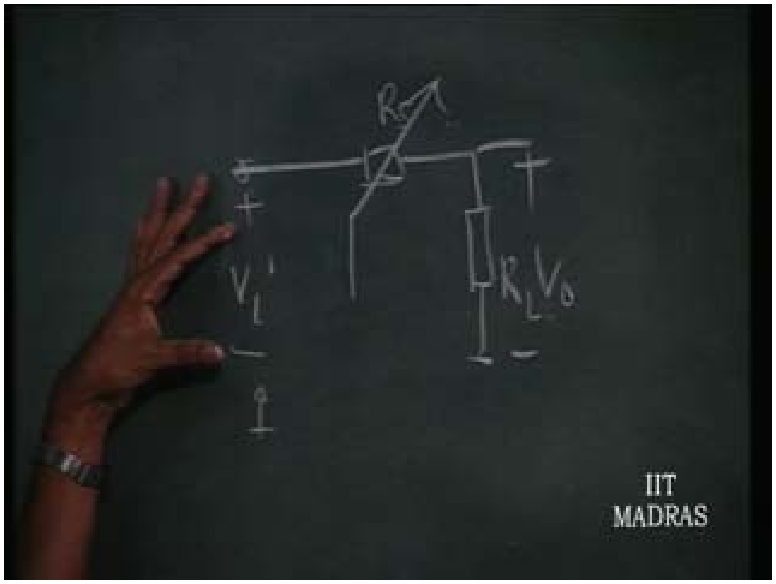

Obviously if input voltage is varying by a very large extent then we have serious problem about power dissipation in the IC increasing particularly when V_i is reaching V_{imax}. So this cannot be avoided in this. So this series regulator is not an efficient scheme. Obviously we must not use this when we are dealing with limited power particularly in satellite applications where the power is limited and we would like to conserve space also the size should be small and power is limited and we have to have energy efficient circuit systems there. Therefore most of the regulators which came up particularly for satellite regulations were called as switching regulators.

Of course now we see t_1 television receivers and others make use of this because it is very small in size for the same. Not only but it is very efficient in spite of a large variation particularly in a country like ours where the input voltage variation is very large we need such regulators to make the circuit still remain functional.

Now what is the basic principle under this?
I am illustrating this basic principle here as an application of this IC regulator only to bring out the factor that later on we will use the same principle in a variety of places like class D power amplifier and multipliers. So the idea behind this control scheme is very important and that is what we are going to illustrate by taking the regulator as an example. Let us understand something about what are called converters.

Once again in power business these converters are now available in a variety of packages for you and these are very useful components. Like the regulator ICs. These are also other IC components which are universally used in a variety of applications particularly power applications.

What is a converter here?

I want to convert a voltage V_i into another DC voltage in a very efficient manner, what does it mean? The efficiency should be hundred percent. How to convert a DC into another DC?

So, what is done here is using switch and then charge a capacitor. The capacitor can store energy for us so use a switch to charge a capacitor and then when the input voltage is removed you must still have some means of keeping the capacitor charged. This is something not done very efficiently by any scheme other than any other energy storing device.

Basically now you would like to have a voltage here which is being switched from V_i to 0 in a complementary fashion. So what happens, V_i for tau and 0 for rest of the time. Capacitor means I am not changing the voltage but I am just charging it and going to use the same voltage for further applications. Now I would like to charge and discharge so that the average voltage resulting out of this is charged to V_i and discharged to 0 immediately. So it is V_i into tau by T. This is the DC component of this.

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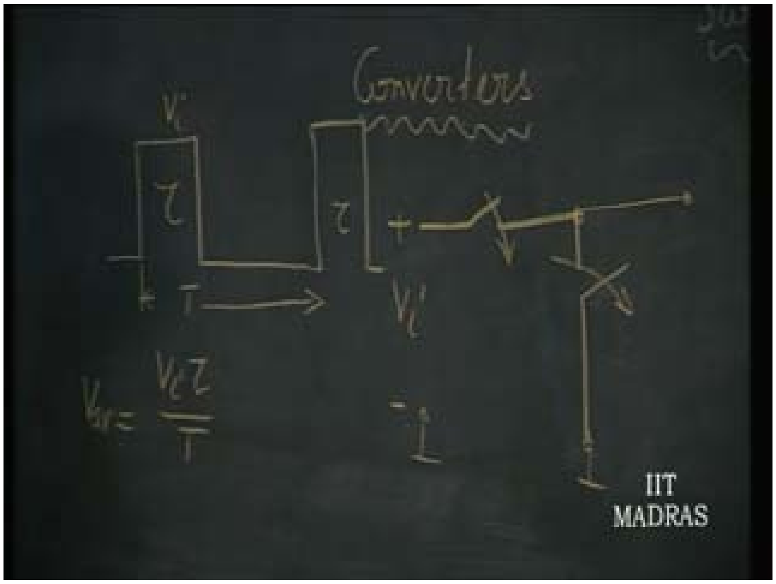

This is a very efficient converter so far. But how to obtain the average, the waveform obtained here is this. The waveform is still having all sorts of repels so we have to get rid of repels. So how do you do it is you have to put a very efficient low pass filter.

What is a low pass filter?
Put a series inductor and capacitor this is an efficient low pass filter. I can also build a filter using R and C but again r is a dissipative element. So I do not want to use any dissipative element. Now you see that this is the most efficient DC to DC converter one can think of.

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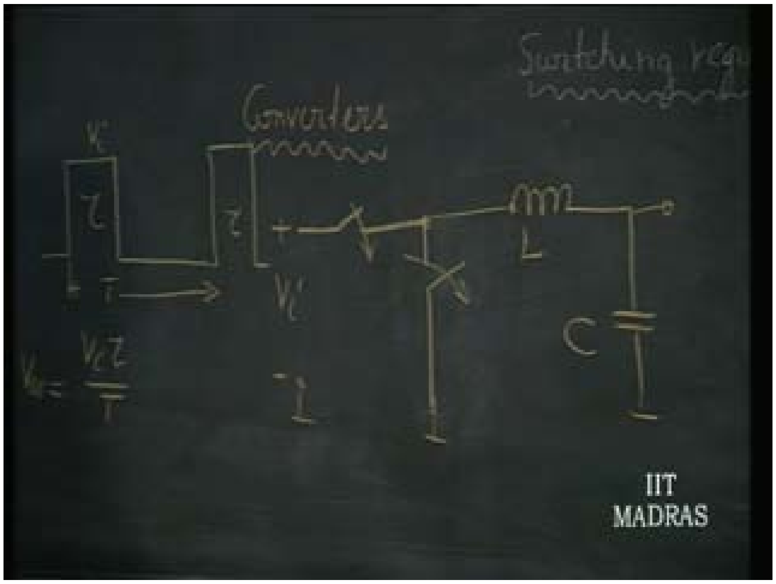

I have put only one lC filter block and if I put more number the filtering is going to be better. But for illustration we will go to the simplest converter available and here the voltage is going to be V_i tau by T and you can draw your current I_0 from this. That means we have to have two switches and switches are again ideal elements having zero power dissipation. These switches are going to be active switches in the sense they are going to be Mosfets or transistors.

Ideal inductor is zero dissipation and ideal capacitor zero dissipation. The places where dissipations occur you have to again keep a note of so as to see how far it is going to be close to hundred percent efficiency. In this case obviously input power is going to be V_i into I_i average and output power is going to be V_0 into I_0 average. Now input power is going to be V_i into I_i and it is conducting only for tau. So this is nothing but the output power so efficiency is hundred percent.

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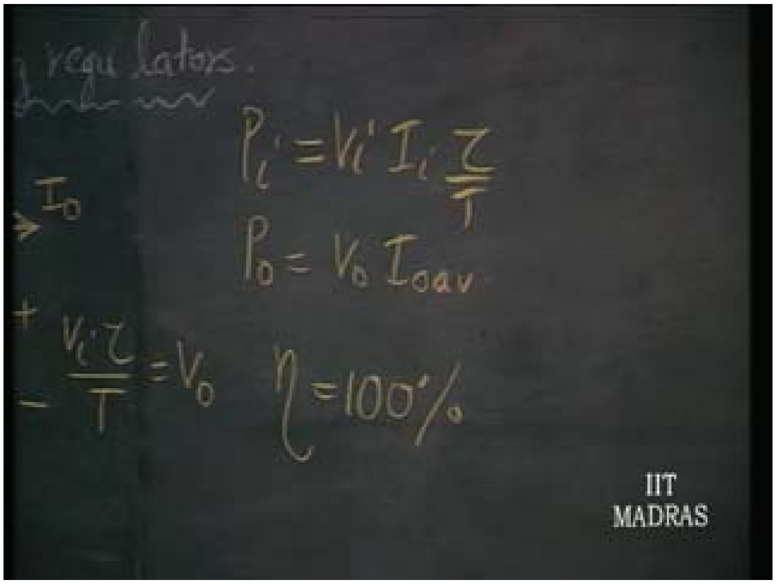

The Ii average is same as I_0 average. Efficiency is equal to hundred percent. The cause for the efficiency to deviate from hundred percent is going to be the fact that switches are going to dissipate certain amount of power because they are going to be transistor switches.

In the case of digital scheme we discussed it thoroughly. When this diode or transistor is on the power dissipated is V_{CE} sat into I_0 whatever current that is flowing through it. And when it is off whatever voltage is coming across it into the leakage current which is going to be very small normally. So these switches also dissipate power. There is going to be some DC resistance or AC resistance here which is going to cause some certain amount of power dissipation. There is also going to be a leakage resistance here which is also responsible for certain amount of power dissipation.

The primary power dissipation occurs in featured power regulators in the switches when they are on and the inductor because of the finite resistance. Rest of the power dissipations negligibly components are small.

Now how do we analyze this?
Analysis of this is one of the most exciting piece of engineering approximation because if this analysis is done, how can we do it? There are a variety of methods of doing it. You can use your Laplace transform, you can replace this waveform by its transform equivalent and replace the entire thing by the corresponding transform after this. You know the waveform and obtain the output and that is going to be a good job for networks. Or you can find out the Fourier components of this and for each component you can find out the output component since you know the L, C and R components in this. But we are not interested in such a thing; we are interested in designing a good converter efficient converter. What it means is the ripple voltage here is assumed to be extremely small. Already you are assuming that L and C have been chosen and such a manner that V_0 is

for all practical purposes equivalent to a DC. Therefore let us use this information in coming up with the solution for this. This is V_i for tau and this is T.

What is the voltage across the inductor?
This is going to be V_i when this is open and 0 when it is closed. So, when it is opened this is V_i.

What is the voltage here?
At all times it is V is equal to V_0 which is an approximation but that is good enough. So this is V_0 and this is V_i. So the voltage across the inductor when it is connected to the supply is V_i minus V_0.

What is the current through it?
It is V_i minus V_0 by L into T. A DC voltage is applied across the inductor of magnitude V_i minus V_0 so the current in the inductor is going to be 1 by L integral V_{dt}, V is constant V_i minus V_0 so this is going to be V_i minus V_0 by L into T, it is increasing linearly. Once again this is an approximation. I have already assumed a steady state solution. That is why we are assuming V_0 to be already a DC. That means when it is off what will be the voltage?
V_i is 0 and V_0 is remaining V_0 so it is minus V_0 by L into T what does it mean?
The current is decreasing. The increase in current must be the same as decrease in current because after all again it is going to start.

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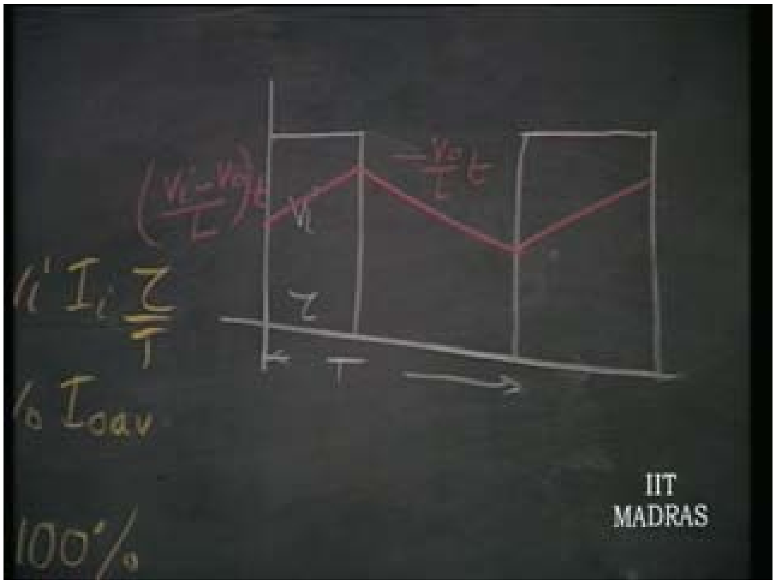

This is the steady state waveform. That means delta i_L is going to be V_i minus V_0 by L into tau that is the increase within a time tau and that is going to be equal to V_0 by L into T minus tau. This is not a new relationship this is nothing but again V_i tau by T relationship. If you remove the L you will get the relationship which is V_0 is equal to V_i tau by T. This is also going to result in the same relationship V_0 is equal to V_i tau by T.

But what it tells us the extent of current variation occurring in the inductor. Now, that is important because I must design the inductor also.

The current is I_0 and where is this I_0 flowing? It is flowing through this and this DC current cannot flow through the capacitor. So there is an average current in this which is I_0. Around the average current the current is increasing above it by certain amount and decreasing. So that is the idea of negative current. It is not negative, current is flowing only in one direction through this. So current is always flow in this way. What happens is it is going to be delivering both the load current and the capacitive current when it is connected to input and only the load current when it is not connected to the input. This change in current is important.

Normally in a good design if you want the ripple at the output to be small delta i_L itself should be small. This is the change in current which will be flowing through a combination of resistor and capacitor. If this itself is made small the ripple will be smaller. So how do you make the ripple small is by making L large. L cannot be made too large because the size of the switch mode regulator itself will increase. So typical value of delta i_L excepted in a normal design is about ten to twenty percent of I_0. I_0 is the average current for which you are designing. Take a problem like, 5V converter you would like to design for delivering a current of 1 ampere. That means delta i_L will fix it at something like 0.2 amperes in order to keep l in the limited manner. This current comprises of both the DC current and change in current. The DC current will flow into the resistor now you have to assume obviously.

And AC current that change in current will flow entirely into the capacitor if you have done a good design and develop a voltage dependent upon what the current is.

How do you find out the voltage across the capacitor? You know the current waveform, triangular, so what is the waveform of voltage across capacitor? What is the value of voltage how do you find it out? It is integral idt, you know the current, what is integral idt pictorially? What is the operation integral idt? It is area under the curve. What is that area? What is the width of this triangle? It is a periodic waveform T by 2. So the width of the waveform is T by 2 into the height delta i_L by 2 half of it is the area, 1 by c what is this voltage? This is the voltage. This is the way voltage is going to increase and decrease. Voltage is going to increase up to this it becomes maximum at this point and then decrease. So this voltage is nothing but peak to peak ripple.

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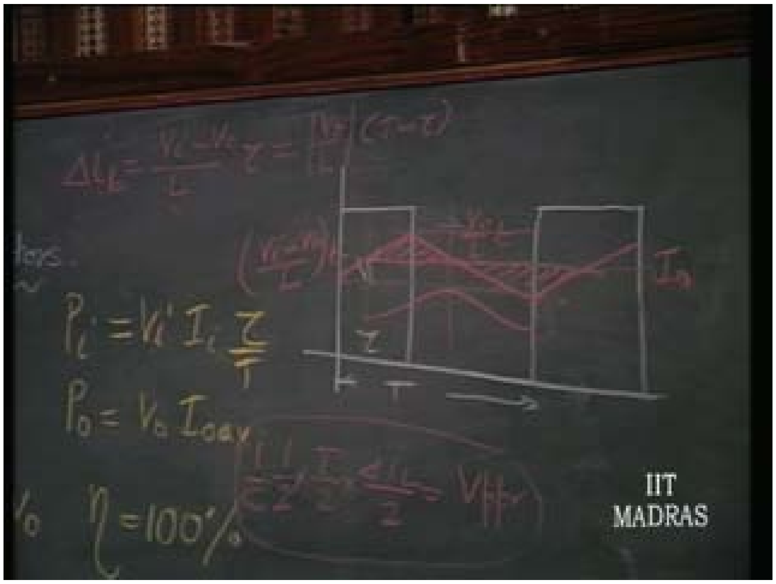

So we have very simply obtained it. We already know delta I_L in terms of V_i minus V_0 by L into tau. T is equal to 1 by frequency and frequency with which this switch is getting switched on and off. So tau by T is nothing but what is called as the duty cycle. This is a very good approximation. We call it approximation because strictly speaking this is not triangular because I have estimated the output voltage to be constant.

But now I am proving output voltage as a ripple to a very small extent. So this peak to peak repel you will make it very small purposely by using this value of the capacitor here. And if you do that and select the L properly then all your analysis is perfectly valid. This analysis is not valid for a general case of a network problem and that is pretty complicated, we need not even how to solve this.

Therefore, for switched mode regulator this is the kind of analysis that we are going to adopt in evaluating the value of L, C given the specification V_0I_0. This is only a converter design DC to DC converter and we have not yet come to the stage of designing switched mode regulator. The voltage DC is converted to another DC in a most efficient manner.

Now what should I do in order to regulate?
It is obvious that now I can control tau by T and as V_i changes I will change tau by T in such a manner that V_i into tau by T remains a constant. And this idea of voltage regulator is very important because you are multiplying this now. This is going to be done by another control voltage or something. So this is another idea for some very efficient multiplier. So we will see in next class how further we can convert this whole thing into an efficient voltage regulator.