Analog ICs

Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 11

IC Voltage Regulator

In the last class we saw circuits which can give us voltage references voltage sources. Today we will continue further and see how these voltage references are used in certain applications. That is, one of the most important IC in terms of numbers as far as analog circuitry is concerned is the voltage regulator IC because it is used whether the circuit involved is a digital circuit or analog circuit the system has no consequence even if it is a mixed mode system or anything. Today we will discuss about voltage regulator ICs and their applications.

Basically the voltage regulator IC is of two types. One is called 5 terminal depending upon the number of useful terminals available to the user, 5 terminal voltage regulator ICs and 3 terminal voltage regulator ICs. In the 3 terminal obviously you have the input unregulated, output regulated and the ground common so no other terminal is available to you. It is called fixed voltage regulator IC. Basically this kind of IC is available for digital applications wherein the voltage requirement is already known 5V. So 5V fixed regulator IC requiring certain current output etc is already fixed. You have to just purchase this 3 terminal regulator and use it straight away.

There is nothing that the designer has to do extra in order to design anything in this, everything is designed for you. The other IC which is somewhat a general purpose IC regulator is called 5 terminal voltage regulator. What are the 5 terminals? Obviously input output and the ground will be the common terminals with the fixed regulator. The other terminals will be obviously inverting and non inverting terminals of the comparator which will be made available to you. Therefore sampling the output voltage and feeding it to the inverting terminal is your job.

Similarly, taking a reference and connecting it appropriately to the comparator is again your job. The 5 terminal regulators are general purpose regulators and 3 terminal regulators are for specific applications, fixed regulators.

We already saw the internal circuitry of RCA regulator chip or bell regulator chip 3085. And we saw how the voltage reference is derived, how the temperature coefficient of that voltage reference is very nearly 0, how it is achieved and how it requires a starting circuitry so as to make sure that the operating point of the voltage reference is always the desired one. This voltage regulator we are considering today is also one of the popular one VA723 [f…] if it is or signetics 52723 so 723 is the ending number. That is a popular 5 terminal voltage regulator. Let us see how the voltage reference is derived.

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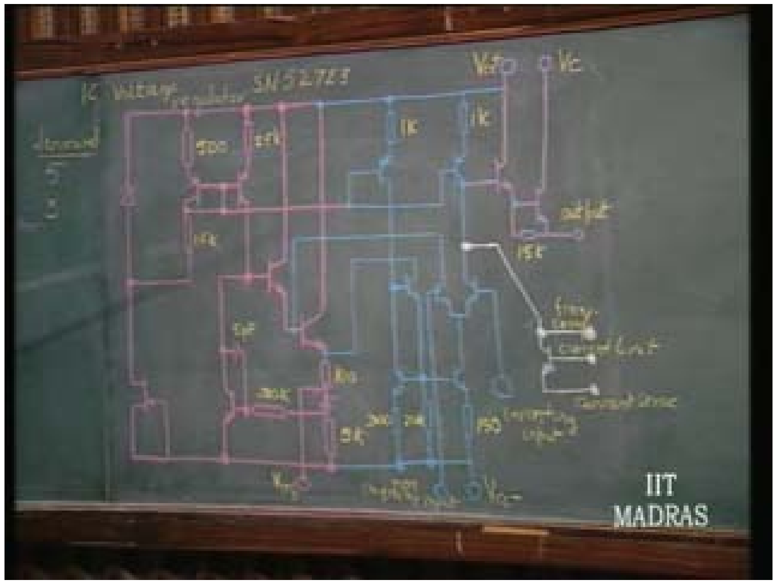

This portion is the voltage reference. Once again the idea is the voltage reference should be independent of the power supply. We had done it in one way in the earlier three 3085 chip. Let us see how it is done here. These two ideas will give you most of the techniques adopted in obtaining voltage reference independent of power supply and having a temperature coefficient very nearly 0. This is illustrative of that. This is the voltage reference.

Basically this is the Zener which is biased by means of a, do you remember this when we discussed about building blocks, the current sources, we said this is a unique current source which can be obtained using jfet without using any resistors. That is gate to source shorted. It will have a current of idss flowing through this automatically and that current is going to be biasing the Zener so that is V_z which is 6 to 7V. So, by using this current source to a certain extent we have made this reference here, this voltage relatively independent of the supply not totally.

Now it is made totally independent of supply by using this voltage as a reference to derive other currents. You can see this current mirror here, this is PNP current mirror with emitter degeneration put in here. So 500 ohms and 25K accordingly the current ratios will be 1:50 kind of a thing. So this current is fifty times this current. That is the technique of obtaining high impedance, dynamic impedance for the current sources and having different currents at different points for biasing purposes.

Here this current source is now going to be used to develop a constant voltage through this. Here this is another Zener diode. This Zener diode comes in series with this junction. So this Zener diode's temperature coefficient is exactly canceling this junction which is coming in series. Here this 30K has no use as far as DC discussion is concerned. It is predominantly meant for frequency compensation. Wherever there is negative feedback the circuit will start oscillation. There will be local problem otherwise here of oscillations. So, even you find such local negative feedbacks used very often in integrated circuits and you will find some peculiar configuration like this.

Sometimes the capacitor may be there and sometimes may not be there but when the capacitor is not there it simply means that capacitor of collector base is to being used by the circuit designer in order to compensate the circuit and prevent the frequency. So you will find a simple resistor being shown there. It is nothing but a dominant pole generated by this resistance as well as this Miller effect capacitance. This is found in almost every structure where there is local negative feed back with might cause oscillation problem. This is nothing but a feedback structure here, the voltage is sensed here voltage is sensed and fed back as a current. This whole configuration is similar to our current mirror which is Wilson current mirror type of feedback.

Voltage is sensed here, this is more like our Widlar current source. Voltage is sensed and that voltage is proportional to be output current and that is fed back so the current gets stabilized. So this is the mode of current feedback that is adopted to stabilize the current. And the reference voltage is taken here which is nothing but V_z plus 0.6 and it has almost nearly zero temperature coefficient. There is no other technique other than just using the Zener in series with the diode.

Now, unlike the 3085 we have this terminal made available to the user with the recommendation that you should not draw too much current. That means the resistance to be used here should be pretty low so that you can obtain a V reference which is alpha times the original V reference as stable as the previous one but less than that so that you can derive output voltages which are very low for regulation purposes.

Suppose we have like in the case of 3085 just v reference directly connected whatever it be, unless that itself is very low if it is already connected then you can get a value of output voltage which is only 1 plus R_2 by R_1 times this is nothing but h feedback structure, non inverting and inverting amplifier kind of thing. So this voltage reference is applied to the non inverting input and to the inverting input you apply a sample portion of the output that is R_1 by R_1 plus R_2 times the output is fed to inverting input. So this is acting as the comparator. You put an external resistance in order to derive some portion of the output and feed it to the inverting input.

Therefore the output is going to be 1 plus R_2 by R_1 if R_1 is the grounded resistor and R_2 is the other resistor connected here, so 1 plus R_2 by R_1 times V reference. If V reference is fixed only then you can make the output voltage higher than V reference. The flexibility of making it lower is not there. This flexibility is there in this IC so that you can make it as low as you please. So let us consider this, I am putting the entire circuit together and say that this is the ultimate V reference fed to the plus terminal. And then we have, this is the series pass transistor.

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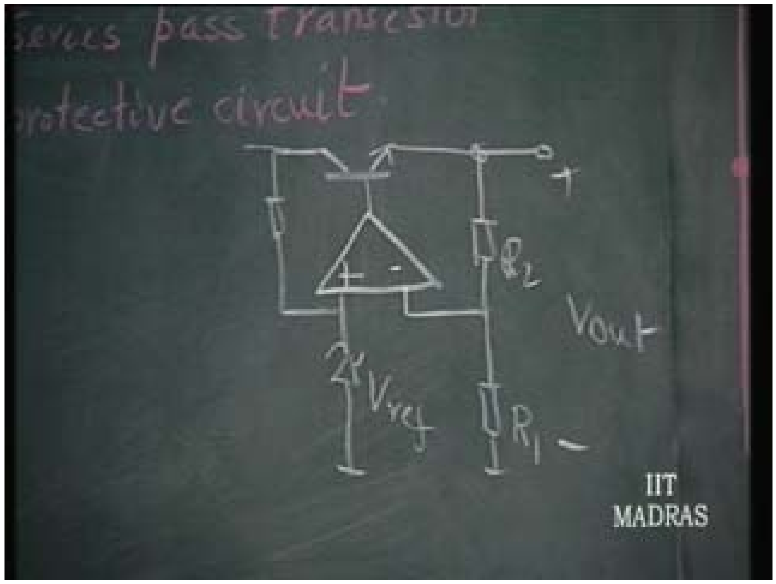

Let me remind you of the basic building blocks of regulator.
Voltage reference: Voltage reference is a fairly sophisticated arrangement here in an IC whereas in a normal circuit you might just put a Zener like this which is getting biased from the input voltage which is unregulated. Therefore you get a voltage reference.

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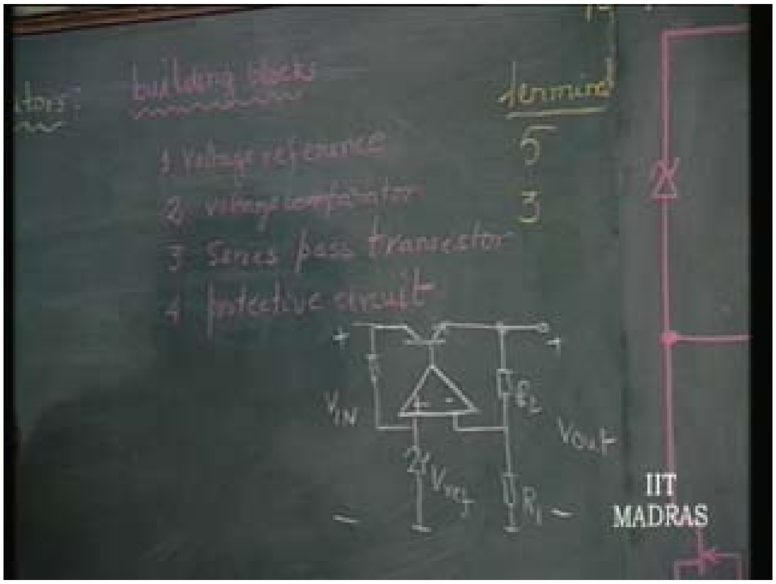

This is fed to one end of the comparator and at the other end of the comparator t you apply the sampled output voltage that is R_1 by R_1 plus R_2 times the output voltage is what is fed to the inverting terminal. So essentially this is nothing but an Op amp whose output voltage now is equal to, this voltage here is going to be equal to V_{IN} itself because the loop gain is high this is an [un….] this voltage is going to be equal to this voltage, this is V_{IN}. So V_{IN} by R_1 is the current in this and same current will flow through this like this and therefore output will be V_{IN} 1 plus R_2 by R_1. You recollect this kind of principle was also used in deriving the Zener V_z into 1 plus R_2 by R_1. In this arrangement output voltage is always greater than V reference. If it is not connected then I put an attenuator here 1 minus alpha times R alpha R so I get alpha times this so this becomes alpha times that.

You have a flexibility of selecting alpha into that R_2 by R_1 is not at all necessary, you can make it V reference alpha into V reference is less than that. So this is the flexibility of this voltage regulated. Please be careful as to not load this too much then the temperature coefficient is going to get affected. Again this 5 Picofarad is to prevent this local negative feedback circuit from oscillating and you have this transistor connected at the diode resulting in a current source here. These current sources are also derived current mirrors for other various purposes.

Basically we have seen this portion of this circuit which is another V reference. Now voltage comparator is nothing but a differential amplifier. So, that differential amplifier configuration is also forming a part of the voltage regulator chip, you can see these pair forms the differential pair, this terminal is the non inverting input, this terminal is the inverting input and it is biased by means of a current source which is deriving its current from this PNP current source biasing this current sink and then you have a sophisticated current mirror here so that this current is exactly this. This is a current amplifier again derived in order to make the two currents this one and this one become more equal than otherwise. We have also derived this structure. This is the current amplifier used to bias these two current mirrors. While accordingly we have the current developed here and this particular thing since it is not being used for any practical purposes but normally you would have connected it to the supply.

In voltage regulator you will never do that because anything connected to supply is going to link the supply through its impedance. You will always connect it to another derived voltage source wherever it is available. So this is simply connected to a voltage source. The inverting input is essentially not connected directly but it is going to be connected through a current source that is the load, so this is the load. This is not really a differential amplifier we discussed about where we had put current mirror as the load but this is going to give you gmR_C by 2. One portion of the stage is not used for contributing to the gain but only this single stage and the output so it is half the gain. RC is made very high now by using emitter degeneration.

Unlike the other one 3085 you will see that, there, for the differential amplifier we have used a current mirror. So you can see the various designs of voltage regulators. Here they have used emitter degeneration to obtain very large dynamic impedance for this so the loop gain of this is pretty high as it is and they are not bothered about the loss of gain by a factor of two. Therefore that is connected to the pass transistors. This is called so because this will pass the input to the output through it and will command depending upon this one, that, if the voltage is likely to become higher as input voltage is higher then immediately control the drop across it so that output voltage is maintained at a constant value. This can be connected as a Darlington pair when you connect V_{cc} plus V_c. Again these are all minor points. Whenever we connect a Darlington pair we will again find between base and emitter some resistance port.

Here this 20K was not necessary in this circuit because this was necessary to give the base diode to this, why did they put a 20K resistor?
All these have a common answer. The answer is the same. If this resistance is not there or if this resistance is not there then the base current of this is going to be the operating current of the first transistor, same is the case. The base currents of these will be the operating current these transistors. That is beta times less than the emitter current itself. That current may fall to such a low value that the very purpose of connecting it in a Darlington pair is lost because beta itself decreases as current decreases. It is the variation of beta with respect to current. So, the very purpose of connecting a Darlington pair is lost if you have to let the operating current go down very much. So this is called a bleeder resistor. That means there is a voltage always which is equal to 0.6 and that 0.6 divided by 15K is the additional current that will flow through the transistor in order to maintain the beta at a sufficiently high enough value.

Normally the beta of a composite transistor is beta 1 into beta 2 and we invariably take it as beta power 2 which is not correct because this transistor is operating at a beta plus 1 times less current than this. You will also find this connection almost in every IC this is called a bleeder resistor because this current is of no other use other than making this operator sufficiently high current so that the beta is high. The same thing is applicable for this 20K resistor in order to make sure that this current is not going to such a low value that its very purpose of being connected as a current amplifier is lost if the beta were to fall heavily. So, as far as the series pass transistor is concerned you are permitted to connect if you think that you have to make this regulator operate at higher power levels for higher terminal current level you are permitted to connect any number of such transistors.

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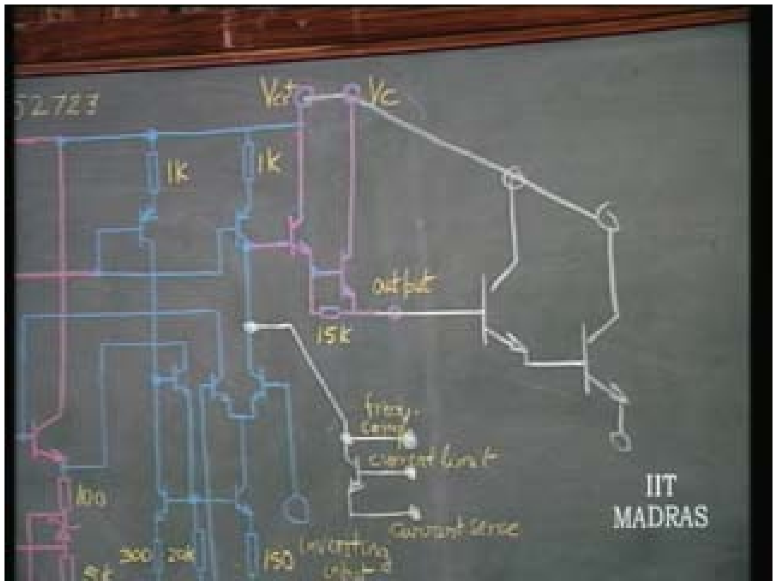

So you can see some pyramid like structure like this for high power regulator chips. There is this transistor which also is not really in use when the voltage regulator is operating properly that is why we have separately drawn it. As the name itself indicates it is for protecting the series pass transistor that means the regulator itself. It is the series pass transistor which carries the highest current in the whole circuit and also the series pass transistor which dissipates the maximum power in the whole circuit and the IC power dissipation is totally due to this.

In advent in shorting of the output you might draw too much current and destroy this IC. So, in order to prevent it this is there. Let us see its functions. We have the protection circuitry, we have the pass transistor circuitry connected within and externally if necessary to improve the power rating and the differential amplifier and the current mirrors here for biasing and finally the voltage reference. You should be now capable of analyzing this structure. This is a negative feedback structure. It is the h feedback, the output voltage is sensed and voltage is fed in series with the input. This is h feedback.

This is a classic case of h feedback application and you can simplify the circuit in the following manner:
The entire voltage reference can be simplified as also the rest of the circuitry. This whole thing we put as an Op amp, with its finite input impedance gain and output impedance being put there for complete analysis of the h feedback structure. It is a non inverting

amplifier where we can treat this as the input and this as the output. Input is nothing but V reference because that is independent of the actual input to the DC to this, it is a constant voltage. So a voltage regulator is a simple application of non inverting amplifier. So, if you want a simple voltage regulator you can as well use a single ended Op amp. That is, you can use the Op amp with power supply terminal connected like this and ground the other power supply and use the Op amp in this configuration. This can be a discrete circuit design whereas in an integrated circuit that portion of the Op amp is the operational amplifier which is composite. You can say this differential amplifier with the output stage put together is nothing but a mini operational amplifier.

Let us now discuss the important properties of a voltage regulator. Whether it is IC or discrete it does not really matter. We would like to know, if you are going in for purchase of a voltage regulator chip what should you look for as the parameters associated with the voltage?
First part is, obviously it should regulate, the name itself says regulate. So we have to define how properly it can regulate. What does change? What are the things that will prevent it from regulating properly?

First of all the input voltage changes as V_{IN} changes, V_{IN} changes from a minimum to a maximum particularly in the context of India this is really a wide variation. All the way our power supply drops to 110 may be and goes up to 280 and so on. So, over this variation because you have put a rectifier after a transformer is put, you have put a filter may be a good LC filter and obtain unregulated output voltage. This is going to vary to the same extent as the main supply. So that variation is the minimum to maximum. When that variation occurs V_0 should remain constant. Obviously the measure of this, this is called line regulation. It is nothing but the percentage variation with respect to the nominal value of output around any operating point. You should know that the load is constant.

So how much variation is occurring in the output voltage?
This is not a small signal parameter. You cannot obtain this by replacing the transistor by means of their small signal model, this is not a small signal model.
V_{IN} changes from a minimum to maximum and it is a large signal variation. So this has to be observed most of the time. If you put the non linear model for the entire thing you may be able to work out this variation. You have to force the load to remain constant. Constant current is being drawn. You are not changing that. So under those circumstances you are measuring the change in output voltage. If you have designed your regulator well this change is going to be very small with reference to the nominal value of output. And this is line regulation.

The second thing is, obviously what you are saying is, the load might change from zero current to I_L is equal to I_L max whatever it be. It is maximum current it is supposed to work for. Again you see that this is not a small signal parameter. When the load is changing by that much amount this should be measured again as delta V_0 by V_0 for constant input voltage V_{IN} to V_{IN}.

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So what is the percentage change in output voltage?
For a constant input voltage when the load current changes from 0 to its full value you are loading it fully here, no load to full load. This is the way regulation anywhere is given. It is not strictly applicable this alone. For all generators this kind of definition is valid. Of course this also must be made as small as possible. Basically if you plot, this is load regulation characteristics V_0 versus IL, it should be remaining absolutely constant up to the maximum current that you design. Beyond that current you have some trouble associated with the regulator itself if you try to draw. That means there is a maximum current up to which you can make this IC work. So we have to go back to the IC and see what the important limitations are on the IC. Consequent to all these now you have to understand what are the important limitations on the IC.

Apart from this what other parameter is important?
Similar to this but this is a small signal parameter, this is called ripple rejection factor.

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It is already known to us that we are deriving the input from means. If it is a full wave rectifier we definitely have a ripple. However good your filter may be you will have a ripple. If its main frequency is 50Hz you will have a ripple at 100Hz. This ripple is riding over the input voltage. This is a small variation occurring over and above the quiescent input voltage. So you can treat this as a small signal variation. This input therefore may percolate. Let us put this instead of using that whole circuit. As this voltage varies this current varies and as this current varies this voltage is going to vary. This voltage is simply amplified as V_z into 1 plus R_2 by R_1 at V_0. So delta V_0 is nothing but delta V_z into 1 plus R_2 by R_1. Now obviously a circuit which is not connected to input for deriving this voltage reference is going too far better and in terms of repel rejection. This is one way to look at it.

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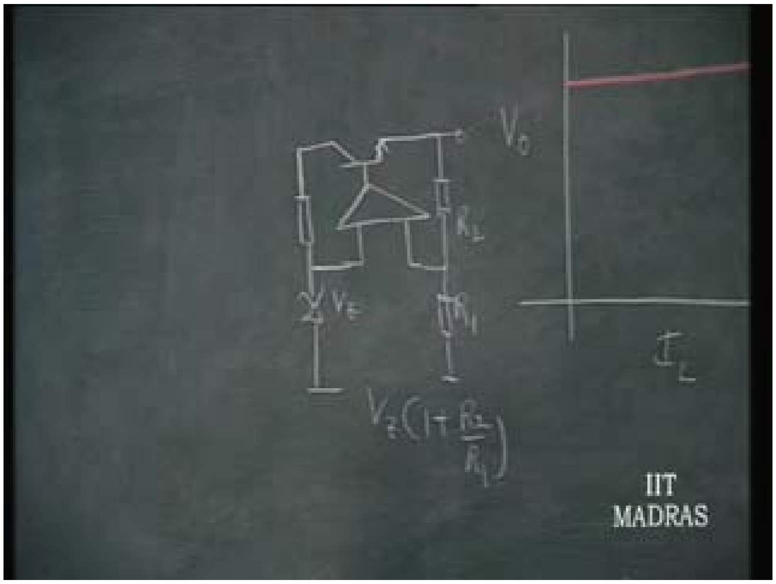

So, one might come up with elaborate arrangement to connect this terminal not here but at the output. But this will cause us a starting problem because this is not going to break down unless it is biased this is not going to be biased if it is connected here. That means you have to have a starting circuit. Either you have to have a starting circuit and connect the reference to the output or you can derive things like that we did in 723 and obtain this kind of a thing. When there is good line regulation it is likely that you are going to have good repel rejection but these are not one and the same because this is a small signal parameter and that is a last signal parameter.

Therefore how do I establish that this is going to be made very small?
I can do this even by simply putting this kind of thing here, I can transmit this DC as such but this is going to be AC at 100Hz so I put a filter here externally and reduced the repel rejection factor by this artificial means. So this kind of technique of reducing repel or obtaining good repel rejection factor, therefore the definition of repel rejection factor is, delta V_0 by delta V_{IN}.

For a small change in V_{IN} what repel will be permitted to appear at the output for the regular operating point?
It is V_{IN} remaining constant and the load remaining constant. So, evaluate this by using small signal equivalent circuit for the entire system and see how it is. This is one of the parameters wherein small signal becomes important. The final and the other important parameter is nothing but the output resistor. These are all parameters and we will come to the limitations again later. The significance of this is highly last in most of the design. This is the most important small signal parameter in any regulator IC. The output resistance by definition is delta V_0 by delta I_0 at the operating load for a constant load.

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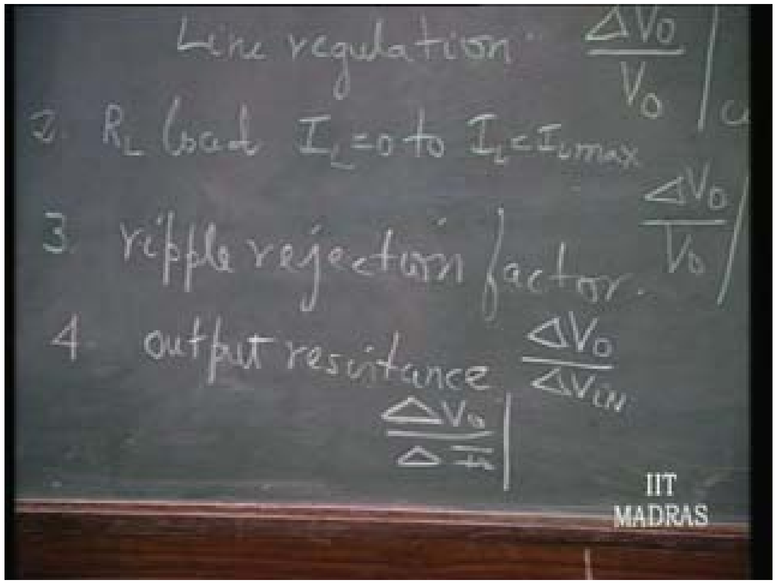

This is once again a small signal parameter. Why is this important?
A regulator has lot of responsibilities. It is giving power to almost all subsystems in the entire system. Unless if the output impedance is low there will be coupling between one sub system and another sub subsystem. It will cause a very serious problem of positive feedback at very high frequencies resulting in oscillation.

How do you make this output impedance very low?
Even though this is a DC voltage regulator its output impedance should be very low for AC for which it is going supply power at high frequencies. Therefore this output impedance should not be evaluated at low frequencies but this output impedance has to be evaluated at the frequency at which the circuit to which it is applying power is applied. This is something which is never thought of in most of the designs. That is the response we will think for failure of almost all resistances.

As we are not talking of VLSI design and things like that the regulator will be a part of the entire system. When you are designing such a thing, you must make sure that this circuit functions with low output impedance at high frequency. This is a common thing that you have to bear in mind even in your designs in the laboratory. That means, if the same person is deriving power from a common supply it is likely that if your circuit is a high frequency circuit it is going to misbehave simply because you have chosen a bad supply and let another person do something else there. He is designing an audio power amplifier and you are designing an R_F circuit, both are using the common supply. Your R_F circuit is misbehaving that much that you are trying to get your mind examined because you have done the design properly. There was nothing wrong with the design. When it is built and you have connected it to the power supply it is not functioning it is also [r….]. So please bare this in mind. In any of you future designs connect it with voltage regulator.