Electronics for Analog Signal Processing - II
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Lecture - 23
Class B & C Power Amplifiers

Last time, we were discussing Class B power amplifier and how one could get rid of the so called cross over distortion where the voltage cross over from...crosses over from negative to positive. The transistors do not conduct until V Gamma is reached. So, because of that, particularly when the voltage level is low, you get this cross over distortion.

So, this this torsion can be reduced by Class A B biasing, pre-biasing. So...but there is another way of getting rid of this cross over distortion by using negative feedback.

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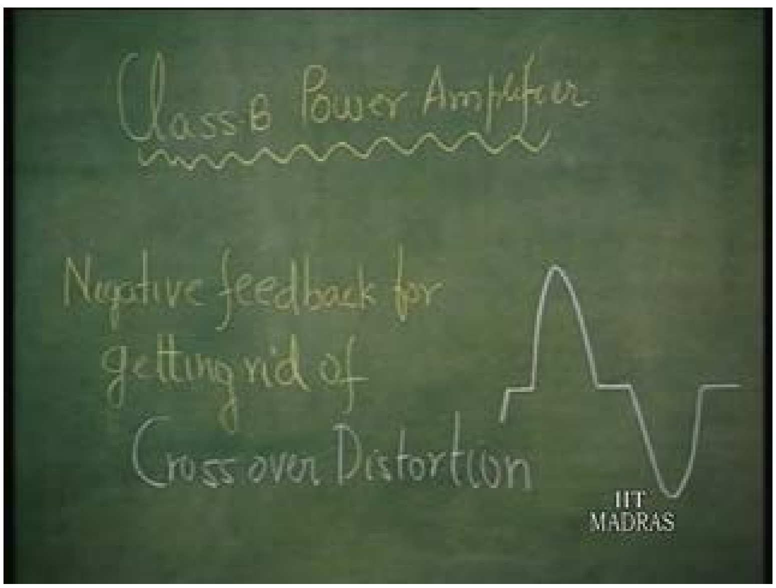

So, today we will discuss how we can get rid of the same cross over distortion by using negative feedback. This is this is the stage which we had discussed; complimentary symmetry output stage wherein, input is given here and output is taken here. This is the output and this is the input.

So, until V Gamma is reached, this transistor will not conduct. Thereafter, this will conduct and V naught will be equal to V i. It will conduct as a common collector stage. Until minus V Gamma is reached, this will not conduct. Thereafter, for more negative voltages, this transistor will conduct and V naught is going to be equal to V i. So, that output form is going to be obtained.

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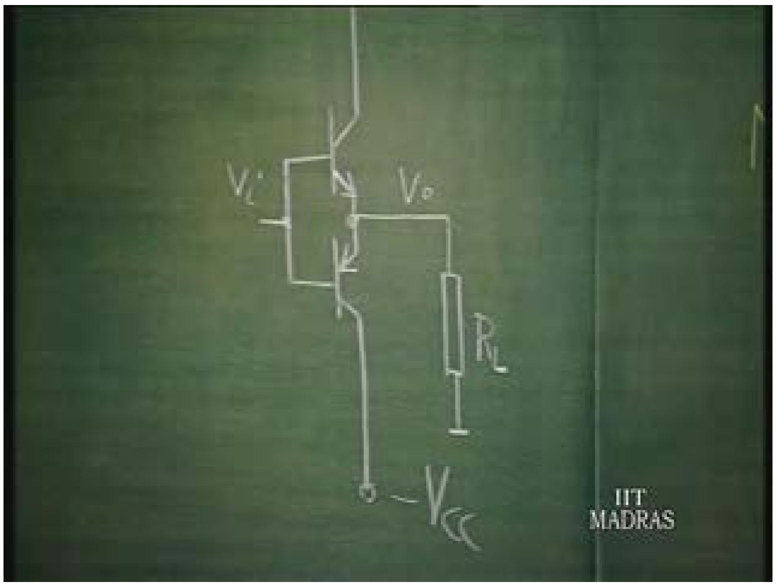

Now, how to get rid of cross over distortion using negative feedback? Use an op amp as a driver stage for this output stage and then connect the op amp in its negative feedback configuration. So, this can be connected in negative feedback configuration either by using inverting stage or a non-inverting stage. Now I am going to do it by using an inverting stage, negative.

So, if this is R and this is R, since there is a feedback here, if this is V i, as V i goes positive like this, if there is feedback, this is virtual ground. So, current is V i by R and this current will flow through this and develop a potential minus V i, because the resistances are the same. So, V naught is going to be equal to, in this case, minus V i.

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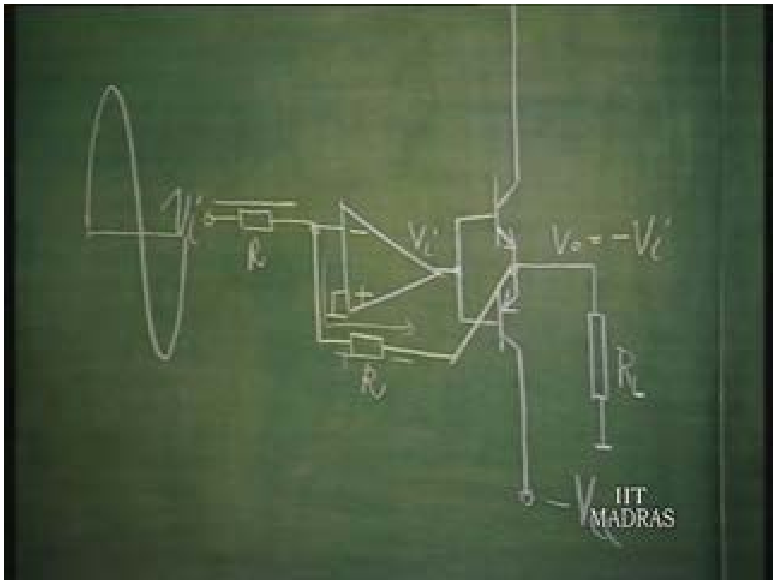

Now, let us see what happens really if the diodes do not conduct. When this voltage is zero, obviously, these diodes do not conduct. When the diodes do not conduct, there is no feedback from this. This, we will call it as V i dash now. There is no feedback from the output of the op amp to the input. If there is no feedback, this is under open loop.

So, even if this voltage goes above V i slightly, this will try to go to negative saturation. While trying to go to negative saturation...so, this will jump; try to go to negative saturation. But the moment minus V Gamma is reached, this transistor will start conducting and once conduct... it conducts, it gives negative feedback, this is maintained at virtual ground; and therefore, this output will be automatically followed at the output of the...with the phase different, output of the stage.

So again, the moment this voltage comes towards zero, this will come to zero. The feedback is broken and the moment this goes negative slightly, the output will try to go to positive saturation. So again, there is a jump of V Gamma and thereafter there is negative feedback and it follows.

So, this is the kind of output that you get. There is going to be jump here; from plus V Gamma to minus V Gamma; and thereafter, the output will be following the input. This kind of output is what is going to be obtained at V i dash. This is V i dash and here obviously, you will get the neat way form at...that is, corresponding to positive, it will be negative and for corresponding to negative, it will be positive.

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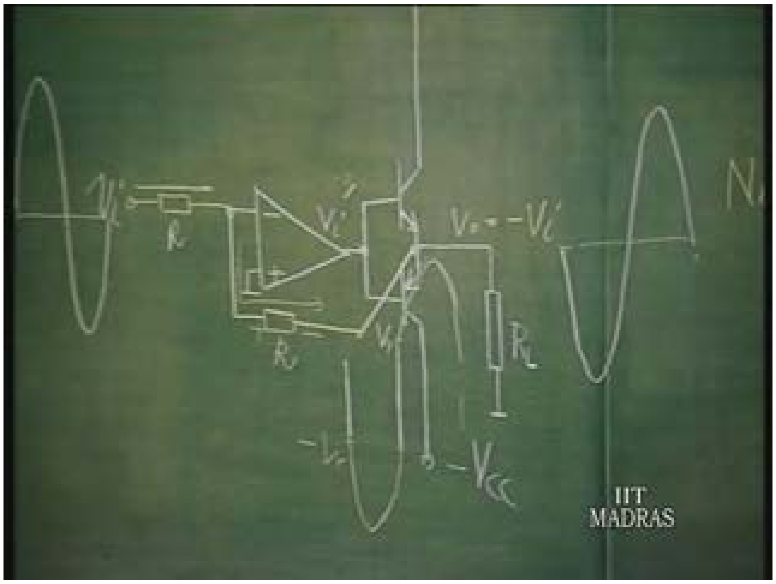

So, even if this voltage is of the order of hundreds of millivolts peak, even though this is going to be of the order of point 6 to point 7, that hundreds of millivolts peak will be super imposed over this, in this manner. So, this is what is called pre-distorted drive for this, so that the output is going to follow the input as though the negative feedback is all the time, there. So, this way, we can get rid of cross over distortion very easily.

The idea is the op amp and the negative feedback will formulate the proper drive for the Class B stage such that it will jump at the zero cross over point, biasing the appropriate transistor, so as to receive the signal immediately.

So, this kind of characteristic will result in... If you plot, basically your V naught over V i, there is going to be unity gain with inversion. So, it will be perfectly linear. It is going to be linear here. As far as this is concerned, this is going to be linear after a voltage of... So, this is for V i dash. With respect to V i dash, this is for V i. V naught versus V i dash, V naught versus V i. This is going to be plus V Gamma. This is going to be minus V Gamma. That is, if the gain is infinity, this is the jump. If the gain is very high, there will be a certain slope here; and therefore, this is going to be V Gamma divided by A, V Gamma by A naught, where A naught is the D C current.

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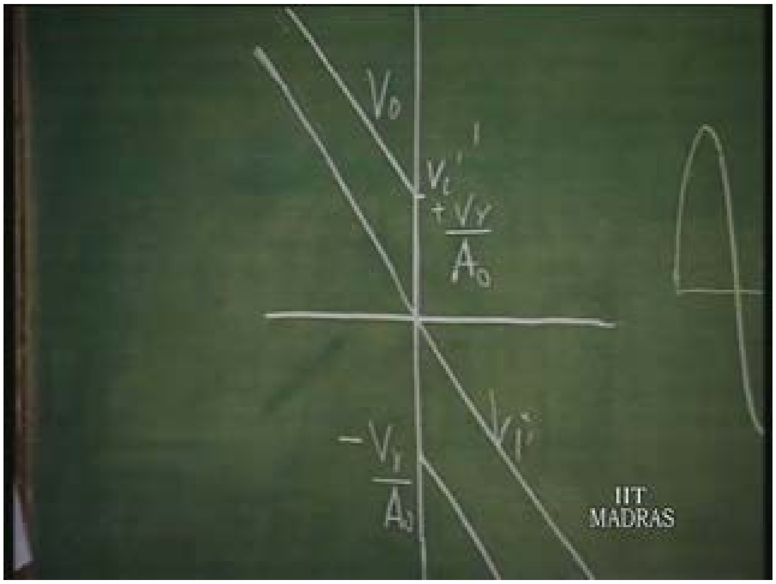

So, because at this particular point, this is the characteristic. At this point, it is going to be V Gamma up and V Gamma down; and the voltage here is going to be V Gamma by A naught. So, that is the error. So, as you see, this... just, let me say. This is V Gamma. This is minus V Gamma. This is plus V Gamma; and these points will be respectively reduced by V Gamma by A, at this point. So, that means the characteristics will be pretty close. If A naught is infinity, this is going to be V Gamma, minus V Gamma. These will be almost merging with zero here. So, this will be perfectly linear.

So, this kind of reduction of the cut-in voltage by V Gamma by A naught is possible for this combination of transistor with op amp. This kind of circuit can also be used for rectification, etcetera. Later on, you will see how precision rectification can be achieved also by similar combination of op amp with diode.

So, cross over distortion is one factor which is somewhat irritating in the efficient power amplification; that is Class B. And since that can be got rid of by either biasing it using Class A B mode of operation or negative feedback, that is not going to be any disadvantage.

So now, we will go to Class C, tuned power amplifier.

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Class A and B are essentially power amplifiers which can be used for wide band applications without any problem. Class C on the other hand is restricted to only tuned power amplification. We will see where, why, such a restriction has been input. Obviously, it cannot be used for audio or video power amplification here. It can be used only for, specifically for, r f power amplification where, for transmitters, where power output needed is considerable; and specifically, narrow band application.

So, what is Class C? In Class B, we made the transistor, individual transistor, operate only for half the time period. The other half is taken care of by other transistor, two transistors made up the full sine wave. Here, on the other hand...and of course, the operating current was, quiescent current was, zero. Here, the operating current still remains zero. Not only that, it is reverse biased; base to emitter junction is reverse biased so that the conduction angle can be made much less than the 180 degrees that is normally there in Class B. In Class B also, it is less than 180 degree because of cut-in voltage. So, if you apply a reverse bias, it can be made much less than the 180 degree, degree.

So, let us see how doing that kind of thing, we can achieve better performance. Obviously, in in Class B, we got 78 point 5 percent efficiency. We have to see whether Class C operation can make it more efficient than that.

But, we have to now make use of only part of the time of conduction. That means, if let us say, for a transistor in normal current wave form, output current wave form is this; and the peak current, let us say, is I p is going to be conducting only for part of the p rate. Let us say, this is the thing and this is let us say, Theta.

So, it is going to conduct only for part of the p rate. This is pi. This is 2 pi and... this is actually Omega t we have plotting here; and then this is V... Sorry, I. So, this p rate Theta, this is actually corresponding to pi by 2. This point is going to be pi by 2 minus Theta by 2. This point is going to be pi by 2 plus Theta by 2. So, this is the way it is going to conduct.

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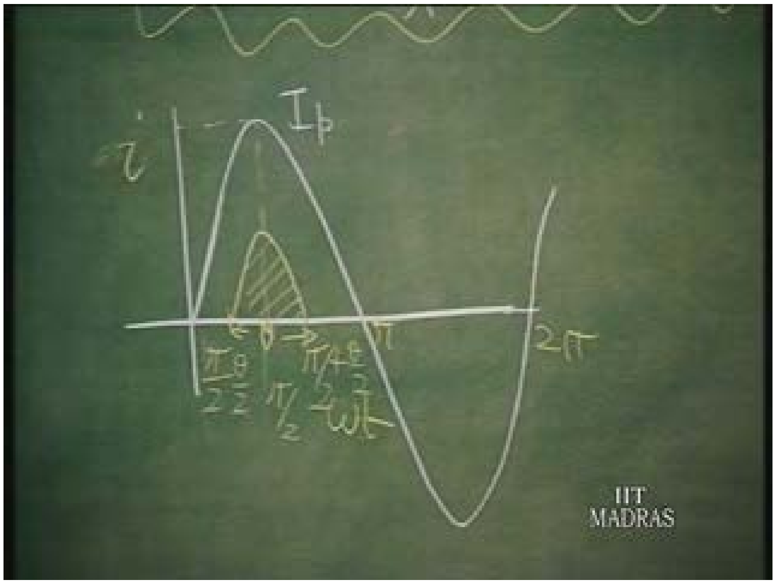

Next period, of course, it will bring about the same thing. If such is the repetitive nature of this wave form here, we know that this can be expanded by its fourier series expansion into a D C. We call it A zero or something like that; and fundamental component with peak A 1, second harmony, third harmony, like that.

So, we can select the wanted component; let us say the fundamental, by putting a band pass filter at the fundamental frequency so that all the other harmonics are rejected. Only the fundamental component is selected. So, this is the idea behind Class C tuned power amplifier. Tuned means it is resonance circuit at the output made up of a tank circuit; so-called tank circuit; we can store energy. So, L and C connected in parallel; and effectively, the load comes across L and C. So, it is L, C and R.

So essentially, it is going to be a tuned circuit L, C and R. This R may be the resultant effect of the load, the antenna load on the primary side of this coil; and this coupled by means of a coil so that the maximum power developed at this point, is transferred to the load; that is antenna. So, that is why you have a sort of transformer coil kind of arrangement here so that these are all tuned power amplifiers. In all these tuned power amplifiers, maximum power transfers, both at the input as well as the output is done so that it is able to give you maximum available power gain. This active device is able to give you maximum available power gain, as far as the...from the source to the load is concerned.

So, this is normally what is going to happen. There is a load; that effect also is going to come as a shunt resistance across this. This will be the output resistance of the device under consideration and the capacitive leakage resistance and coil resistance, all put together.

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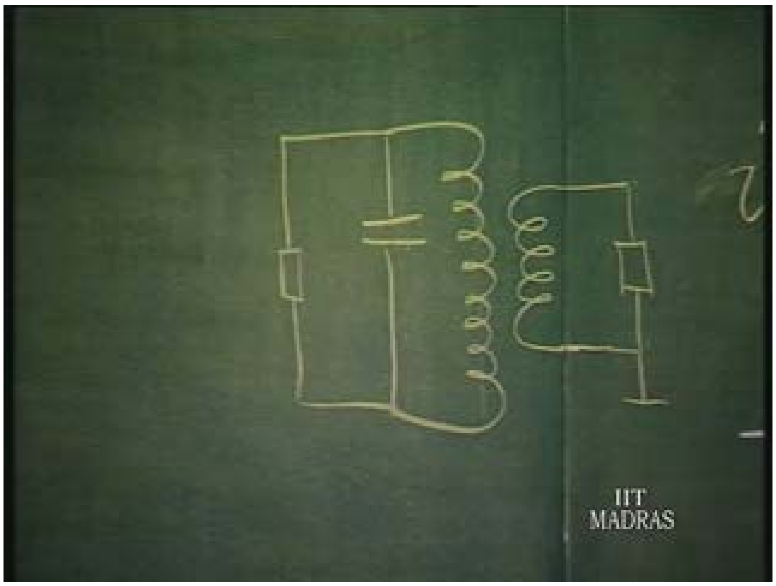

So essentially, we have a current drive here and this is connected to, let us say the supply voltage V c c; and we have the device simply connected like this, with may be a reverse bias, here minus V B B, appropriately; and actually V i so that this is going to be a combination of the reverse bias and V i.

And the moment it conducts, there is going to be a current injected here, signal current injected, which is essentially made to flow into the transistor base and base times, base current times Beta is the collector current. It is going to therefore conduct only during part of the time. So therefore, if V i is sinusoid, the base current wave form is going to be sinusoid; and therefore, we are perfectly justified in assuming a linear relationship between the base current and the collector current. So, Beta times base current is also going to be part sinusoid. So, this much is the way how biasing is done for Class C operation tuned amplifier. Tuned here. Class C means it is this; that is biasing.

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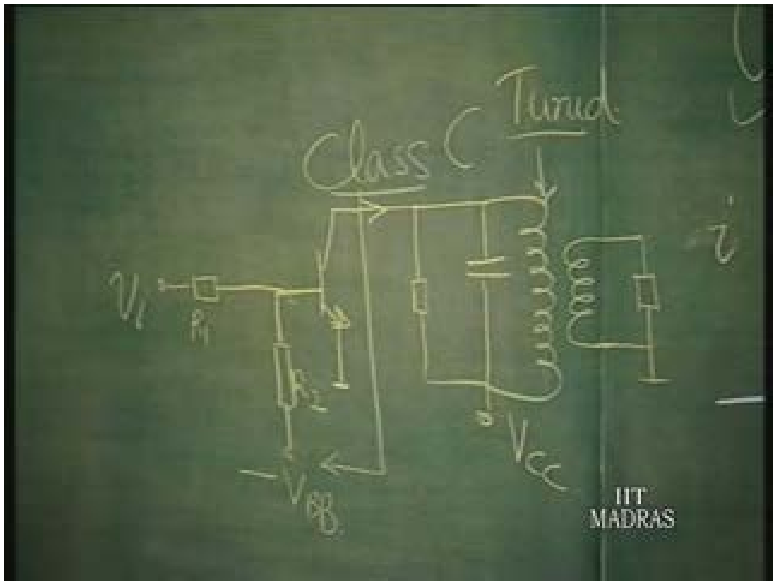

Now, we have to understand how much is the input power. That is very easy. V c c is going to be the supply voltage, D C supply voltage to this; and therefore, through this, an average current flows and that average current corresponds to the average of this particular wave form, this current wave form.

So, that therefore is nothing but V c c into I average, is the power input. We are of course neglecting the effect of the input to the transistor itself because when the transistor conducts, there is certain amount of power inputted to the transistor. That is not taken into consideration here because we are assuming that the...most of the power input comes from this supply. That is justified because the current of operation is much higher, Beta times higher than the current of operation here. So, this is negligible.

So, V c c into I average is going to be the input power. How to find out I average? I average is nothing but 1 over 2 pi of this wave form, whatever wave form. This wave form exists only from pi by 2 minus Theta by 2 to pi by 2 plus Theta by 2. Rest of the point, it is zero. So, we can integrate from pi by 2 minus Theta by 2 to pi by 2 plus Theta by 2. In fact, we do not have to integrate all the wave because we can just integrate for this and double the area. So, I will do that. We can integrate up to pi by 2 and say it is double the area.

So, this is what we are going to integrate now. So, this wave form is nothing but I sine Omega t. This whole thing is I p sine Omega t. This is I p sine Omega t, minus whatever value is there for this at that point; that has to be subtracted.

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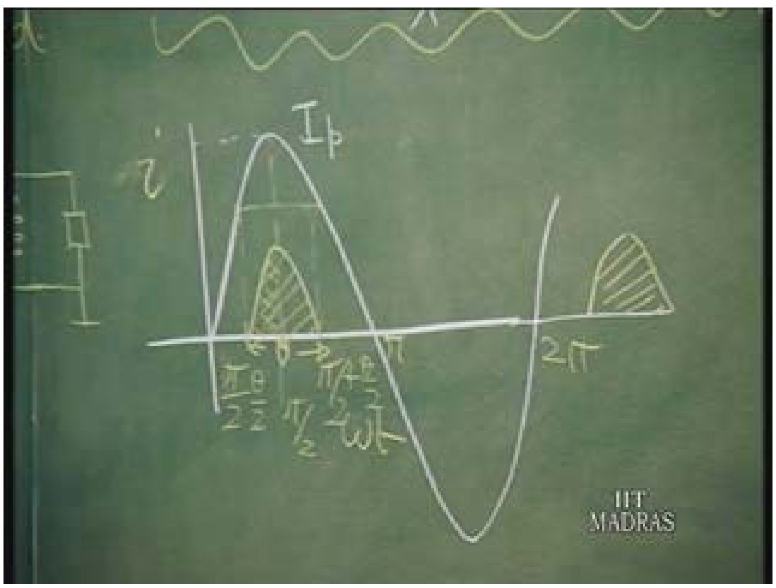

So, that corresponds to I p. This value is sine pi by 2 minus Theta by 2, which is cos Theta by 2.

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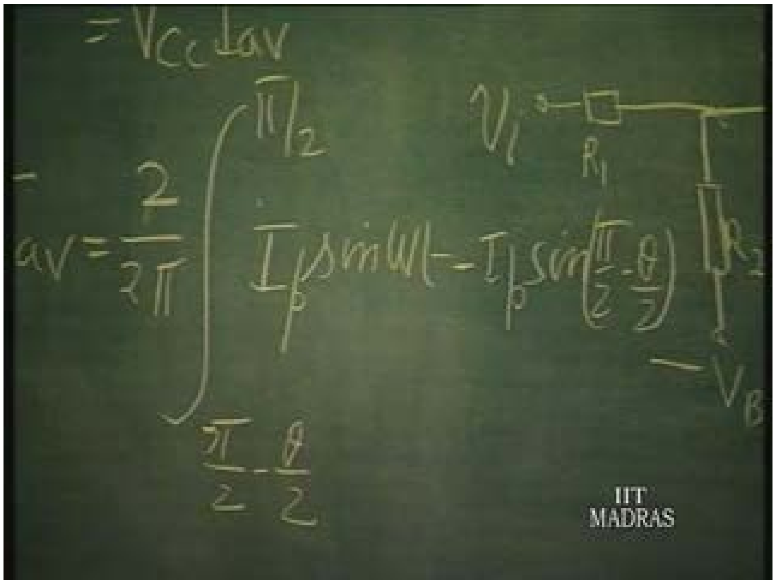

So, this value is simply cos Theta by 2. So, essentially therefore, this is the integration. Is it clear?

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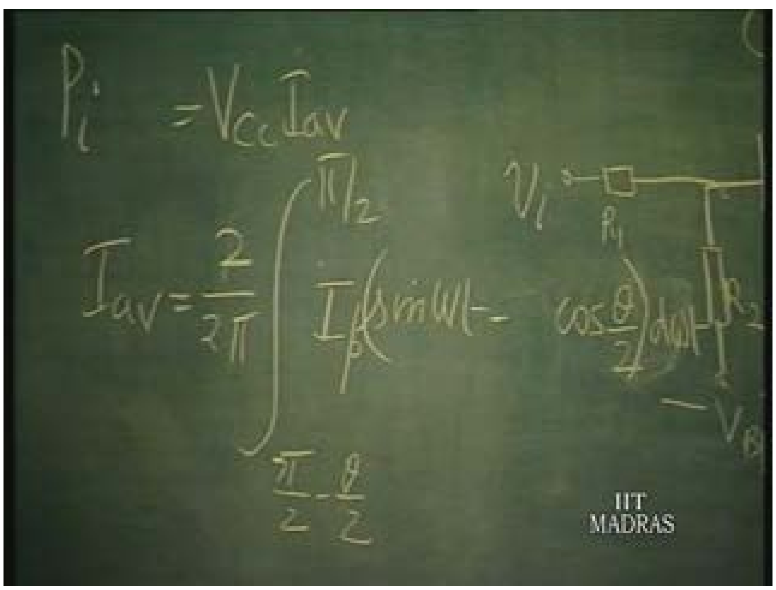

So, this is nothing but I p by pi. This I p divided by pi into integral of sine Omega t is minus cos Omega t minus Omega t cos Theta by 2; the limit from, let us say, pi by 2... minus Theta by 2 to pi by 2. So, this is the average.

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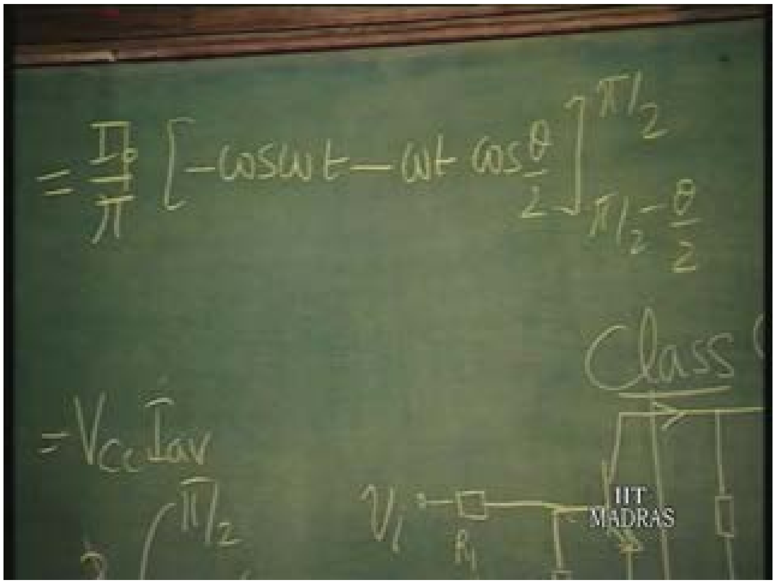

So, this is equal to I p by pi, minus cos pi by 2 is zero, minus pi by 2 cos Theta by 2. Then the other limit which is minus, minus this. So here, it will become plus. Both will become plus. And therefore, plus cos Omega t - cos pi by 2 minus Theta by 2 which is sine Theta by 2; cos pi by 2 minus Theta by 2 which is sine Theta by 2. That is over; plus pi by 2 minus Theta by 2 cos Theta by 2.

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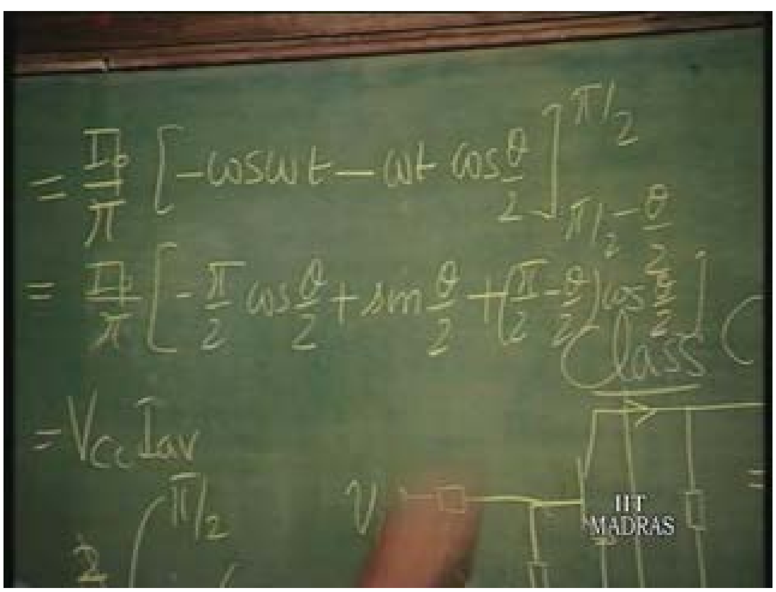

So, we get pi by 2 cos Theta by 2 - minus sign; pi by 2 cos Theta by 2 - plus sign. So, those two get cancelled. So, the answer is...this is equal to P i average therefore is equal to I p. This is I average by pi into sine Theta by 2 minus Theta by 2 cos Theta by 2. This is I average.

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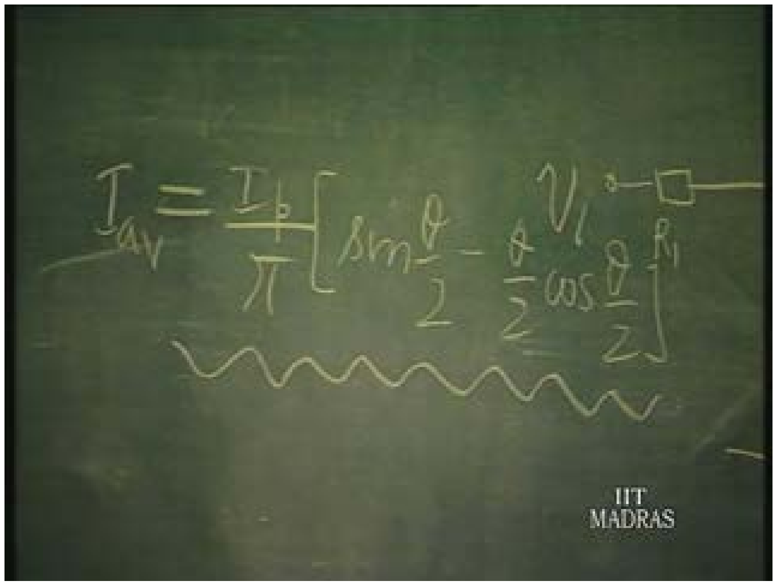

That means Pi input, power input, which is nothing but V c c into I average therefore equals, V c c I p by pi sine Theta by 2 minus Theta by 2 cos Theta by 2.

We can check this by putting Theta equal to pi; by putting Theta equal to pi. In fact, there was a minus sign which is already taken. So, Theta equal to pi. You will get sine pi by 2 which is 1, pi by 2 cos pi by 2 zero. So this is 1. So average is I p divided by pi. For a half wave rectified wave form with a peak voltage equal to I p, the average is I p by pi, we know. So, for Theta equal to pi, it is satisfied. So, P i is this.

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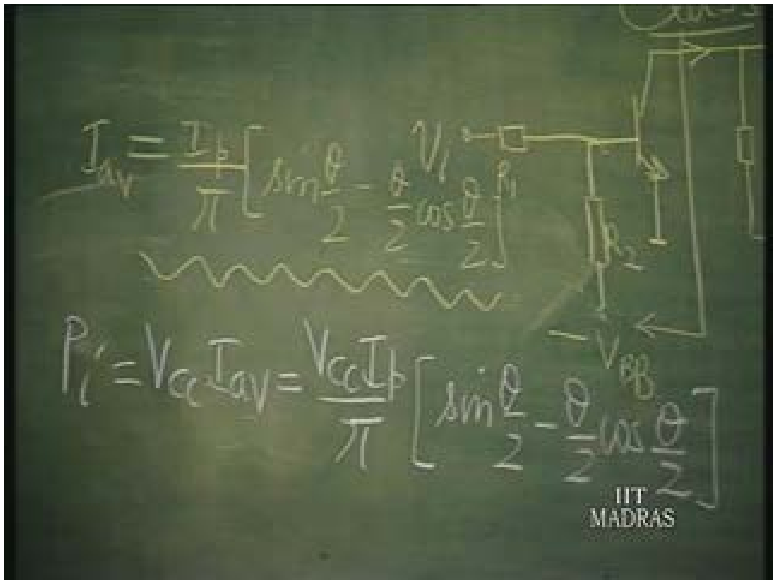

Now, we would like to find out the power dissipated during that time. You look at it. This is the time during which there is a current pulse by the transistor. This is the time during which the transistor is conducting. Now we can clearly say that when it is not conducting, the potential here is going to be V c c. This is a coil here. So, the potential here is going to be V c c. No current is there.

So, if you now plot the voltage V c e as a function of time, it will start at this point with V c c because there is no current all the way up to this point; all the way up to this point; and after... this current pulse is going to generate only voltage wave form corresponding to fundamental.

So, the voltage that is going to be generated across the tuned circuit is going to be some V p sine Omega t. The V p can reach as much as... since this is starting with V c c, almost V c c itself, the peak voltage. It is capable of generating that much value of the peak voltage. So, we will assume that it is almost V c c itself, the peak voltage. Rest of the harmonics are not capable of generating any voltage because L C circuits actually suppresses all the harmonics.

Therefore, we will have a voltage which is V c c minus V p sine Omega t which is V c c sine Omega t. That means actually, if you assume that this is almost nearly sinusoidal, this is going to be a wave form, which is going to be sinusoidal this way, all the way up to this; and since it is not going to be of interest for us, as far as the rest of the angle is concerned, this wave form is going to be of no concern to us; this portion of the wave form of the voltage. So, it is this that is of interest to us; instantaneous value of voltage wave form during the time the tube or the transistor is conducting.

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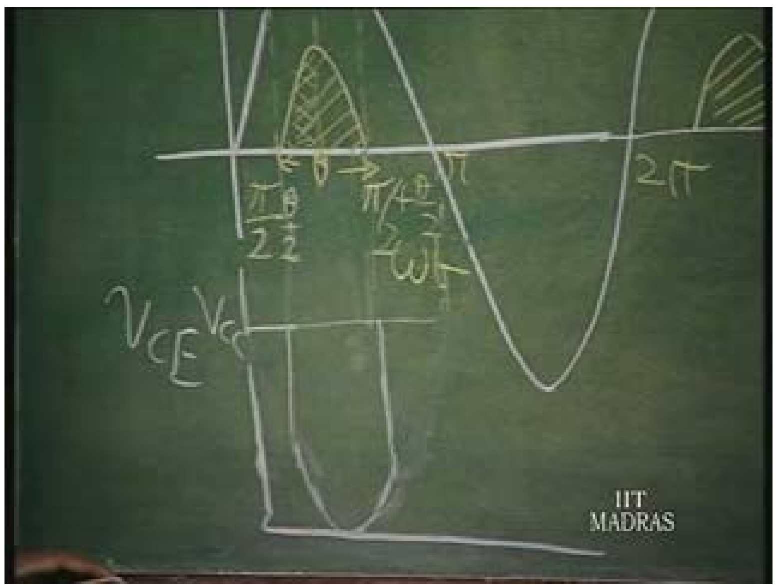

So, this instantaneous value of current into this instantaneous value of the voltage will give you the instantaneous power.

That means V c c minus...actually speaking it is V p, which is assumed to be V c c itself, sine Omega t. This is the voltage wave form here. That into the current wave form which we have already defined as I p into sine Omega t minus cos Theta by 2. This has been already defined. This into d Omega t is the energy that is stored, energy dissipated in the transistor, during the time period pi by 2...to pi by 2 plus Theta by 2, and again we can say that the limit is...because these are symmetric around, this pi by 2 will put the limit instead of pi by 2 plus Theta by 2, just pi by 2; and that will be twice the area, twice. That divided by 2 pi is the average power that is dissipated.

So, power inputted, which has already been evaluated by us minus power dissipated is the output power. So, efficiency therefore is nothing but output power divided by input power.

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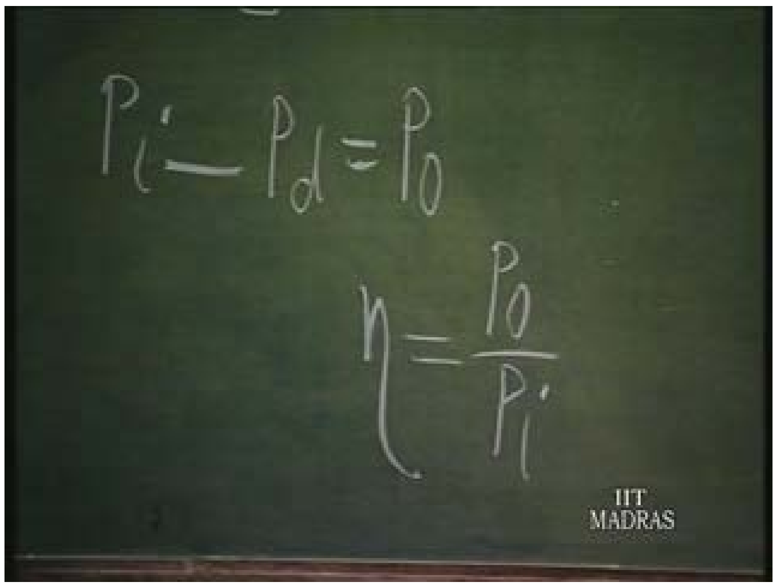

We can once again evaluate this.

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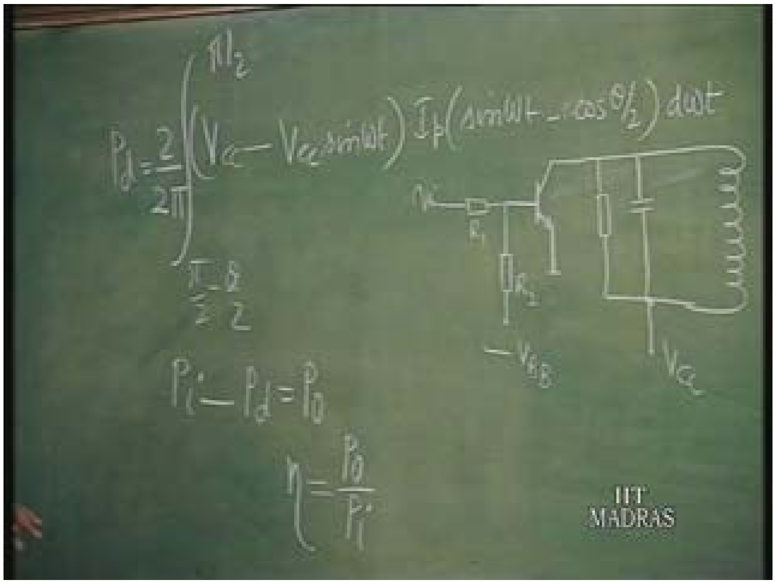

So, if you work out this integral, it will come out to be V c c I p by pi into sine Theta by 2 minus Theta by 2 cos Theta by 2 plus sine Theta by 4 minus Theta by 4. So, this is the power dissipated in the transistor; average power dissipated in the transistor. So, this will be very helpful for you to find out what the transistor rating should be.

Now, what we are interested in is power output. Power input minus power dissipated is power output; and we already have obtained the power input. Power input we had earlier obtained is nothing but V c c into I average, which is V c c I p by pi into sine Theta by 2 minus Theta by 2 cos Theta by 2. This is going to be the power that is inputted.

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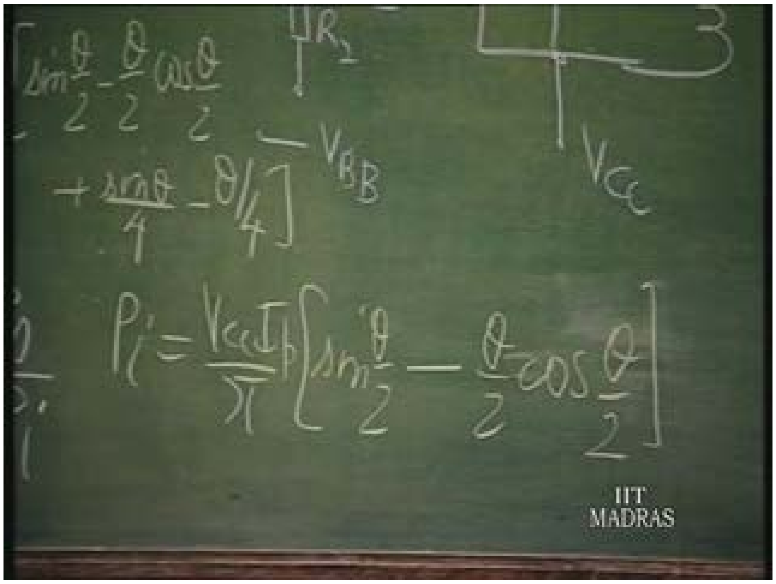

So, we have to subtract this power dissipated from the power inputted. You can see this. Power dissipated at V c c I p by pi sine Theta by 2 minus Theta by 2 cos Theta by 2, which is nothing but the power inputted. So, this portion is nothing but the power inputted. So, power dissipated is going to be subtracted from power inputted.

So, this has to be subtracted from... So, subtract this from power inputted. So, Pi minus P d is P naught. We will put this. V c c I p by pi into sine Theta by 2 minus Theta by 2 cos Theta by 2. This is nothing but power inputted. Now, the extra thing is, plus sine Theta by 4 minus Theta by 4. This is the extra thing. So, you see that the power output is going to be nothing but...this gets cancelled here, this gets cancelled here.

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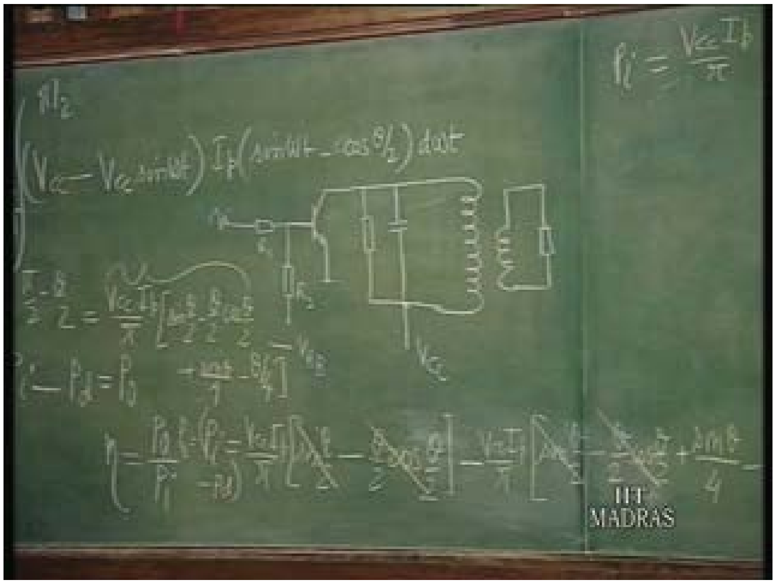

So, output power is going to be V c c I p by pi; same thing, into Theta by 4 minus sine Theta by 4. Simple expression. So, our 4 you can take out; 4 pi...Theta, minus sine Theta. So, this is the output power.

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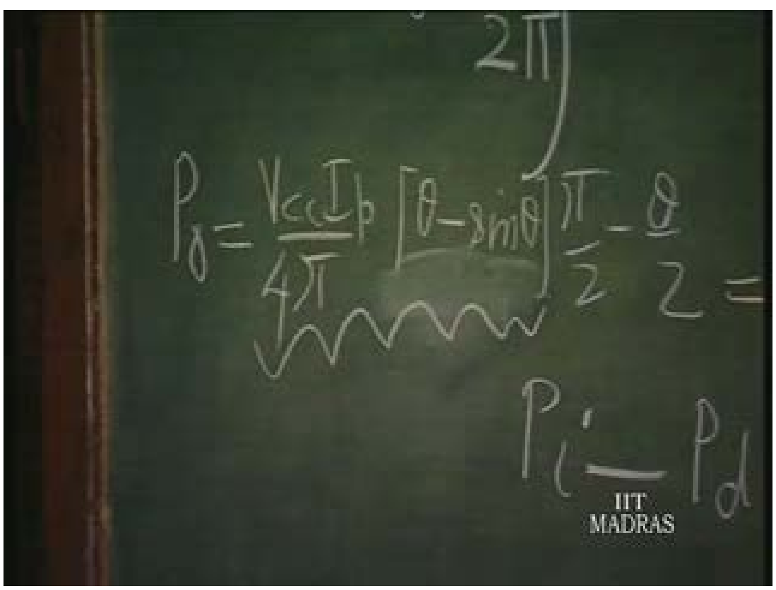

So now, we are ready for the efficiency which is output power by input power. So, the efficiency equals output power by input power; output power being V c c I p by 4 into Theta minus sine Theta divided by input power – this is V c c I p divided by pi into sine Theta by 2 Theta by 2 cos Theta by 2.

So, V c c by I p – it is therefore independent of that. V c c by...that is pi by 4 Theta minus... I think pi also gets cancelled. 1 by 4. In fact, it is in both the things V c c by I p, V c c I p by pi; in one it is by 4. So, only 4 will be there. Theta minus sine Theta. Just verify this at Theta equal to pi. This should be the same, 78 point 5. So, Theta equal to pi. This is pi, sine pi, zero. So, this is pi by 4; sine pi by 2 - 1; cos pi by 2 - zero. So, it is pi by 4 which is 3 point 14 by 4.

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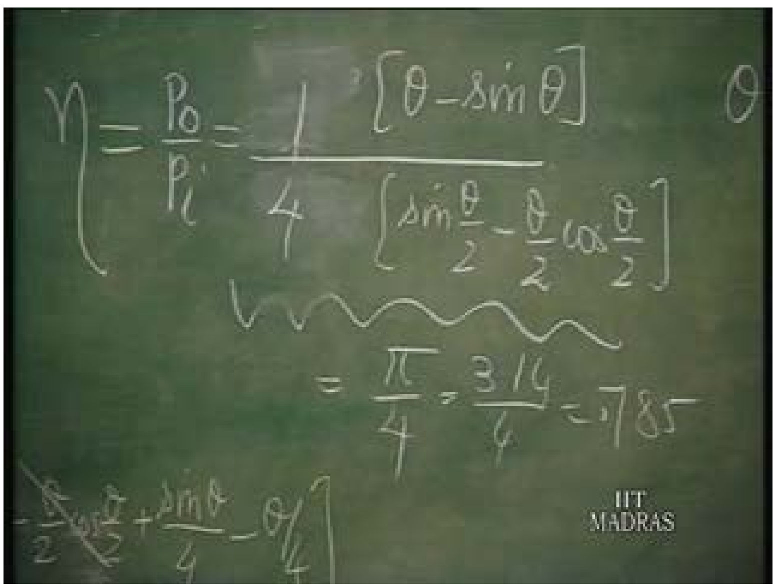

So, it is correct expression. Therefore, you can see that efficiency is going to be, let us see...because it should be higher than 78 point 5 for less than pi. Now for Theta very small, we can make approximations.

Theta very small; sine Theta is Theta minus Theta cube divided by 3 factorial. Rest of the things you can ignore. Sine Theta by 2 is going to be Theta by 2 minus Theta cube by 8 into 6; and cos Theta by 2 is equal to 1 minus the angle square divided by 2 factorial. So, Theta squared by 4 into 2. Pardon. 1, 1 minus...the Theta has to be always such that this 1 minus... it should be less than 1. So, Theta squared by 4 divided by 2.

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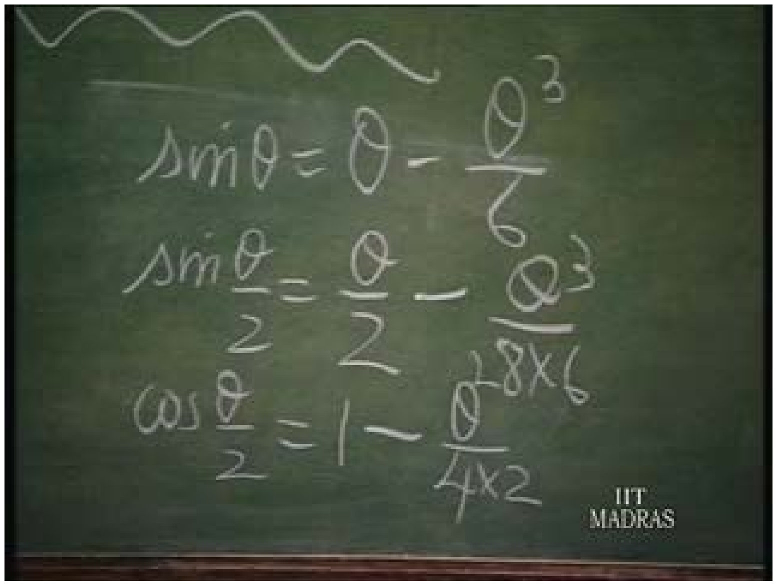

So now, we can substitute these things. So, this is for Theta small. This is 1 by 4...Theta, minus sine Theta, is going to be Theta cubed by 6. Theta, minus sine Theta; Theta, Theta, get cancelled. Theta cubed by 6. Then, in the denominator - sine Theta by 2, which is Theta by 2 minus Theta cubed by 48. Theta cubed by 48. Then, minus Theta by 2. That is remaining as such, into cos Theta by 2, which is 1 minus Theta square by 8.

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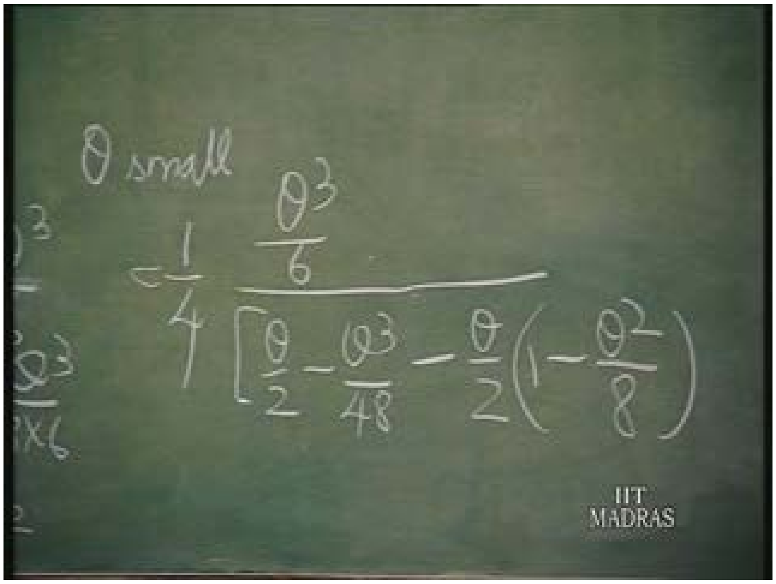

So once again, you have Theta by 2 getting cancelled with Theta by 2. So, this is equal to Theta cubed by 6 divided by minus Theta cubed by 48 plus Theta cubed by 16 which is nothing but 48 into 3. This is 1 by 16. So, it is 2 by 48. This whole thing divided by 4. So, this comes out to be 1. 3 by 48 minus 1 by 48 is 2 by 48, which is, how much is it? 1 by 24 is 1 by 6; Theta cubed by 6, Theta cubed by 6...100 percent efficiency.

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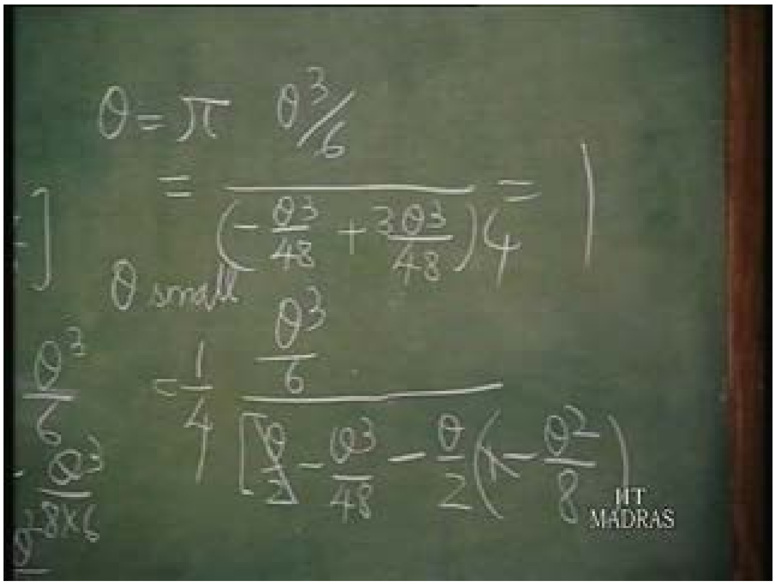

This is a theoretical efficiency. Of course, this is not possible because you cannot make Theta equal to zero because certain amount of power has to be given. Theta has to be non-zero and therefore it cannot cannot be 100 percent. It is always less than 100 percent because Theta cannot be made equal to zero. Theta going towards zero, efficiency is very nearly equal to 100 percent.

So, it is going to decrease from 100 percent up to 78 point 5 for Theta equal to pi. So, this is 100 percent. Now, this is the maximum ever possible efficiency under the assumption that we have swung almost up to the minimum which is zero, etcetera; and therefore these are all not valid. Therefore, efficiency is typically of the order of 70 to 80 percent. For a practical Class C power amplifier, which is going to deliver a useful power of about 200 watts, we can use currents of the order of 10 to 15 amperes working at about something like 50 to 60 volts, the transistor stages; we can get output power of the order of 100 to 200 watts.

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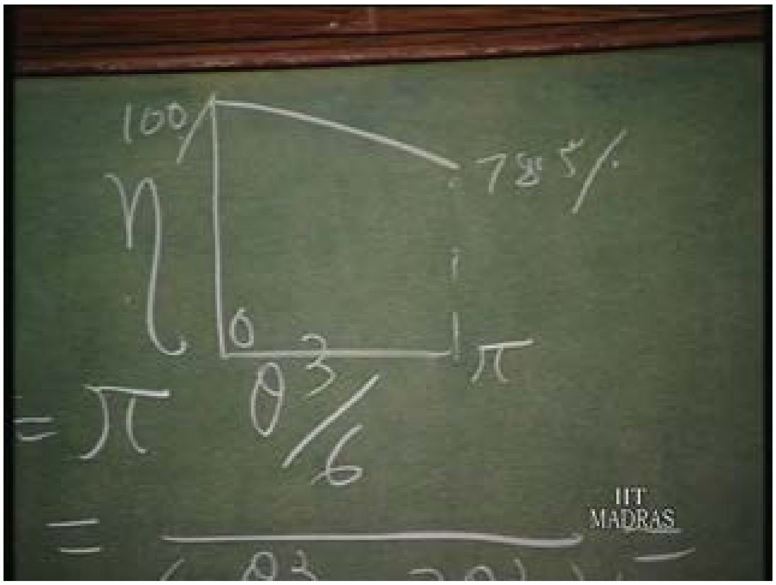

Now that we have understood how Class C power amplifier works, let us illustrate it by an example. Design a Class C power amplifier; this is a typical design; tuned to FM transmitter frequency 108 megahertz using 28 volts, typical supply used for this transistor power stages; supply and power transistor S D 1 4 6 0. Specifications for S D 1 4 6 0; surge current 65 to 70 amperes. This is just one time surge current which might flow because of sudden change in the voltage or something like that. So, I c max is equal to 16 amperes.

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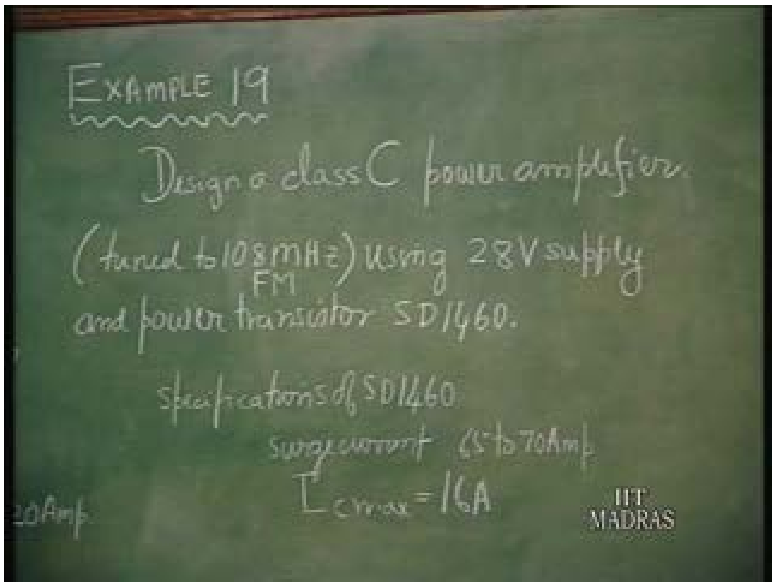

So, what is important here is the supply voltage and I c max in our design. Let us see.

We just said this shall be a transistor with a tuned circuit. This might really go to the antenna like that. So, we have here now an arrangement, let us say, to bias it, so that it will work with certain amount of conduction angle. So effectively, we said there is going to be a current pulse here, angle of conduction being decided by us. Smaller the angle of conduction, better is the efficiency. Of course, the output power delivered depends upon the angle of conduction. If you want to deliver large output power, it has to conduct for a longer duration.

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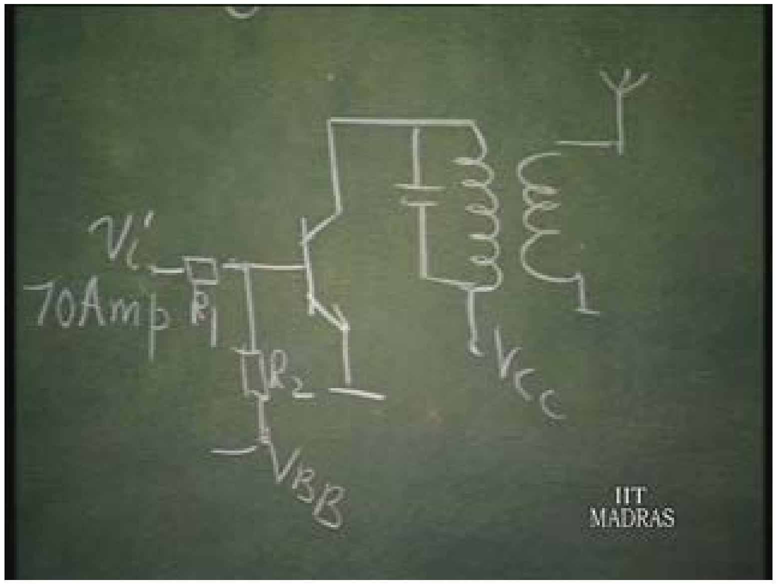

So, let us now see the design. How this is going to work. I max is chosen from this I c max, the collector current, 16 amperes. So, we will... let us select something like 10 amperes as the permissible maximum current we will have for the transistor, typical operation.

So, I therefore...the current wave form shall have 10 amperes as the maximum current units. It is part of a sine wave. So, we would like to know what the peak amplitude of the current is, of which this is a part. So, I is equal to I p sine Omega t minus cos Theta by 2, is the definition of the time wave form of the current. And therefore, maximum occurs at this point. It is I p. This is happening when this is equal to 1. 1 minus cos Theta by 2 is equal to 10 amperes. That is fixed. So, I p will be 10 by 1 minus cos... Now, Theta is to be fixed.

Now, let us take Theta, typical angle of 120 degrees. This is for ease of calculation only; for demonstration we are doing. This is around, typically, 120 degrees. So, cos 1 Theta by 2 is cos 60 which is sine 30 which is half. So, 10 by point 5, which is 20 amperes.

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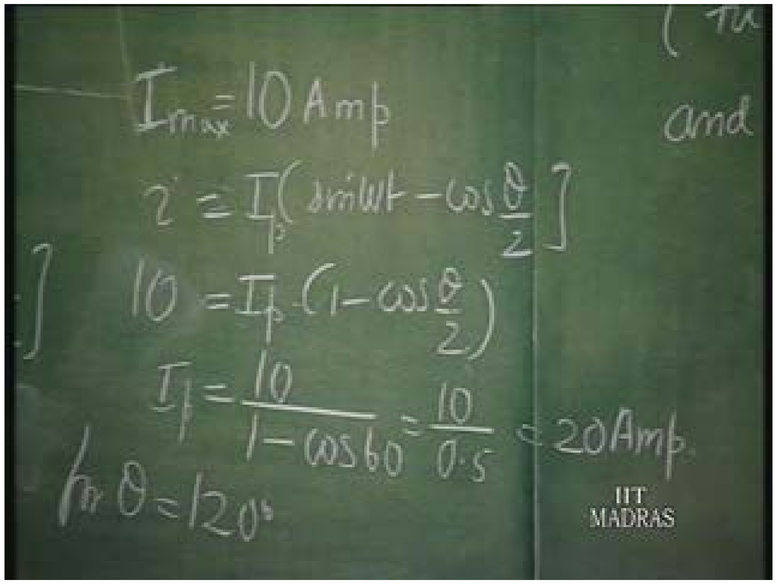

What it means is, this is a part of a sine wave whose peak current is 20 amperes. So, you can define this current wave form as 20 sine Omega t minus half. That is the definition of this wave form. 20 sine Omega t minus half. This is the definition of the wave form. So, it has a peak current of 10 amperes.

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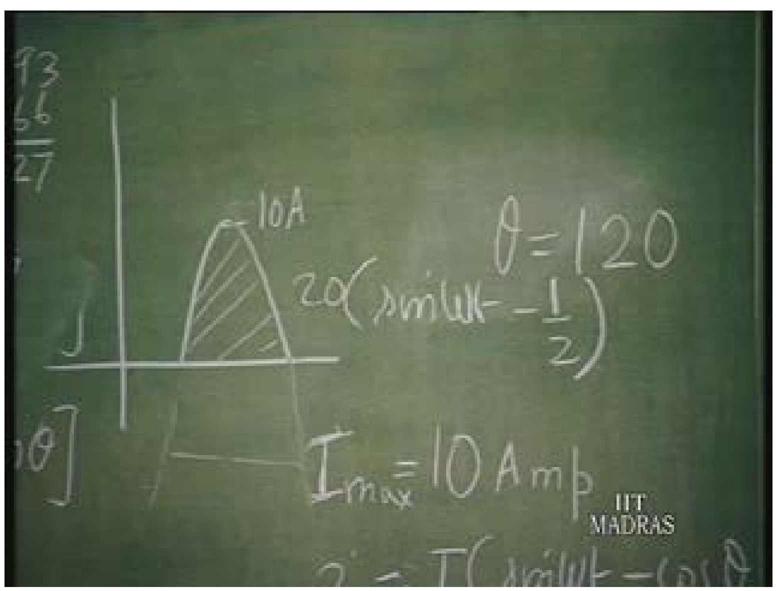

So, the current wave form is... we will define now.

Now, as far as the transistor is concerned, the voltage specification using 28 volt supply...28 V c c into I p divided by 4 pi Theta minus sine Theta is the output power as derived by us last time. So, this is 28, this is 20, as calculated now, by 4 pi into Theta being 120, which is 2 pi divided by 3 minus sine of 120. Calculating this, you will get it as 1 point 227. This is the calculation. 2 point 093 minus point 866. 1 point 227. This is really the output power which is 28 into 20 by pi into point 3074 - 1 point 227 by 4 which is approximately 56 watts.

So, this is the output power – 56 watts.

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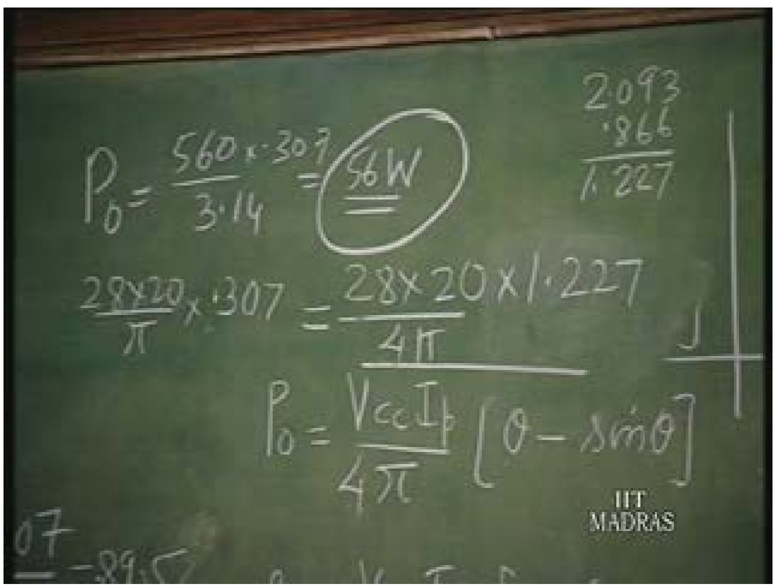

Now the input power, let us find out. V c c I p by pi into sine Theta by 2 minus Theta by 2 cos Theta by 2 is defined as the input power, which is 28 into 20 by pi into, sine Theta by 2 is sine 60, into Theta by 2, Theta being 2 pi by 3. So, 2 pi by 6 into cos Theta by 2 is half.

So, pi by 6 - you get there; the evaluation of which will give you 28 into 20 by pi into point 343, this factor.

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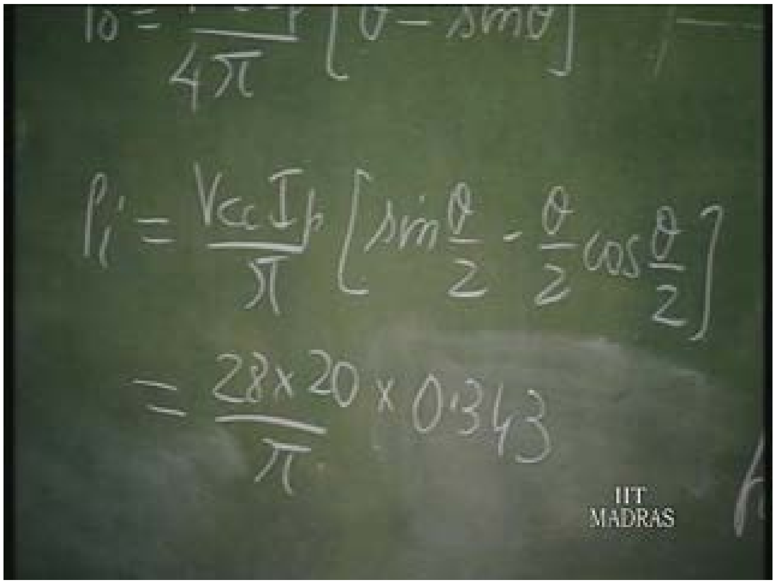

So, if you now take the ratio efficiency, these being common in these two, output power by input power, these will get cancelled. You will get the point 307 divided by point 343 which is about point 895; or efficiency is almost nearly 90 percent; 89 point 5 percent. This is the other answer.

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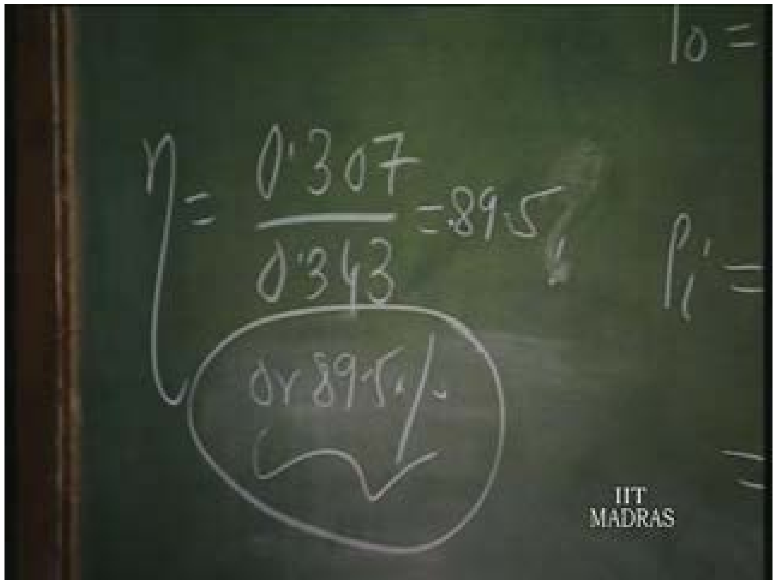

In the design, output power is 56 volts; efficiency is nearly 90 percent. That is, 10 percent of the power is only wasted in the device. So, once you have this efficiency, the input power is going to be output power divided by the efficiency. So, which is very nearly 56 watts divided by point 9. I am approximating point 895 as point 9. This is... how much? About 63 watts? Yes, 63 watts. Pardon? Yes. So, 63 watts is the input power.

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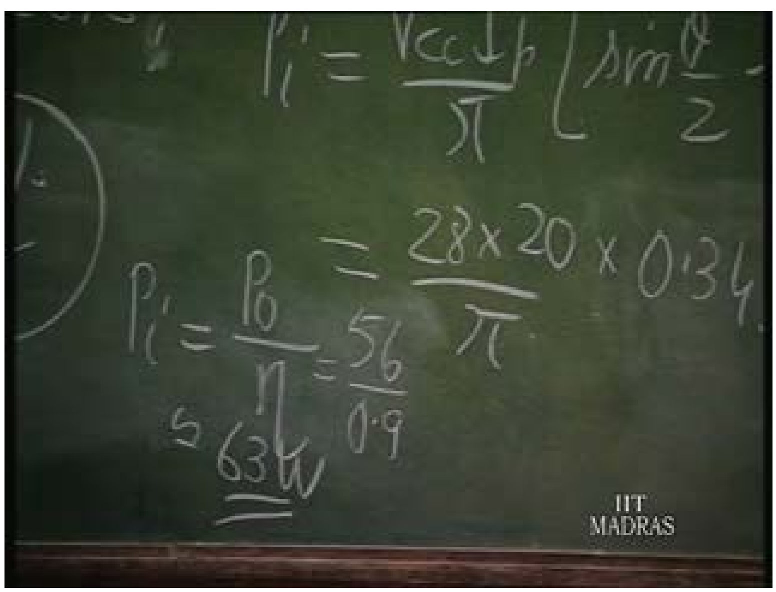

That means actually, power dissipated, which is also an important thing in the transistor, is going to be 63 watts minus 56 watts which is going to be about 7 watts.

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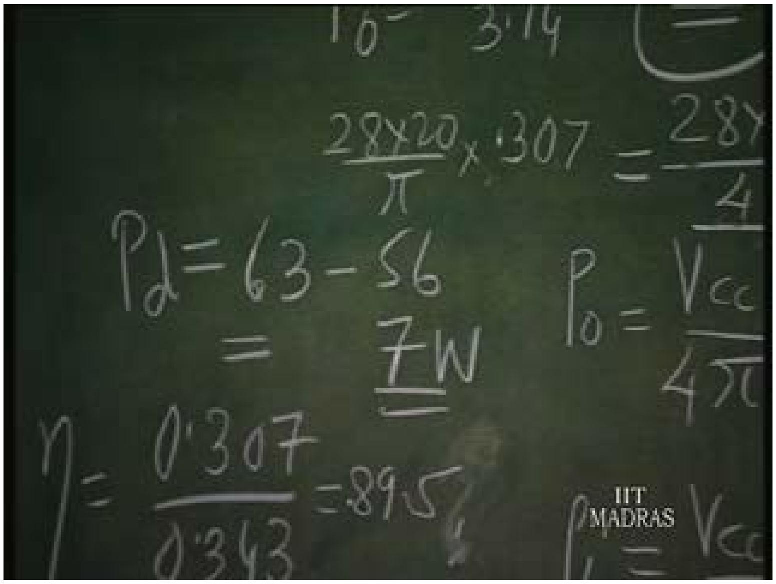

So, this is the power dissipated in the transistor, average power dissipated in the transistor. Peak power is going to be more than this. So, average power dissipated in the transistor is 7 watts. That means the transistor that is used should be capable of dissipating this kind of average power; and as far as the average current is concerned, that is going to be... what is that value?

63 divided by...what is it? 28 volts, which is 2 point 25 amperes. So, this is the average current supplied by the battery.

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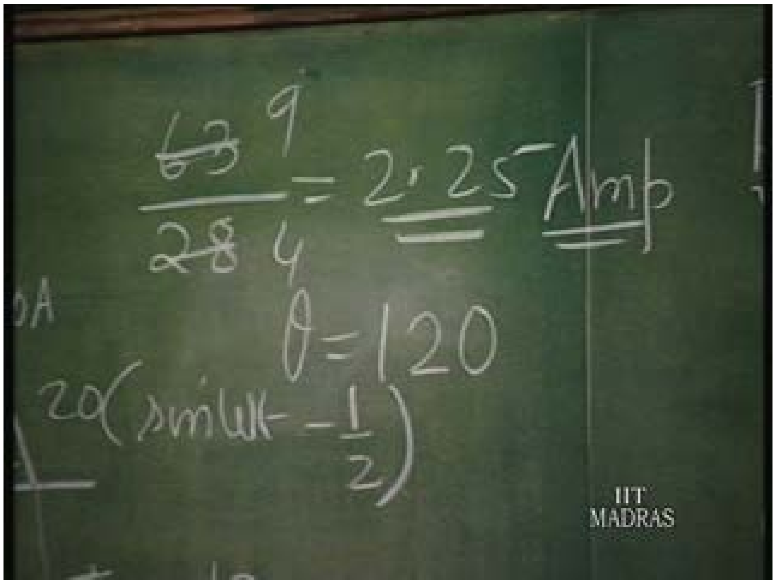

So, this completes... in sense, the complete design of the output stage of our transistor, power amplifier. Input stage - please remember. You have to now design this value of V B B and this value of V i R 1 R 2 in such a manner that this kind of current wave form is coming.

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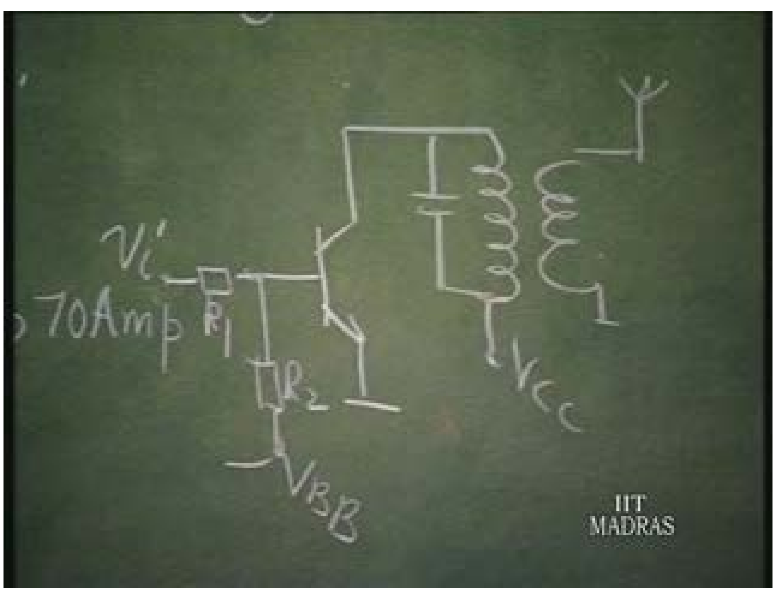

10 amperes divided by Beta. Let us take typical value of Beta. That shall be the peak current of the current wave form that is occurring in the base.

So, the base current is going to be like this - conducting for 120 degrees with... that is 10 amperes divided by the Beta. Let us say it is typically, may be, 50 or so. So, about point 2 amperes. That shall be the current wave form. That current wave form you have to generate using a specific value of V B B and a specific value of peak voltage here with a specific resistance.

You have to assume that the transistor conducts for about, say, 1 volt. V Gamma for all these power amplifiers you can typically take as 1 volts as against point 6 or point 7, because it is operating at parallelly high current.

So, if you take it as about 1 volt, then above 1 volt when it conducts , you assume that it is a battery. That means the entire current which is V i by R 1 will be pumped into the transistor. So, you have to assume that this part of the wave form is going to be generated by a sine wave drive here with specific value of V p so that V p minus 1 divided by R 1 is going to be your point 2 amperes.

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