Analog Electronic Circuits
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Lecture - 37
Power amplifiers - Class A, B, AB, C Class D

So, welcome back to Analog Electronics. Today we are going to be doing a lecture number 37.

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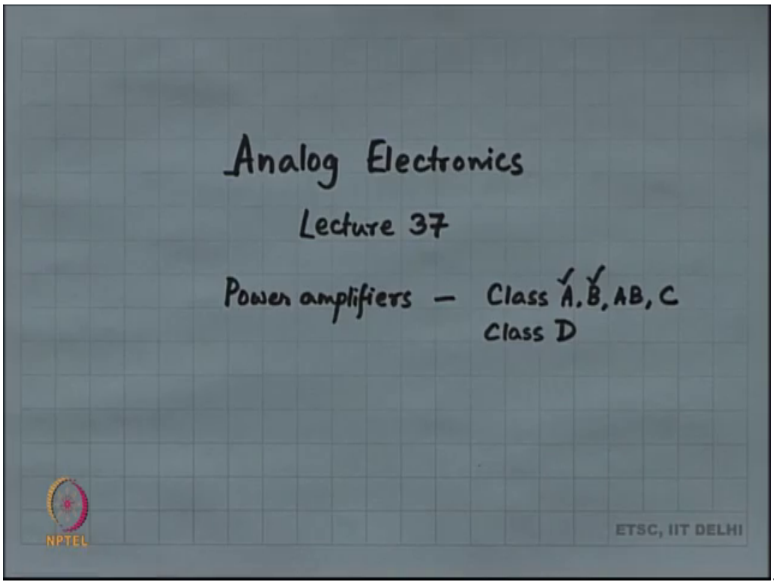

And in the last class, we had been discussing about Power amplifiers. We had studied Class A and Class B power amplifiers we have already studied and in this lecture, we are going to first quickly study Class AB and Class C power amplifiers, then we are going to go back and study a variant of Class B amplifiers and then, we are going to study Class D amplifier which happens to be a totally new dimension altogether, ok.

So, this is the plan for the lecture and hopefully by the end of the class, we will be able to summarise power amplifiers for you, great. So, in the last class we had studied the circuit is the same, right. This is just one circuit for the power amplifier, then that is what it is, ok.

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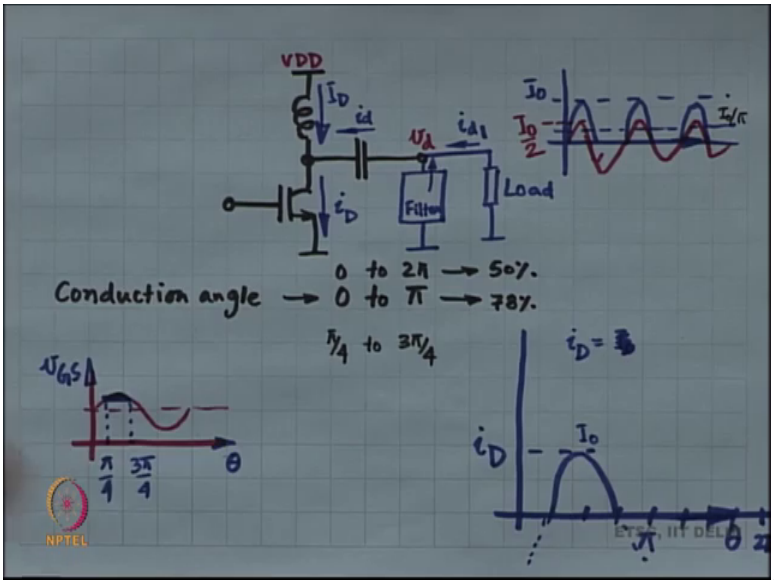

So, single transistor, huge inductor, huge capacitor, this one circuit for the power amplifier, all that we are tweaking is the gate bias voltage. So, in the last class we had kept the gate bias voltage, such that the MOSFET conducts only for half of the duration.

So, instead of conducting throughout the cycle, throughout the input signal phase, it is going to conduct only for 0 to 2 pi, right and then, we saw that the current now look, starts looking like this, ok. So, this waveform of the current and this is this particular current. Then what did we do? We split up this current. The portion that comes through the inductor is capital I D and the portion that comes through the capacitor is small i d and then, what did we do? We split up small i d further into the fundamental and its harmonics and we made sure we placed a filter over here, ok.

We made sure that the harmonics come this way and only the fundamental comes through the load. So, i d 1, ok. So, that is the fundamental component of small i d and we found that alright this is I naught, right. The DC quantity is capital I naught by pi ok, but the fundamental is a sine wave with an amplitude of I naught by 2, ok. That is what we found. The amplitude of the fundamental is nothing but capital I naught by 2, where I naught was the original peak.

Alright, we did the Fourier analysis and so on and so forth and then, what did we do? We found that there is some power in the load. The power in the load was the amplitude of V d. V d happens to be a sine wave because this current is a sine wave. So, the amplitude of

V d times the amplitude i d 1 of i d 1 times half that is the power in the load. The power in the power delivered by the voltage source by the DC voltage source is capital VDD times capital I D and capital I D is I naught by pi, alright. So, this is what we had figured out and then, we did some calculations and found that for this conduction angle.

So, this is called the conduction angle. The technical term is conduction angle. So, if the conduction angle is from 0 to pi, might have of studied thyristors. At some point of time, you might have studied thyristors. They also have conduction angle power electronics, ok. They also have conduction angle. So, if the conduction angle is from 0 to pi, then the fundamental is I naught by 2. The DC quantity is I naught by pi and we found that the efficiency, the maximum efficiency is pi by 4, ok. This is what we have found.

Now, of course who says that the conduction angle has to be 0 to pi, ok. We said that 0 to 2 pi gives me 50 percent efficiency. So, that is bad. 0 to pi is giving me 78 percent efficiency, right. You might think of a conduction angle between pi and 2 pi, right. Let us say 3 pi by 4 you pick, right and clearly if you look at the numbers, you will expect something in between 50 percent and 78 percent, right and the hope is that if you reduce this conduction angle, reduce this number, let us say you make it pi by 2, right.

What stops you? Nothing going to stop you, all you have to do is reduce the gate bias voltage. Let us reduce the gate bias voltage even further, right and you know what, it is no longer going to conduct from 0 to pi maybe is going to conduct from pi by 4 to 3 pi by 4. So, total angle of pi by 2. So, what I have done is this was your gate voltage and I am saying that only this portion of the waveform, the MOSFET is conducting fine.

So, this is the plan and what do I have to do, what is the current now going to look like? i d is now going to look like, so, this is pi by 4, pi by 2, 3 pi by 4 pi, ok. This is how i d is going to look like or in other words, i d is equal to some I naught. It is hard to put a function over here, right. It is hard to write it is a function, I mean you can imagine this starting over here, finishing up over here right, but one can still write it up as a function. You just have to be a little creative.

So, let us try to write it up as a function. So, i d has to be written up as a function in terms of these angles, alright. Then, what do we have to do? We have to find DC part in that and we have to find the fundamental part in that, alright. The voltage V d will still have a maximum amplitude of capital VDD, alright and this i d 1, the fundamental part of the current i d 1 times the amplitude of the voltage maximum amplitude of the voltage is going to be VDD divided by 2 is going to be the power delivered to the load. Power drawn from the source is going to be VDD times the DC part of this wave and then, we are going to work out the efficiency. This is the plan, fine. So far so good this is the plan. Now, all I have to do is work out a function for small i's of capital D. So, let us think of it this way.

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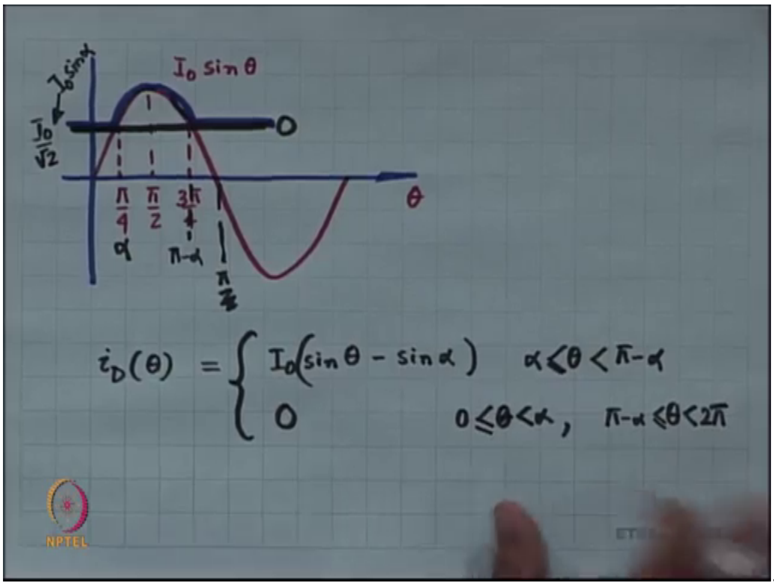

Let us say this is some I naught sin theta, ok. This is the sine wave. Now, we are going to draw a line and above that line, it is going to conduct, below that line it is all going to be 0. In such a case, our line is going to be at 45 degrees. This is the line, fine. What is the value at that line? I naught sine pi by 4 which is I naught by root 2, alright. Above, that it is going to conduct; below that it is we are not going to bother.

Now, what we can say let us make it, let us make it a little more general, instead of pi by 4, let us call it some alpha, ok. Let us call it some alpha and naturally this angle is going to be this is pi by 2, no this is pi. So, this is going to be pi minus alpha. So, it is going to conduct from alpha to pi alpha right. In the class B case alpha happened to be 0. It was conducting from 0 to pi, alright. So, now we want it to conduct only from alpha to pi minus alpha and what is this value going to be in such a case? It is going to be I naught sin alpha.

In this specific case, it is I naught by root 2, alpha is pi by 4, alright. Now, let us subtract this out from the waveform. So, I am going to write i D of t, i D of theta as I naught sin theta minus I naught sin alpha for theta greater than alpha and less than pi minus alpha and for all others 0, fine. This is going to be my definition of the current waveform. This is how the current waveform is expected to look. This is my 0 point. So, I am going to start with 0, then I am going to build up and then, again 0, fine. This is how it is. This is my definition of i D of theta and then, what do we have to do? We have to do two things. We have to find out the DC part of this and we have to find out the fundamental part of this and we are done, right. What is the DC part of this? DC part of this is just the average, right you integrate i D of theta.

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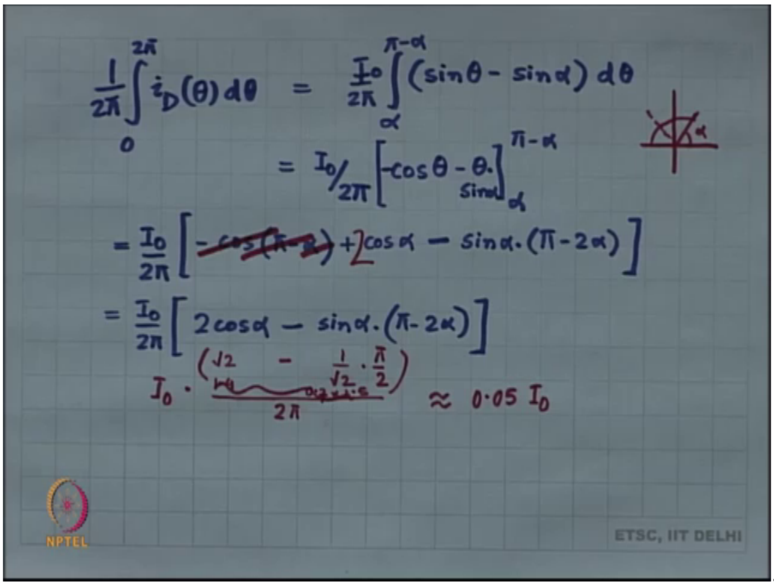

So, its 1 by 2 pi integral 0 to 2 pi i D of theta d theta, but in our case i D of theta is mostly 0, it is mostly 0, its non zero only during this angle right. So, all that we have to do is 1 by 2 pi integrated from alpha to pi minus alpha.

And what do we have to integrate? This is the function we have to integrate ok. So, for example, when we had pi by 4 over there alpha was sine alpha was just 1 by root 2. So, this is the known number. Integral of sine theta is minus cos theta; integral of a constant is just theta sorry theta into sin alpha. So, minus cos of pi minus alpha plus cos of alpha minus sin alpha times pi minus 2 alpha. Is this ok? What is cos of pi minus alpha or do you remember your trigonometry? I always you know.

So, this is alpha, this is pi minus alpha and cos is the base by the hypotenuse. So, the base is negative; the hypotenuse is fixed. So, therefore it is going to be just minus of cos alpha. So, minus cos alpha minus of that will give me another cos alpha. So, this is not really needed. We just put it 2 over there, 2 cos alpha minus. So, this is very complicated and let us just plug in the number because this is I mean this I mean closed form. We are getting a result that is alright, that is fantastic. We will be able to get a closed form expression alright, but unless we have a physical number, it is not really making sense ok.

So, let us pick a physical number. Let us say alpha is pi by 4; 2 times cos alpha is 2 by root 2 which happens to be root 2. So, this is root 2 minus 1 by root 2 times pi minus 2 times pi by 4. So, that is pi by 2 and this whole thing divided by 2 pi and times I naught. Now, if you have a calculator, you can calculate, right. What do you expect? You expected to be so first we started with I naught, then it became I naught by pi. Now, it is going to be even smaller than that, ok. So, root 2 is 1.4 minus this is 1 by root 3 is 0.7, pi by 2 is another 1.4 1.5, ok. So, 1.5 times 0.7 is something like 1.1 1.4 minus 1.1 is 0.3 by 2 pi. So, 0.15 divided by another factor of 3, so, of the order of 0.05, substantially smaller than I naught just a rough calculation overall calculation tells me it is I have approximated pi as almost equal to 3 over here and root 2 I have approximated with as 1.4 1 by root 2 is 0.7 pi by 2 is 1.5. There are lot of approximations have happened 0.05 roughly there about is what I will get. Is it?

Student: (Refer Time: 23:13).

Of that order 0.048 0.05 something like that, ok.

So, what have we got over here? This is the DC quantity, this is the current I D, this is what I have calculated this current and I have figured that this current is something like 0.05 times I naught, alright. Next what I am going to do is, I am going to find out i d 1. Now, how do I do i d 1? Remember the DC quantity also is part of the Fourier series. The Fourier series had 0th term that was the DC quantity and this is exactly the relationship how you find that out.

So, now what we are going to do is we are going to find out the Fourier series a1 component and b1 component, ok, a1 and b1 or all we are going to worry about, we are not going to look at a2 b2 and so on and so forth.

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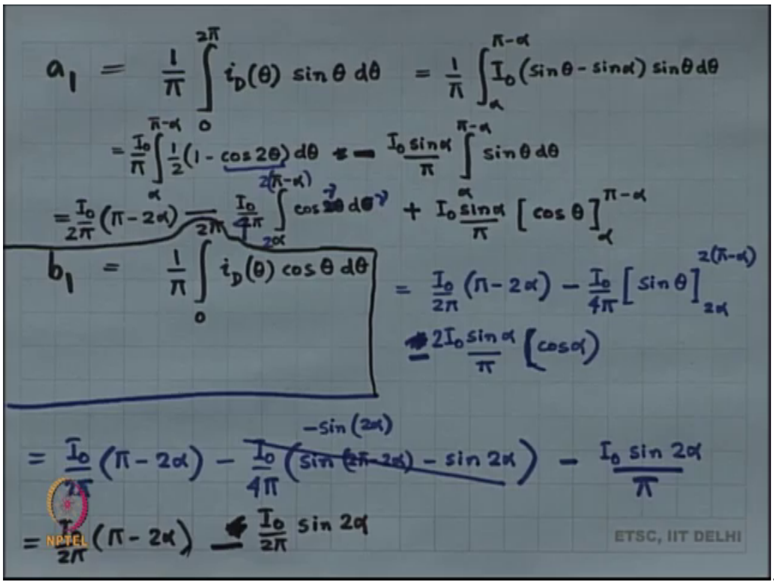

So, a1 and b1 and the last time we worked it out, b1 happenned to be equal to 0. How do we work out a1? It is going to be once again 1 by pi. It is actually 2 by the period, 2 by the period, period is 2 pi. So, it is 1 by pi integral from 0 to 2 pi i D of theta sin n equal to 1, this is what we are working out and for b1, we will have to do the same thing, but with cos theta. Now, the nice thing about it is that i D of theta is mostly equal to 0. All of this region i D of theta is equal to 0. We only have to integrate between alpha and pi minus alpha. Is that ok, integrating only between alpha and pi minus alpha and that is it. Now, this integral has a sin square theta portion and a constant time sin theta portion. So, those two will have to be handled separately.

So, I have 1 by pi integral and it is always integral alpha 2 pi minus alpha. Let us take I naught outside I naught by pi sin square theta d theta is half of 1 minus cos 2 theta d theta, ok. So, I have split it up into two portions; I naught sin square theta d theta is half of 1 minus cos 2 theta d theta I naught and the other portion is I naught sin alpha sin theta I naught sin alpha integral sin theta. Now, this integral also splits up into two portions. There is a half and there is a cos 2 theta.

So, half d theta is an easy integral. Half d theta just gives me theta by 2 from the range alpha to pi minus alpha and then, I have a minus sign integral cos 2 theta d theta. You want to write 0. It is not really 0, right, 0 would have been if you are going from alpha equal to 0 to pi, ok. That would give you a full cycle of cos 2 theta. This is not really going to give you a full cycle of cos 2 theta unfortunately, ok. So, you have to be a little more patient. You need to work this out as well.

2 theta is going to be replaced by all alpha is taken. So, something else beta or k or something else, cos what you want to write; gamma, let us call 2 theta as gamma. So, d theta is gamma by 2 and 2 times theta is gamma. So, gamma has to go from 2 alpha to 2 times pi minus alpha. So, these are the adjustments, next one. Next one I have a sin theta d theta integral. Integral of sin theta is minus of cos theta. There was a minus sign in front which makes it plus I naught sin alpha by pi, fine. This is how we are doing it, cos gamma d gamma integral of that is sin integral of cos is sine cos pi minus alpha is minus cos alpha minus a further cos alpha.

So, the 3rd part is done, the first part is done, the middle part sin is yet to be done. You see everywhere you have to do hard work, ok. If you want a result, hard work is required, sin of 2 pi minus 2 alpha minus sin 2 alpha. Now, tell me what is the relationship between these two? They are equal, right; sin of 2 pi minus 2 alpha is nothing but sin 2 alpha. So, this is 0, right.

So, what you had pointed out that this portion is going to be 0 is indeed correct, ok. I had straightaway ruled that out, but that is indeed correct, ok. So, the middle portion works out to be 0 and the last portion is I naught sin 2 alpha by pi. Now, whenever you do these complicated things, you always have to do a sanity check. Now, our sanity check is going to be to plug in alpha equal to 0. My result should be the same as the class B power amplifier and in the class B power amplifier, I got I naught by 2 as the answer right for a1. So, I plug in alpha equal to 0. The first term over here is giving me I naught by 2 sin of 2 alpha is 0.

So, I still have sense. There is sense in this answer, ok. It is not absolutely nonsense. It might not be correct, but it is fitting at least one point alpha equal to 0 fits. So, I have got a1.

Student: That one is minus sin 2 alpha. (Refer Time: 35:08).

The middle term?

Student: The last.

The last term?

Student: Yes, the last one.

The last term is minus 2 I naught sin alpha cos alpha.

Student: sin of 2 pi minus 2 alpha minus sin 2 alpha, alpha is pi by 2.

Sin of 2 pi minus 2 alpha, ok. So, the middle term is not 0 is what you are complaining, ok. So, the complaint is that this term is just minus sin 2 alpha. They are not equal.

Student: (Refer Time: 36:03) pi by 4.

So, this is sin 2 pi minus 2 alpha. Now, my trigonometry is all hazy.

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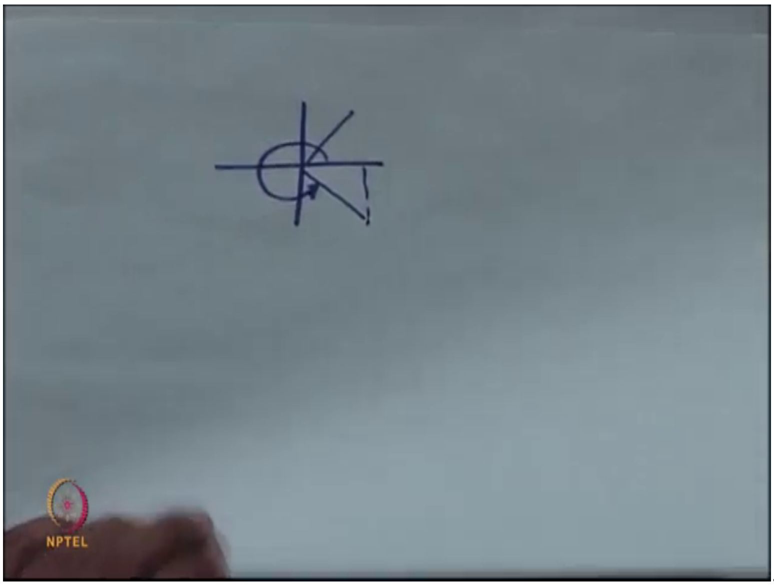

So, 2 pi minus 2 alpha. So, if this is 2 alpha this angle is 2 pi minus 2 alpha and sin is indeed negative, its height by hypotenuse. So, height over here is negative and therefore, it should be negative. So, this should be minus sin 2 alpha minus of further sin 2 alpha. So, I should not cross it out. This should be minus I naught by 2 pi. It should be plus I naught by 2 pi times sin 2 alpha and then, this is a minus I naught by pi sin 2 alpha.

The net result is going to be minus I naught by 2 pi sin 2 alpha after combining two terms, ok. Thank you, for the correction. This would have easily gone unnoticed, ok. So, again sanity check plug in alpha equal to 0. This term cancels out, this time goes away, all you get is I naught by 2. Then, sometimes sanity check does not work, right. This is a1. We also have to look at b1 and b1 is going to be equally hard, but maybe.

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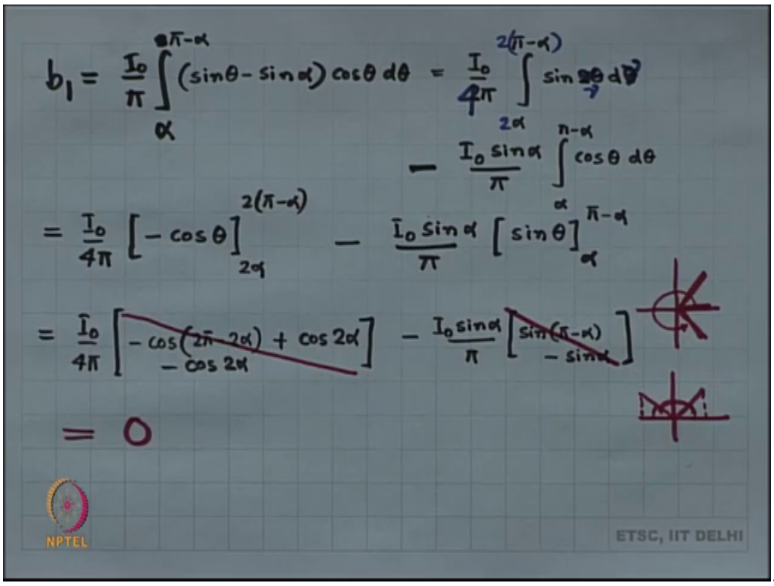

So, this is b 1. We have to work this integral again from alpha to pi minus alpha sin theta minus sin alpha cos theta d theta. So, earlier this was sin theta. Now, it is cos theta. That is all. That is the only change. And to start with sin theta times cos theta is half of sin 2 theta. This is the first part and second part is a constant times cos theta and then, what are we going to do? For the sin 2 theta we are going to substitute 2 theta as some gamma, then theta will be gamma by 2 and the limits need to be doubled, right.

And now, we have to evaluate these two integrals. So, the first part is I naught by 4 pi and then, integral of sin gamma d gamma is nothing but minus cos and then the second part is minus I naught sin alpha by pi and integral of cos theta is sin theta going from alpha to pi minus alpha and then, we plug in the limits, ok. Everything you have to do very carefully.

Minus cos of 2 pi minus 2 alpha happens to be equal to cos of 2 alpha, ok. So, here it is actually going to cancel out; cos of 2 pi minus 2 alpha. So, if alpha is this angle, then 2 pi minus 2 alpha is this angle, right and you are looking at base by hypotenuse. So, it is the same as both are positive, right. It is the same as cos of 2 alpha. So, this is just cos of 2 alpha and cos of 2 alpha cancels out politely, fine. So far so good and then the second term minus I naught sin alpha by pi sin of pi minus alpha minus sin of alpha and once again I am back with my trigonometry.

So, if alpha is an angle like this, then pi minus alpha is an angle like this and sin is the altitude by the hypotenuse. So, they have the same positive altitude by the same hypotenuse which means sin pi minus alpha is equal to sin alpha. This will also give me a nice 0, which means that b1 is still equal to 0 and this is not really a surprise because I have so carefully organised my i D of theta. You see i D of theta was built out of a sine wave, there is no chance of a cosine wave coming in the Fourier series, ok.

It is built out of a sine wave, ok. Whenever you construct it like this, you are not really going to get a cosine component at all. You are only going to get the sine components. So, b1 is 0 which is great and a1 is what we have figured out, great. So, what have we done so far? We have done the following. I had this current i D which look like this and then, I figured out that capital I D is the DC component which is written as this happens to be 0.05 I naught in case of alpha equal to pi by 4.

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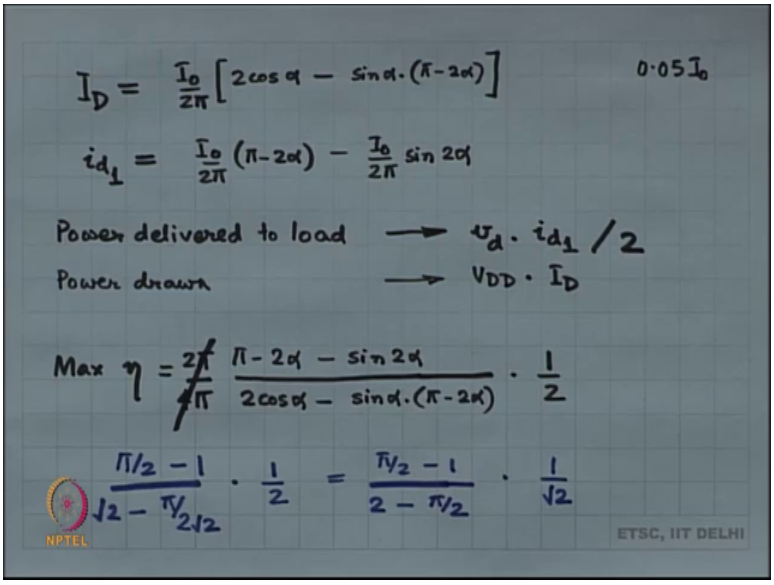

So, I have figured out the DC part. I have also figured out the fundamental and that is just a1. The fundamental amplitude is just a1, right. So, the entire thing is a1 times cos sin of theta is the complete time domain waveform. The amplitude is just a1, fine. Now, what is the power delivered to the load? That is the amplitude of the voltage at the load v d times the amplitude. Actually only the fundamental part will come because the other harmonics have been taken out by the filter i d 1 by 2 and power taken from supply is the voltage source times capital I D and my efficiency, maximum efficiency is when small v d is equal to capital V DD. So, these two are equal V DD V DD and all I need to do is, i 1 by 2 divided by capital I D. I naught will politely cancel out, right. So, all that I will be left with is so this is i d1 by 2 divided by ID, fine.

So, this is my closed form result for different values of alpha, right. So, you can organise alpha to be 0. For example, if alpha is 0, this goes away sin 2 alpha is 0, 2 cos alpha is 2. This is a 0. So, you have pi by 2 by a further 2; answer is pi by 4. So, alpha equal to 0 works perfectly fine, alright. What about alpha equal to pi by 4? Alpha equal to pi by 4, what does it give you? If I plug in alpha equal to pi by 4 pi minus 2 times pi by 4 is pi by 2 minus sin of pi by 2 is 1 divided by 2 times cos alpha. That is 2 root 2, 2 by root 2. So, that is a root 2 minus sin alpha which is again 1 by root 2 times pi minus pi by 2. So, that is pi by 2 pi by 2 root 2. So, you can think of it if I multiply both numerator and denominator by root 2, so, if I multiply the numerator by root 2 for example then I multiply the denominator also by root 2, ok. It looks lot simpler.

Pi by 2 minus 1 is something like 0.5, 2 minus pi by 2 is again something like 0.5. It is a little smaller than 0.5. This numerator is bigger than 0.5, denominator is smaller than 0.5, overall this factor is slightly more than 1, ok. You have to do the numbers exactly times 1 by root 2. You are going to get something of the order of 85 percent, if you do the numbers right, alright.

There is one more test case. These test cases if I plug in alpha equal to pi by 2 that is the conduction angle is almost nothing, alright. I have made VGS such that it barely conducts, fine. So, that is alpha equal to pi by 2. If I plug in alpha equal to pi by 2 pi minus 2 alpha this is 0 minus sin of pi, this is also 0. So, numerator is a 0, the denominator is 2 times cos pi by 2 0 minus sin pi by 2 which is a 1 times pi minus again a 0, ok.

So, you get 0 in the numerator, 0 in the denominator and you do not know what to do, alright. So, this is actually a test case. You are barely switching it on. This actually is also a sanity check. You should get 0 by 0 over here. It is kind of undefined what is happening over here, you are barely switching it on, but then again you are barely consuming current also, ok. Capital I D is also going to work out to 0, i d1 is also going to work out to 0, alright. So, this is also a test case. It so happens that is actually 100 percent, but you will have to take the limits, right. You will have to do some L Hospital's rule and so on and so forth and work out the limits.

When you have 0 by 0 situation what do you do? You are going to say limit alpha tends to 0, sorry alpha tends to pi by 2. You are not really going to plug in pi by 2 and get 0 by 0, right. So, you are going to do limit alpha tends to pi by 2 and you will actually going to it is going to work out to 100 percent, but before that what have we got over here? As we reduce the conduction angle further and further, you are going to see that your efficiency is going to increase. Earlier in the last class, we had discussed some classes of amplifiers.

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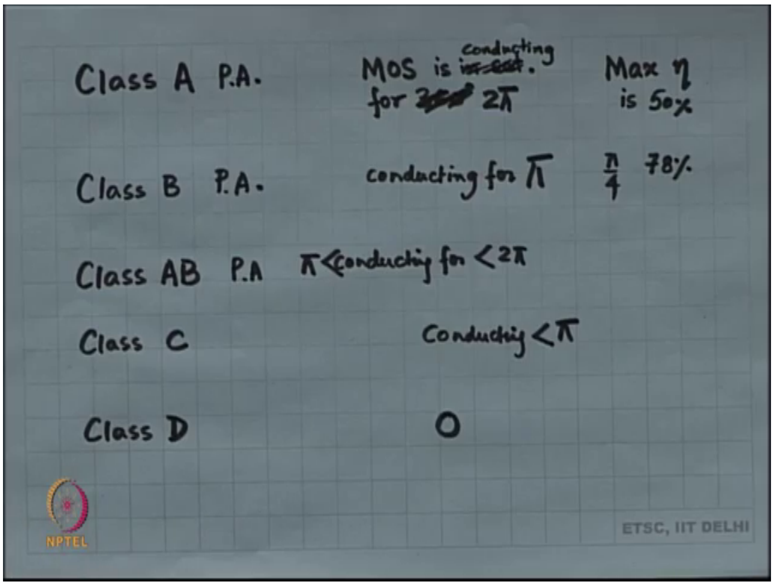

So, here we are going to add in a few more definitions. Number 1 is Class A B and Class AB P.A is between class A and class B. So, it conducts for less than 2 pi, but more than pi; total, alright and the case we worked out is called Class C where it is conducting for less than pi, ok. That is the case we worked out, right. It is conducting for less than even half of the cycle and here the efficiency is going to further increase. This one the efficiency will be in between 50 and 78 percent. So, these are the different classes of the P's; class A, class B, class A B, class C, alright and the only difference between these classes is the conduction angle that is what is the bias voltage VGS.

The DC bias voltage accordingly the conduction angle is going to change, accordingly you are going to decide which class of power amplifier you are in. So far we have discussed class A, B, AB and C, class D is a special amplifier where the conduction angle is 0. It does not conduct at all, ok. The circuit is the same. Remember this 0 by 0 situation that we were just discussing, right. It is a special case, where everything boils down to a big 0. It does not conduct at all, alright.

So, we are going to discuss class D next where the conduction angle is a big 0 and in such a scenario, you actually have, you cannot do as 0 by 0. You actually you have to take limit as the conduction angle tends to alpha tends to pi by 2 in this case, you have to take that limit. So, we are going to work on that in the next class. We are going to discuss class D amplifiers in the next class and in the next class, we are also going to make a slight modification to the class B amplifier and that is our plan, ok.

Thank you very much.