Power Electronics

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Lecture No - 10

We will start today, power electronic circuits and equipments. The, depending upon functions, the entire power electronic circuits or equipments can be classified into 5 groups. The first 1, they are known as the converters. The input voltage is AC, output voltage is DC. When I am saying output voltage is DC, it means that average value of the output voltage is finite, not a necessarily a constant value. The second 1 is inverters: wherein, the input is DC, output is AC. What comes to your mind when I am saying output is AC? Is it a pure sinusoid? No, when I am saying when the output is AC, it means that average value of the output voltage is 0, not necessarily a sin wave.

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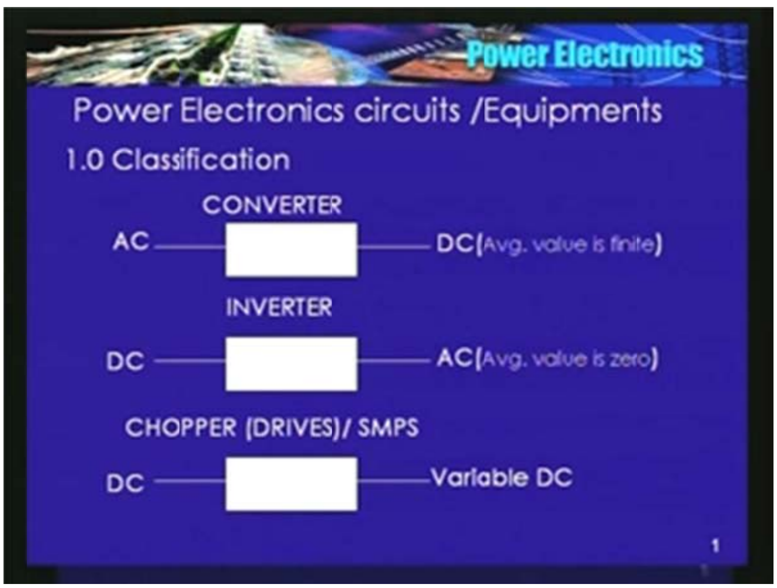

Third one: input is DC, output is also DC. Output voltage can be varied, it could be either choppers or switch mode power supplies or DC to DC converters or DC transformers.

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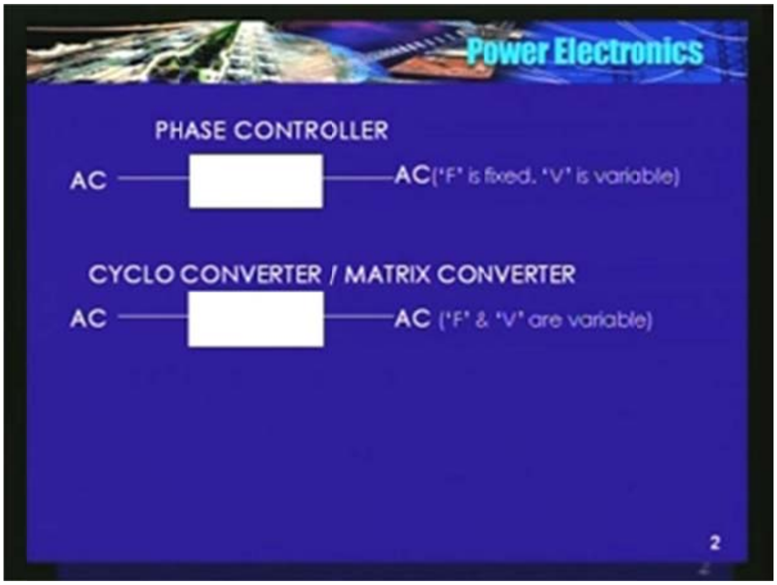

The fifth one, the fourth one: input is AC, output is also AC but the frequency of the output voltage is same as the input, whereas, the magnitude is changing. These are known as phase controllers. They are often used in fan regulators, you might have seen. A small regulator, just by changing the knob you are varying the speed. They are basically phase controllers.

The last 1 input is AC, output is also AC. Both, voltage and frequency are variable. They are cycloconverters. A new group of power electronic equipments, they are also known as matrix convertors. So, last 1 is cycloconverters and matrix converters. We will study each 1 of them in detail.

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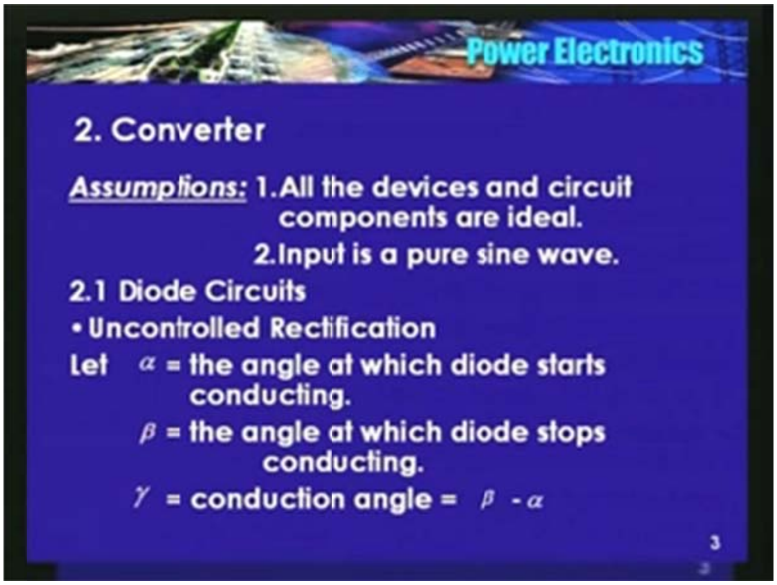

First 1, converters: what are the basic assumptions that are we making? All the devices and the circuit components are ideal. In other words, when the device is conducting, voltage across the device is 0 and when the device is open, then the current flowing through the device is 0 and when I am saying so, passive elements, L is a pure inductor, C means a pure capacitor and input is a pure sin wave. The first one is diode circuits: a low power, a 3 ampere, 600 volt diode. 2 element device: anode, cathode.

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A 40 ampere, 600 volt device, what exactly they mean? I will tell you later. Anode, cathode: these are, directly this device cannot be used in a circuit, this has to be mounted on a heat sink. This is a heat sink. It has to be mounted on a heat sink.

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So cathode, anode: body is anode, this is a cathode. It is a 2 element device. These are known as the uncontrolled device: hence the name, uncontrolled rectification. Let us see, what are the various parameters?

Alpha is the angle at which diode starts conducting: beta, angle at which diode stops conducting. So, what is the conduction angle? It is beta minus alpha. All these angles, alpha and beta are measured with respect to the positive 0 crossing.

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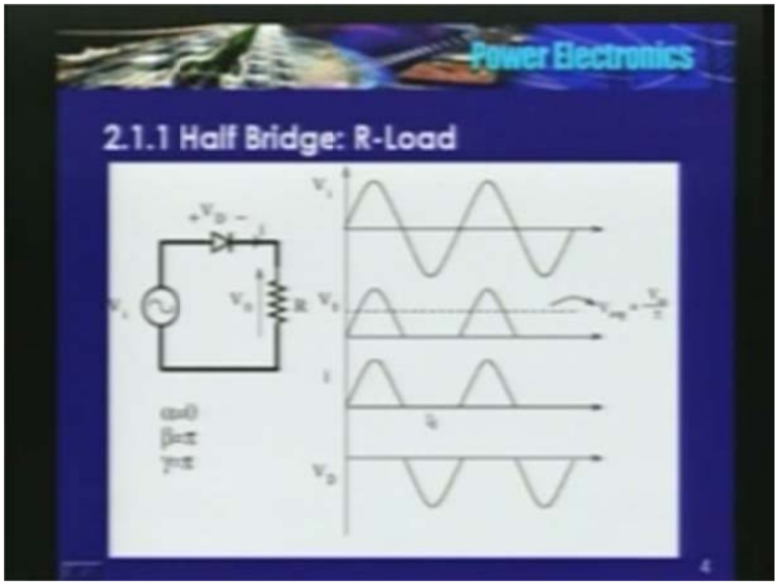

Half wave rectifier, there is only 1 diode connected in between the source and the load. We will consider first, load to be a purely resistance. Input is an ideal sin, here, a pure sin here. Device is ideal, so diode starts conducting at the positive 0 crossing. When the diode starts conducting, output voltage V_0 is same as the input voltage. Load is purely resistive: we know that current and voltage are in phase. KVL says, V_I is equal to I into R or Vm sin omega t is equal to I into R.

So current is also sinusoidal, reaches peak when omega t is equal to pi by 2. At omega t is equal to pi, voltage becomes 0, current also become 0, diode turns off. So, alpha is 0, beta is equal to pi radians, duration for which diode conducts in each cycle is pi radians. What happens in the negative half? There is no current flowing in the circuit. Current became 0 at pi, anode potential becomes negative, diode cannot conduct.

So in the entire half, diode is in blocking mode. So, input voltage comes across the diode. So, the entire voltage, the diode has to block or the voltage rating of the diode should be a minimum, should be Vm. So, if an input is 230 volts, the peak up, the input will be 230 into root 2. That is around 310 volts or so. So, when I have said 40 ampere, 600 volt diode, it means that it can carry 40 amperes and it can block 600 volts.

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In other words, peak reverse voltage that can be applied theoretically is of the order of 600 volts.

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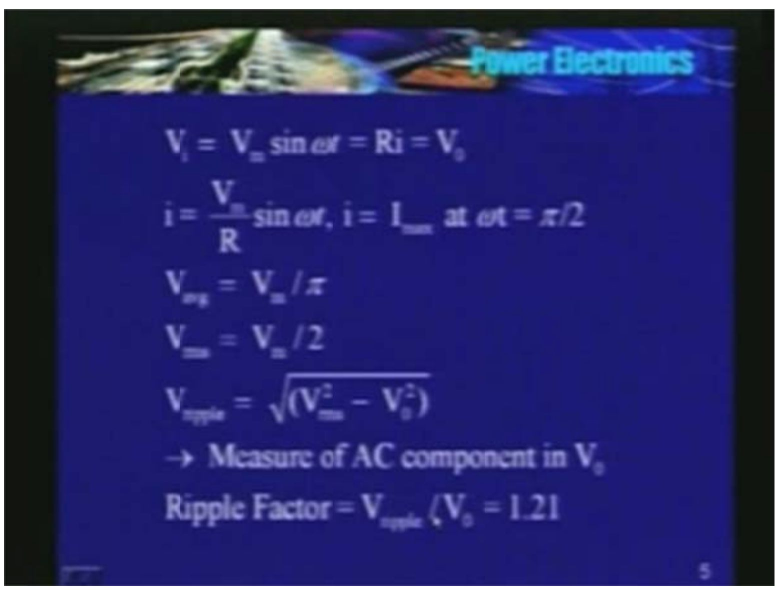

See, these are the various equations, simple equations that I have written. What is the average value of the output voltage? I said, AC to DC converter, output voltage has a finite DC value. The average value is given by V_m by pi. Output voltages are not a constant DC, it has, it is varying from, output voltage are varying from 0 to V_m and to 0, in 0 to pi radians and becomes continues to remain 0 till pi to 2 pi.

So average value, if I integrate it over the cycle, it comes to be V_m by pi. It also has other AC component. If I write a Fourier series of this, is a V_m function, so has an average component and other V_1 frequency components. So, what is the RMS value?

RMS value is V_m by 2. I said, output voltage is not a constant DC, it has an AC component. The measure of AC components in the output voltage, they are known as the ripple voltage, it is given by this expression. What is the ripple factor? Ripple factor is measure of the AC components in the output voltage to the DC value. It is as high as 1.21.

We have discussed about the resistive load. Now, we will replace the resistive load by a pure inductor. Input is a sinusoid, again diode starts conducting at the positive 0 crossing. When the diode starts conducting, the circuit equation is V_i is equal to V_0 that is equal to L di by dt. So, as the input voltages increases, current also will increase. Will it reach peak at omega t is equal to pi by 2, as in the case of resistive load? No, it will reach peak when the input voltage is 0 or it will reach its maximum when omega t is equal to pi.

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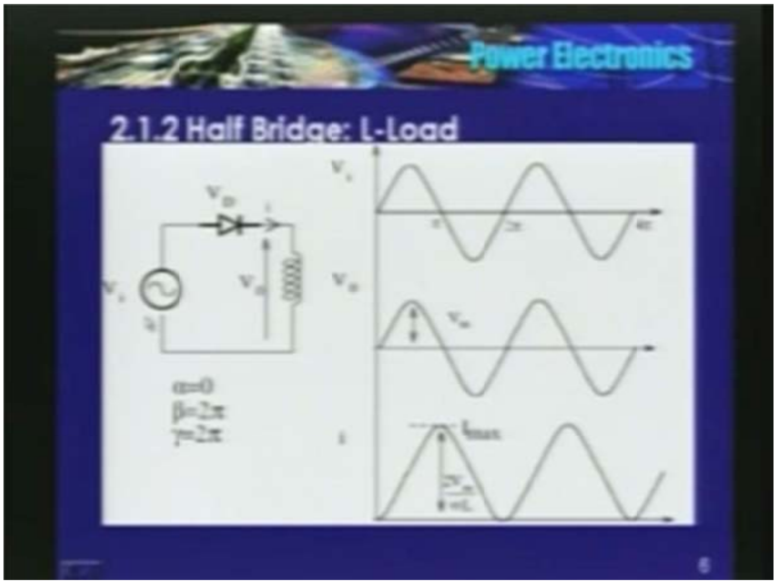

Why am I saying? See, 1 way to analyze the circuit is write a differential equation, solve it or second one is a, use a graphical approach. I will use a graphical approach. I said V_i is equal to L di by dt, instantaneous value of the input voltage becomes 0 at omega t is equal to pi, so, L di by dt also should be pi, sorry L di by dt is equal to 0 at omega t is equal to pi. So, L di by dt is equal to 0, it can happen only when di by dt is 0. So, either it could be positive or positive maximum or a negative maximum.

But then, we know that it started, current started increasing from 0. So, it will reach a peak. Current is in the, current can flow in the only in the positive direction, so therefore, current reaches peak at omega t is equal to pi. Because at this instant, voltage across inductor is also 0, input voltage is also 0. V_i is equal to L di by dt, that is equal to 0. So, from 0 to pi, di by dt is positive, so therefore, L di by dt is also positive. So, area under the curve from 0 to pi is the positive L di by dt.

We know that voltage, average value of the voltage across the inductor is 0. Current reached peak at omega t is equal to pi. From omega t is equal to pi plus, instantaneous value of the input voltage becomes negative. So, L di by dt also should be negative. So, current starts decreasing. Where will it become 0? 0 to pi, it was increasing, reached peak at omega t is equal to pi, so it will reach 0 at omega t is equal to 2 pi.

At that instant, V_i is equal to L di by dt is equal to 0. So, di by dt should be 0. Positive L di by dt should be equal to negative L di by dt. So, diode conducted for the entire 2 pi radians. Beta is 2 pi, therefore gamma is also 2 pi. Average value of the output voltage is 0. Diode conducted for 2 pi radians, but the average value of the output voltage is 0.

I have a question. How that diode started conducting beyond pi? because, input voltage becomes negative. A point to be noted that it is not the anode potential alone will decide the conducting state of that diode, it is the cathode potential also. If the cathode potential is less than the anode potential, diode has to conduct and diode will conduct.

So, what happens beyond pi? Input voltage may be becoming negative, but cathode potential which is also equal to L di by dt, current is also negative because di by dt is negative. So, this polarity as this terminal has become negative and this point has become positive. So therefore, diode continuous to conduct till the current becomes 0.

So remember, it is not the anode potential alone that will decide the conducting state of the diode, it is the cathode potential also. Here, because of the inductor, L di by dt becomes negative, L di by dt is negative because, di by dt is negative. So negative, positive: this is also negative may be, but this point is a bit more negative than this. A positive voltage or positive voltage of 1 volt also may appear across the diode as it keeps conducting.

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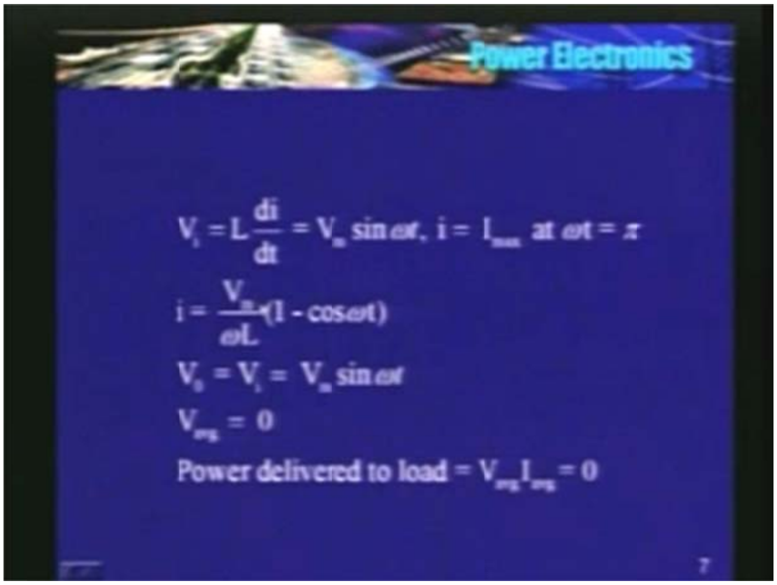

See, these are the various equations, i is equal to omega Vm, we have one minus cos omega t, V average is 0, power delivered to the load V average into I average is 0. Remember, diode conducted for 2 pi radians, average power is 0. In the previous case, diode conducted for pi radians, average power is finite, V average into I average. V average in the previous case is V_m by pi.

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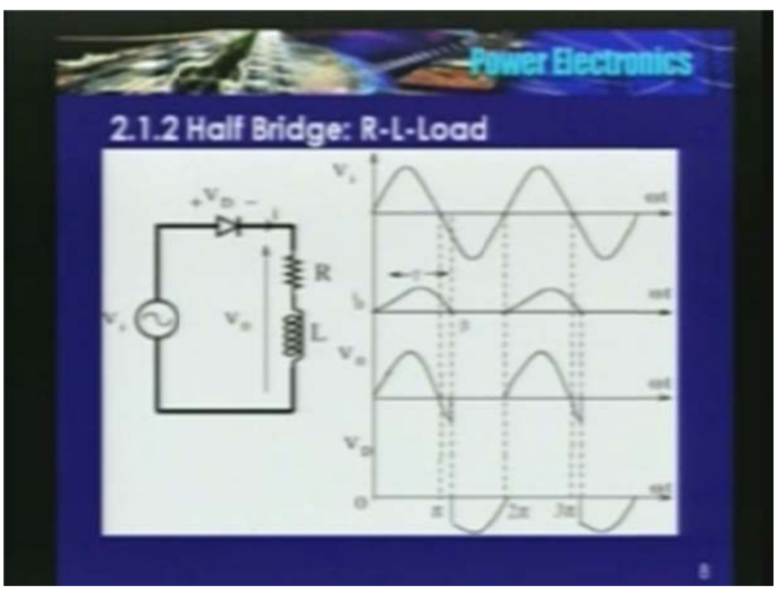

Third case, now we will add, we discussed R, we discussed L, now we will see RL. Again, diode starts conducting at the positive 0 crossing. When diode starts conducting, output voltage is equal to the input voltage and the circuit equation is R into I plus L di by dt is equal to V_i that is equal to V_m sin omega t. First order differential equation that has to be solved.

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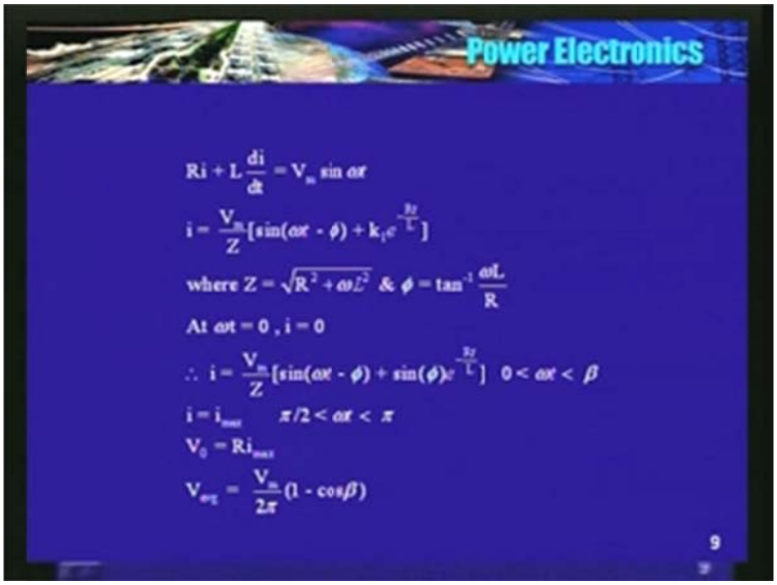

What is the general equation? Sorry, What is the general solution? Has a sinusoidal component and an exponential term. The … is given by this term, pi is sin inverse omega L by r. What are the initial conditions? When omega t is equal to 0, i is equal to 0. You solve it, this is the general, this is the solution for the current.

Load is purely resistive. It reach, current reach maximum at omega t is equal to pi by 2. Load is purely inductive, current reach maximum at omega t is equal to pi. So, if the load is RL, current will reach maximum somewhere in between pi by 2 to pi. Where it will reach maximum? It can be determined by solving the equation, the above equation. But, I know that when current is maximum, voltage across a conductor is 0. So at this instant, the value of the input voltage is I_{max} into R. Is that okay?

When current is maximum, the instantaneous value of the input voltage is I_{max} into R. So, this point, this magnitude could be or is I_{max} into R. Beyond that, current becomes, current starts decreasing. But then, current is always positive, it is flowing in this direction only, current cannot reverse, this is a positive direction of current. So, I into R is always positive. L dr by dt, now dr by dt has become negative. So, this point becomes negative, this point has become positive. Current starts decreasing at omega t is equal to pi, instantaneous value of the input voltage is 0. But then, current is still flowing in the load. So, I into R, L dr by dt should be zero, KVL has to hold good.

Beyond pi, input voltage becomes negative and since there is an inductor in the load circuit and current is decreasing, this current continues to flow beyond pi, that is because, L dr by dt has become negative. Cathode potential is less than the anode potential, if I assume the direct to be a non ideal. If it is an ideal, cathode potential is equal to the anode potential or non ideal diode is, difference could be of order of 1 volt. So, current continues to flow till it becomes 0.

Till a current becomes 0, input voltage is equal to the load voltage or $V_{0.}$ V_i is equal to V_0 till i becomes 0. So, once the diode turns off, the entire input voltage appears across the diode. So, this is the diode wave form, voltage wave form till it starts conducting again in the next …
What is the average value of the output voltage? You need to find out, you have to integrate it. It is given by V_m by 2 pi into 1 minus cos beta.

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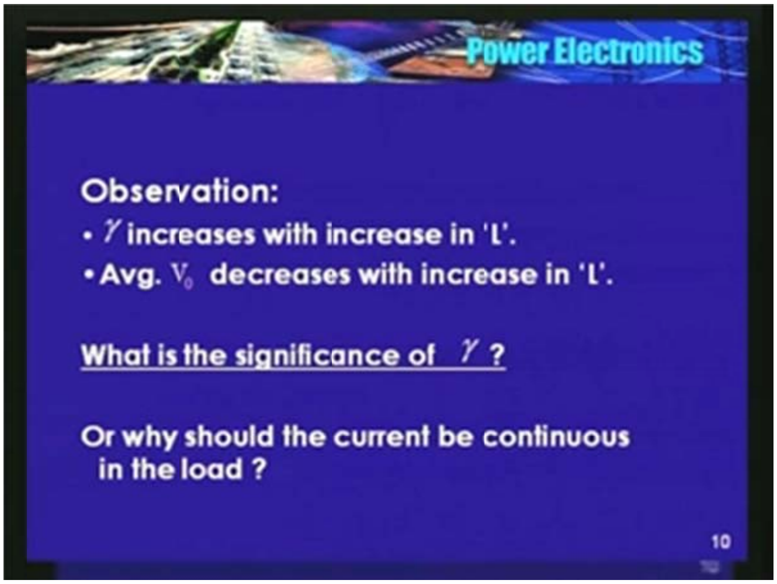

What are the observations? We found that when gamma for a purely resistive load, diode conducts for pi by 2 radians. Sorry, diode conducts for pi radians. When the load is purely inductive, diode conducts for 2 pi radians and for a RL load, diode conducts for durations greater than pi. So, gamma increases with an increase in L. But then, average value of the output voltage decreases with L. Why? Because beyond pi, we are applying a negative voltage to the load.

That is why, average value of the output voltage decreases with increase in gamma beyond pi. What is the significance of gamma? Why the load current should be continuous or why there should be a finite current in the load? What happens?

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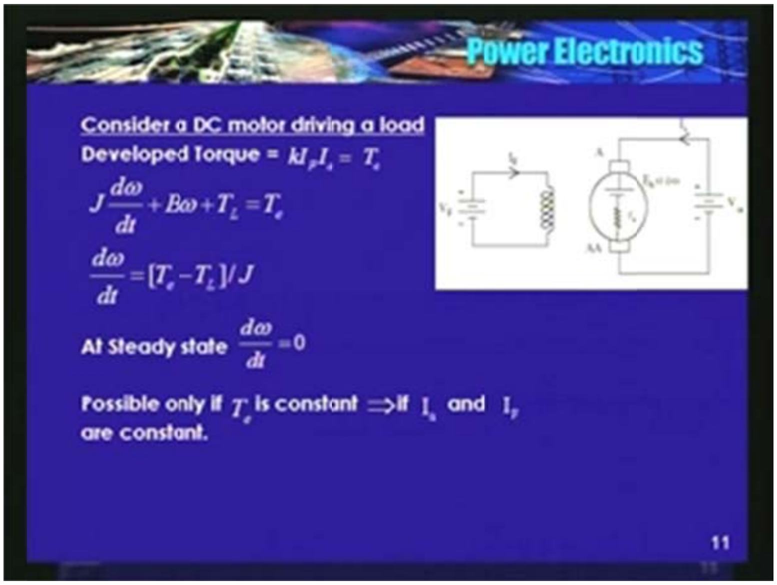

Consider a simple case, I have a DC motor, torque equation is K into phi into I_A and the equation is J d omega by dt plus B omega plus T_L is equal to $T_{e.}$ T_e is the torque developed by the motor, load torque, frictional torque, J is the moment of inertia. So if I neglect the frictional torque, d omega by dt is equal to T_E minus T_L added by J.

So at a steady state, d omega by dt is 0. It possible only if T_e is constant, in other words, if T_e varies with time, d omega by dt also will vary. When T_e will vary with time? Either I_F or I_A or both, if they pulsate, T_e will also pulsate. So, in order to have a constant $T_{e,}$ we should have a constant value of I_F and constant value of $I_{A.}$ So, it is always desirable to have finite $I_{A,}$ if not a constant $I_{A.}$

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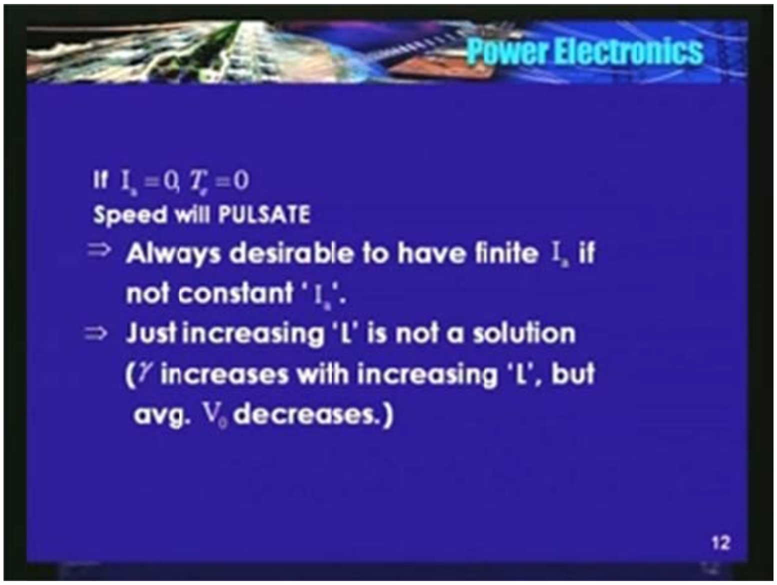

Just by increasing L, we found that gamma may be increasing but then, load voltage, the average value of the output voltage decreases. So just by increasing L, may not be a solution for these circuits. What next? Is there a way out? I think so, there is a way out. What is that?

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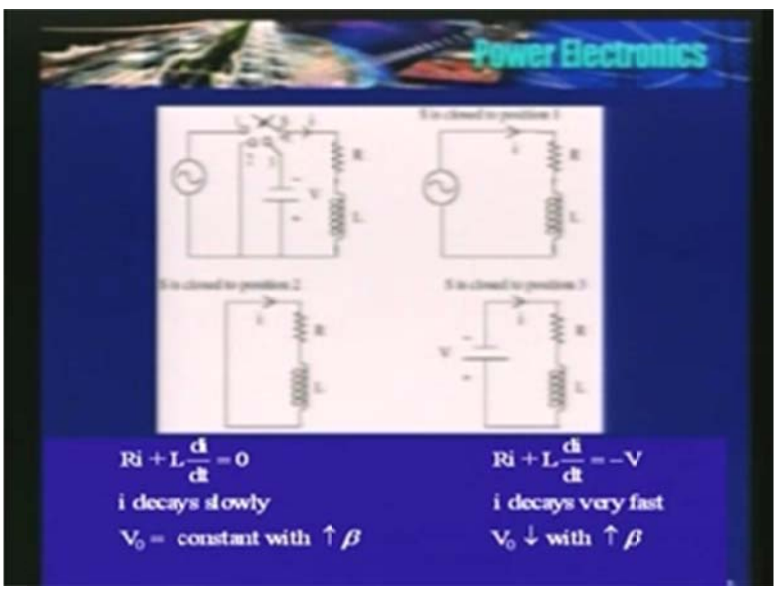

Consider the circuit, a switch, there are switch that can be close to 1, 2 or 3. Initially I will close it to switch 1. What is the circuit equation? This is the circuit equation, R into i plus L di by dt is equal to V. We have studied this circuit. After sometime I would like to open the switch, either I will close it to 2 or I will close it to 3.

What happens if I close it to 2? Voltage applied to the load is 0. So, current decays in this fashion. The circuit equation is Ri plus L di by dt is equal to zero, forcing function is 0, current decays slowly. Whereas, in the second case, forcing function is negative. So, current decays fast. So, by applying a 0 voltage to the load, I have achieved 2 things. Current decays slowly, so in other words, beta increases. But then, I am not applying a negative voltage to the load unlike in this case. So, my average voltage remains constant even though my beta is increasing. Whereas here, since I am applying a negative voltage to the load, current decays faster plus the average voltage comes down.

So therefore, it is possible to increase beta, also increase $V_{0.}$ At what cost? Of course, nothing comes for free. If you are ready to spend something, you will get a, there will be solution for every problem that you have created. That is a law of nature. …

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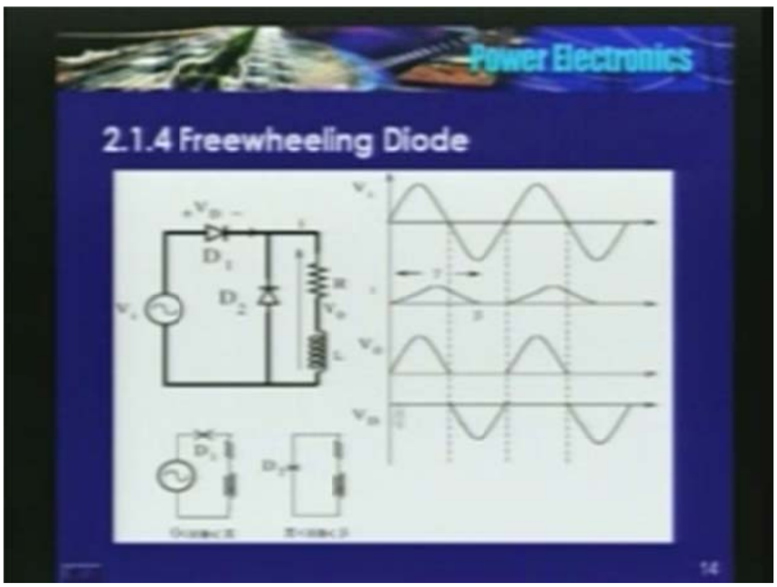

Consider a case, in the previous case, there was only 1 diode, I am connecting another diode across the load. Positive half, only D_1 can conduct, D_2 cannot conduct in the positive half. So in the positive half, D_2 is blocking or D_2 is off, D_1 is conducting. We have this equivalent circuit, input voltage, diode D_1 R into IR and L. Same way, from current increases which is a peak somewhere in between pi by 2 and pi and starts decreasing. At omega t is equal to pi plus, this potential becomes higher than this potential, becomes negative.

So, if D_1 conducts, a positive voltage appears across D_2 which is not possible. So therefore, D_1 turns off, D_2 starts conducting. When D_2 starts conducting, this point gets connected to the cathode of $D_{1.}$ So, negative voltage is appearing across $D_{1.}$ So, diode D_1 turns off or diode D_1 cannot conduct. So, our assumption of, assumption of saying that D_2 conducting in the negative half is proved.

So beyond pi, till the current becomes 0, D_2 conducts. But, I told you that when the D_2 conducts, voltage applied to the load becomes 0. So, rate of decay of current or rate of decrease of the current that is flowing to the load also reduces, current slowly reduces. So, average value is same as that of a purely resistive load: in the sense, output voltage is equal to input voltage till omega t is equal to pi and beyond pi, it is 0.

So, average value is same as that of a purely resistive load. Beta is also increased now. Here the decay is very slow, it depends on the time constant and in the negative half the entire input voltage appears across $D_{1.}$ So, voltage rating of both these diodes is same as the peak of the input. So, D_1 blocks in the negative peak and D_2 blocks in the positive peak. So, this D_2 diode is also known as the freewheeling diode. It provides a path for the current to flow when D_1 is off. Load is freewheeling through $D_{2.}$

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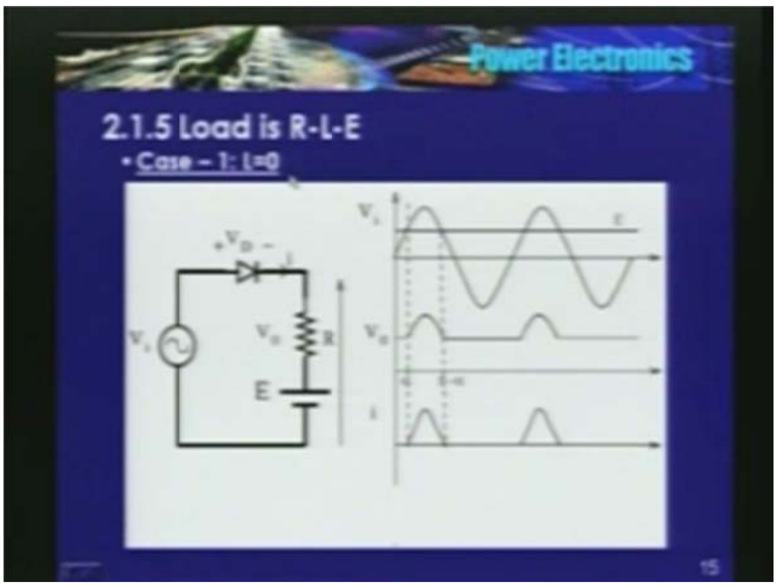

Now let us see, let us discuss about RLE load. The limit in case, L is 0. So, we have R and E. Can the diode start conducting at the positive 0 crossing? No, now we need to know, what exactly is there in the load circuit? If the load is active, we need to know the load parameters. If the load is passive and if the current is discontinuous, we do not need to know, because diode starts conducting at the positive 0 crossing. Now, even if there is no current here, cathode potential is E with respect to this point.

So no current, same potential: this point and this point are the same potential. So, E is the potential with respect to E of the cathode potential with respect to the ground and anode potential is $V_{i.}$ So, diode starts conducting when the instantaneous value of the input voltage is E and once the diode starts conducting, the circuit equation is V_i is equal to R into I plus E or I is equal to V_i minus E divided by R, purely resistive circuit, so these are the equations.

When diode is on, output voltage, when the diode is on, V_i is equal to V_0 and when diode is off, V_0 is equal to E. So, from 0 to alpha, diode was not conducting, output voltage was $V_{0,}$ diode starts conducting at alpha, V_i becomes equal to E again at pi minus alpha. So, diode turns off at this point. Once the diode turns off, till it starts conducting again, V_0 is equal to E. This is the voltage across, V minus C is the voltage across R. So, current is V minus C divided by R. This is the sinusoid, reaches a peak at omega t is equal to pi by 2. These are the various equations.

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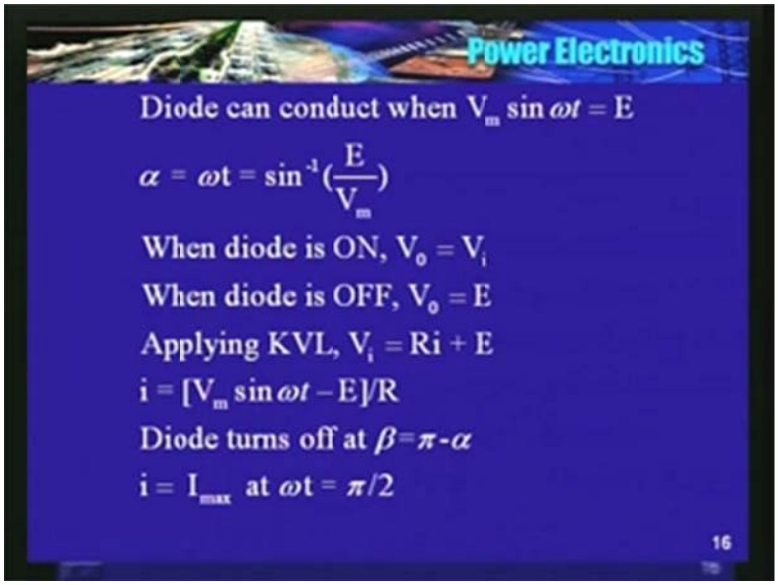

Now second case, now we will make R is equal to 0. We have a diode, inductor and a battery. Same, as in the case of RE load, diode starts conducting when instantaneous value of the input voltage is equal to E, because anode potential is Vi, cathode potential is E.

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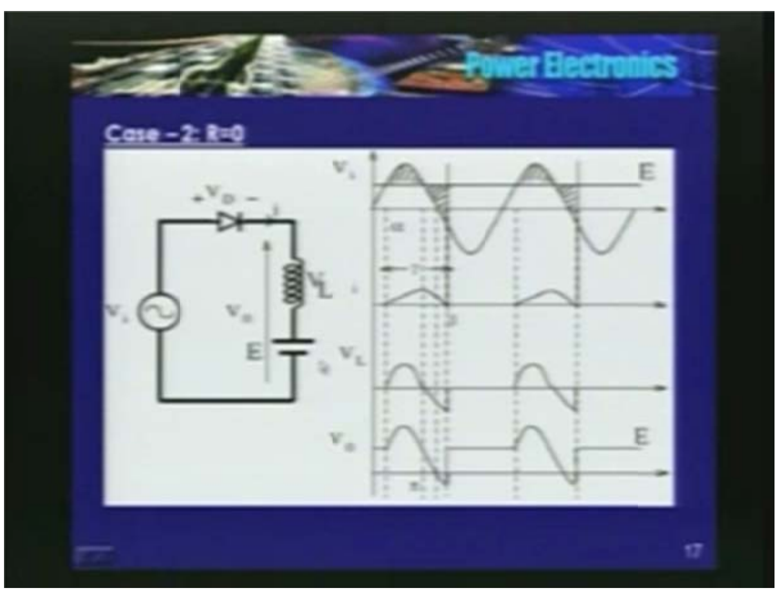

So, anode voltage should be higher than or equal to E for the diode to conduct. Once the diode starts conducting, the circuit equation is a L dr by dt plus E is equal to $V_{i.}$ So, when diode starts conducting, when the diode is on, output voltage V_0 is same as $V_{i.}$ So, difference of input voltage and the battery voltage appears across L and beyond alpha, this voltage is increasing. So therefore, current also starts increasing. Where will it reach peak? Will it reach maximum when omega t is equal to pi to 2, as in the case of resistor? Of course, 1 way to, 1 way to write a differential equation is to solve it. But, if I use a graphical approach, I can say that current will reach maximum when V_i is equal to E at omega t is equal to pi minus alpha, because at this instant V_i is equal to E. So therefore, L dr by dt is equal to zero, in other words, i is equal to Imax.

So, current started reaching started from 0, reached a peak at omega t is equal to pi minus alpha and from there onwards, it starts decreasing. Where will it become zero? Again, it depends on E and L. It can be determined by solving the differential equation. But, I know that average value of the voltage across inductor is 0. So, this is positive L dr by dt. So, current become 0 at that instant or this area should be equal to this area at that instant, current becomes 0.

So, current continues to flow beyond pi minus alpha till negative L dr by dt is equal to positive L dr by dt. So that is the very basic concept, average voltage across inductor should be 0. So, diode turns off at beta. In this case, I have shown that diode continues to conduct beyond pi, it need not be, it can happen anywhere beyond pi minus alpha. So, till the diode is on, output voltage is equal to the input voltage, load has no role to play.

Remember, when the diode is conducting, input voltage and the output voltage are same. It is only when there is no current and if the load is active, in other words, if there is a battery there, we need to know the value of the battery voltage or output voltage is equal to the value of E when the diode is not conducting.

It was not conducting from 0 to alpha and it stops conducting from beta to again 2 pi plus alpha. In this region, $V_{i,}$ this is the input wave side. So, this is positive L dr by dt and this is negative L dr by dt. These are the various equations that I have written.

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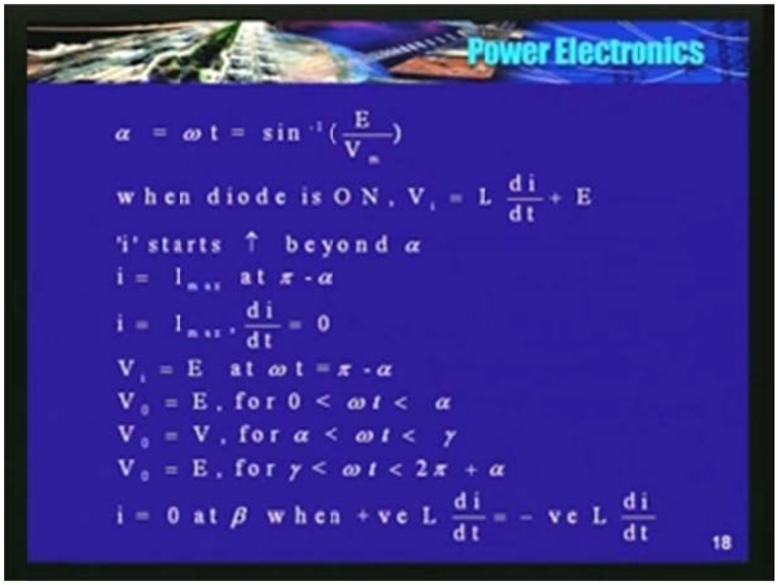

E V_i is equal to E at omega t is equal to pi minus alpha, V_0 is equal to E for 0 to, for omega t in between 0 to alpha. These are the various equations. i is equal to I_0 at beta, when positive L dr by dt is equal to negative L dr by dt.

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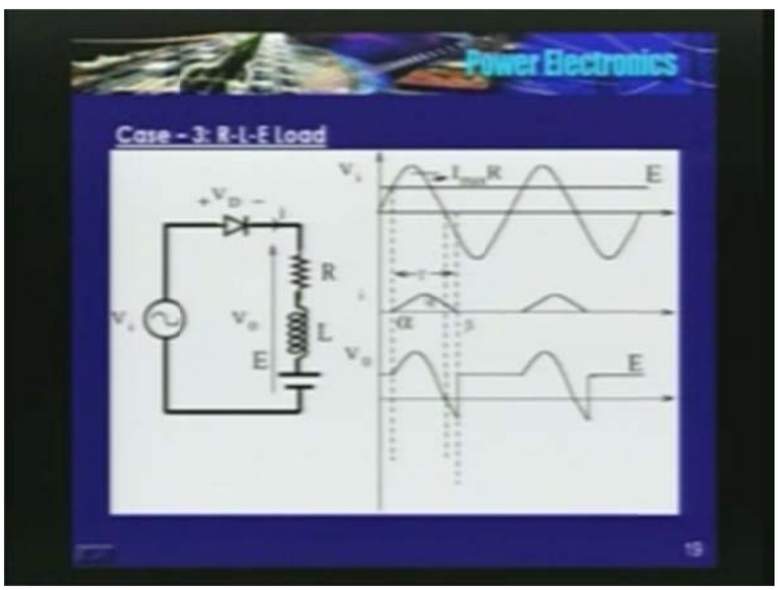

Now, what happens if I put a small resistor RLE? When the load is purely resistive, we found that current reaches maximum at at omega t is equal to pi by 2. Of course it starts, both the cases it started conducting at alpha where alpha is sin inverse E divided by V_m.

In the case of LE load, sorry in the case of EL load ,current reach maximum and current reach peak at omega t is equal to pi minus alpha. So therefore, for RLE load, current will reach peak somewhere in between pi by 2 and pi minus alpha. It reaches peak here, current starts decreasing and it becomes 0 when … somewhere in between ... it becomes 0. It all depends on R L and E. It is a bit difficult to determine now, because there is R is also present. So, till diode is conducting, V_i is equal to $V_{0,}$ when diode is off, V_0 is equal to E.

So, if the load is highly inductive and has a very small battery voltage, beta may be high. Because, if E is low, as E reduces, alpha reduces, because alpha is sin inverse E divided by $V_{m.}$ As alpha reduces, the time available for the current to increase also increases. I mean, because current reaches peak somewhere in between pi by 2 to pi minus alpha. As alpha reduces, time for the current to increase also increases and if I have a substantial value of L wherein, current cannot change instantaneously and if I have a low value of E, this beta can be increased.

But then, beyond pi, we have a same situation, a negative voltage appearing across the load. So, the moment the negative voltage appears across the load, average voltage, average value of the voltage applied to the load also decreases plus current decays at a faster rate. Somehow, I need to stop this. What will I do? I will connect a freewheeling diode across the load.

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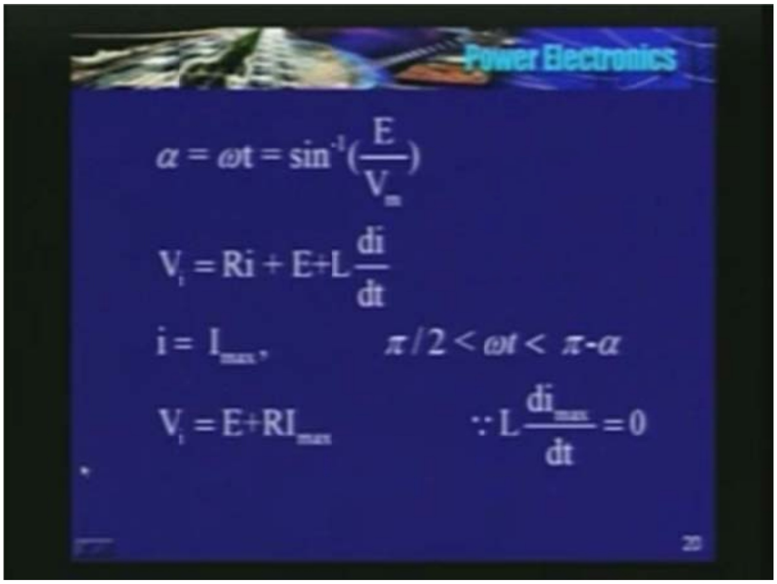

I have connected a freewheeling diode across the load. Till pi, the behavior of the circuit is same as before, no change.

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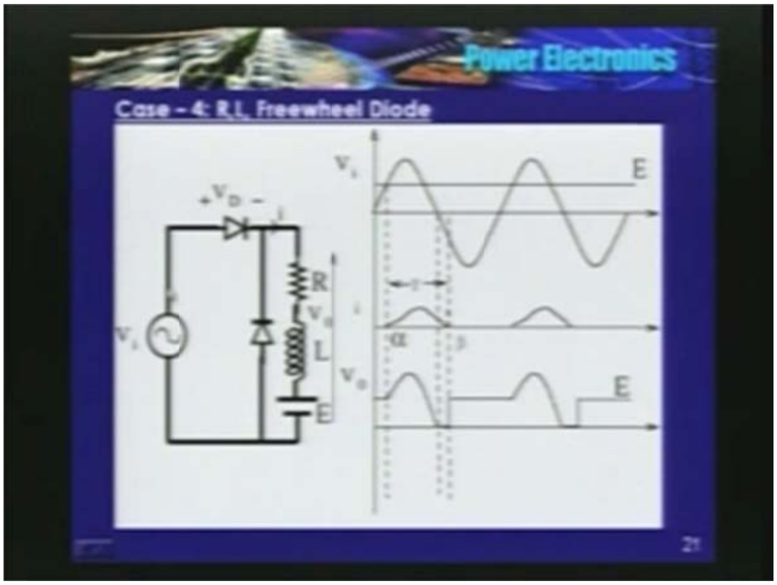

The wave forms also, no change from 0 to alpha, it is the input, from 0 to alpha, it is E because no current. So, V_0 is equal to E. From alpha to pi, assuming that there is some current flowing in the circuit, V_i is equal to V_0, in other words, V_0 is equal to V_i. At omega t is equal to pi plus, the freewheeling diode starts conducting. So, voltage applied to the load is 0, diode turns off. So, it does not supply power to the load. But then, since there is an inductor, the stored energy in the inductor continuous or stored energy in the inductor ensures the current to flow in the load beyond pi.

So at beta, current becomes 0. Once the current becomes 0, voltage applied to the load becomes E. So, difference is only from pi to beta, pi to beta, voltage applied to the load is 0. See, all this circuits can be analyzed by writing differential equation for various modes and solving them. I am not using that approach. You are free to do that, rather I would encourage you to write those equations and solve numerically. So, this is what it is. i starts flowing …

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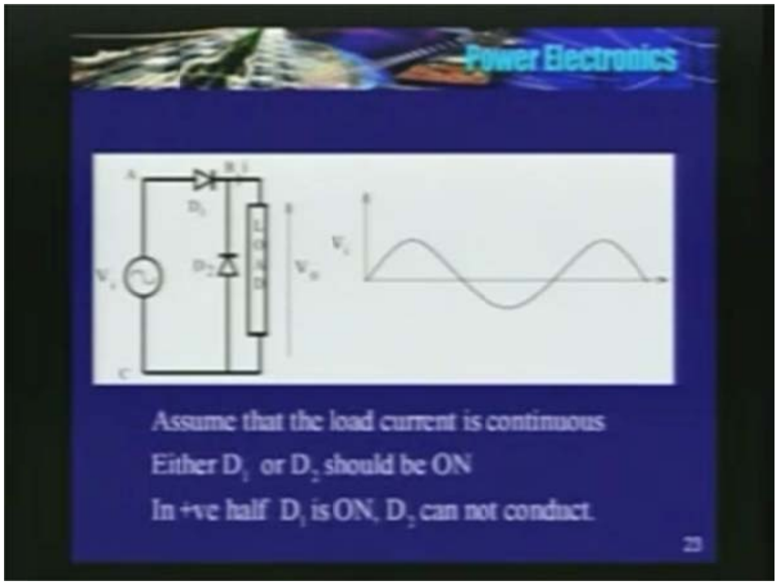

Now, consider a case, assume that load current is continuous. Do not ask me what sort of a load. It could be anything. It could be anything, I mean, it can be LE type or whatever, do not bother. I may have a battery or may not have a battery. Only thing is current is continuous. So, if the current is continuous, either D_1 should be on or D_2 should be on, at any given time. In the positive half, we already proved that D_1 conducts and in a negative half, D_2 conducts. So, at any given time, one of the diode is on: in the positive half, $D_1$is on and in the negative half, D_2 is on.

So, when D_1 starts conducting? D_1 starts conducting when omega t is equal to 0 or at the positive 0 crossing, diode starts conducting. So therefore, if the load is continuous or load current is continuous, diode starts conducting at the positive 0 crossing. Diode starts conducting at the positive 0 crossing and D_2 starts conducting at the negative 0 crossing. So, even if I have a battery in the load and if the current is continuous, it does not matter. D_1 starts conducting in the positive 0 crossing, remember, even if I have an E here, that is because of L di by dt. Because, once the current has reached the peak, in a RLE type of load we found that current reaches peak between pi by 2 to pi minus alpha and beyond that current starts decreasing.

So, L di by dt becomes negative. That will ensure the current to flow. So therefore, even if I have a battery here and if the current is continuous, diode starts conducting at the positive 0 crossing. Please do not say that you have a battery in the load, so that is why cannot conduct till alpha. That is true only when, only when current is discontinuous. If the current is discontinuous, we found that cathode potential of the diode is at E. So, anode potential should be higher than or equal to E for the diode to conduct. That is why it starts conducting at alpha which is equal to sin inverse E divided by $V_{m.}$

So, if the current is continuous, D_1 starts conducting at the positive 0 crossing, an important concept to be remembered. So, these are the proof, so here is the proof.

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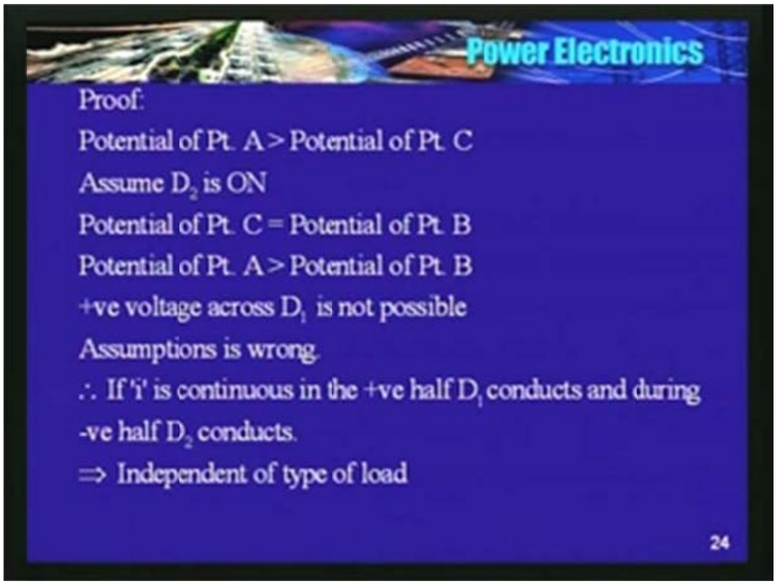

So, potential of A is potential of C in the positive half. I am assuming D_2 is on. If D_2 is on, so, what is, when D_2 is on, Potential of B is equal to potential of C. So, in the positive half, if this occurs in the positive half, a positive voltage appears across D_1. Because in a positive half, potential of A is higher than C and if D_2 conducts, this potential gets connected to B. A positive voltage appears across D_1. So, D_2 cannot conduct in the positive half. So again I will repeat, if i is continuous in the positive half, D_1 conducts and negative half, D_2 conducts, independent of type of load.

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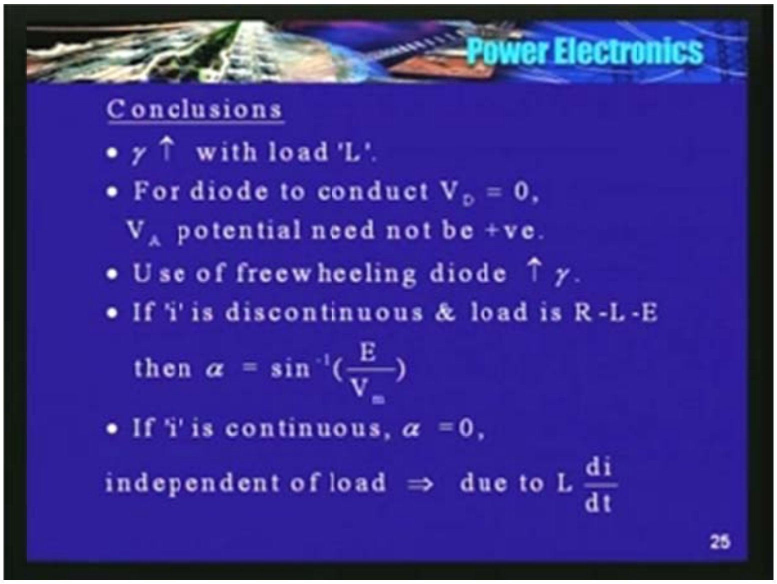

So, what are the conclusions? First 1 is the conduction angle or the duration for which diode conducts increases with load inductance. Second is for the diode to conduct, voltage across the diode should be 0. It is not only the anode potential alone will decide the conducting state of the diode, it is also the cathode potential, it is also the cathode potential will determine whether that diode can conduct or not.

Use of freewheeling diode increases gamma. Why it increases? because, it applies a 0 voltage to the load. It applies 0 voltage to the load, so therefore, decay process also, current decay process also, decay, the rate of decay also reduces. But then, voltage applied to the load is 0. If there was no freewheeling diode, the voltage applied to the load beyond pi is negative, average value comes down, decay process also faster.

So, we are achieving 2 things at the cost of 1 diode. So, next point is if the current is discontinuous and if the load is RLE, the instant at which diodes starts conducting is given by sin inverse E divided by V_m and if the current is continuous, alpha is 0. It is independent of flow. It is because of L di by dt. These are the important concepts to be remembered.

If I know the behavior of LC with sinusoidal excitation, the study of power electronics is very simple. I would encourage you to use a graphical approach rather than the analytical approach. Writing a differential equation, solving it, anyone can do. If you try to use a graphical approach, it will give a better insight rather than writing a differential equation.

So, what did you do in the entire class? We just used a simple KVL and 1 equation, V_m sign omega t is equal to R into i plus L divided by dt plus E. That is the most complicated equation and I have, did not take any time in solving those equations. You can always solve that equation, I use a graphical approach. Somehow, I like it more and I encourage you to use this approach rather than solving it, solving using a differential equation.

Thank you.