Power Electronics

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Lecture - 15

In our last lecture we discussed the principle of operation of fully controlled bridge in which all the 4 switching elements are thyristors. We derived the expression for an average value of output voltage and it is given by 2 V_m by pi into cos alpha. This expression is valid if the current is continuous. I will repeat; this expression is valid only if the load current is continuous.

Let, we found that for alpha in between 0 to pi by 2, average value of the output voltage is positive, current is unidirectional. So, power supplied by the source to the load is positive. So, we call it as conversion, AC to DC converter and for alpha greater than pi by 2, we found that average value of the output voltage becomes negative, current is again unidirectional which is positive. So, power supplied by this source, by the source is negative.

In other words, source is absorbing power. Load is supplying power back to the source. So, we call this as inverter or inversion, power inversion. Average value of the output voltage can be negative for alpha greater than pi by 2, only if the load is of RLE type. It is possible only for RLE type of load.

Motor will act like a generator only if torque developed by it is negative. In other words, torque is given by K pi into I_A, either I_A has to reverse or e has to reverse, polarities of e should reverse. Only by changing or only by increasing alpha greater than pi by 2, machine will not act like a generator. So, for the machine to act like a generator I have to either interchange armature terminals or I have to interchange the field terminals.

Let me tell you 1 thing, convertor fed a DC machine reversing the armature terminals or field terminals using the mechanical contactors does not make a sense, because both are inductive circuits. Field circuit is highly inductive, even armature has a finite inductance. Using mechanical contactors I have to or to interchange the 2 terminals I have to use the mechanical contactors. So, momentarily we are breaking an inductive circuit.

So, what happens if I break an inductive circuit? Arching will take place. That is what I said, using mechanical contactors in a convertor fed machine, to for the machine to act like a generator, does not make much sense. So, is there a solution? Is there a way out? There is, we will see.

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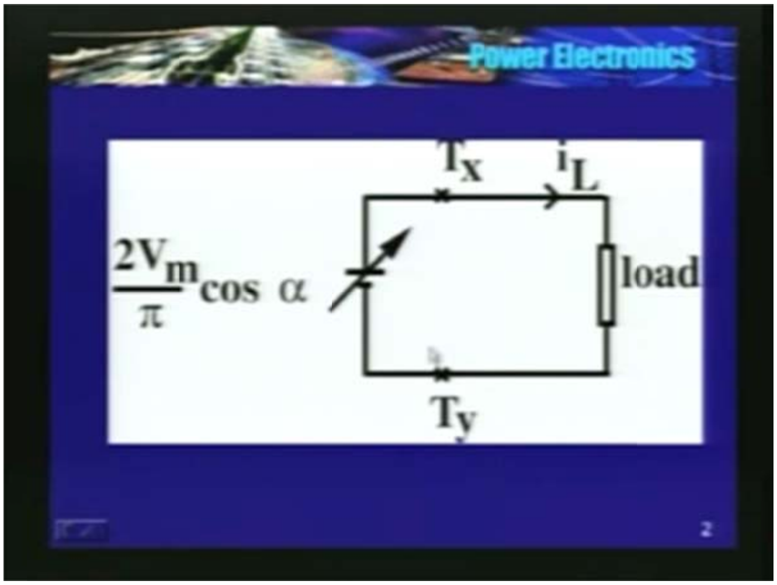

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Say, this is the equivalent circuit of the fully controlled bridge, 2 V_m by pi into cos alpha. So, magnitude of this voltage varies is a function of alpha. There are at any given time, 2 thyristors are conducting T_x and T_y, so either T_1, T_2 or T_3, T_4 and here is a load. So, applied voltage to the load is equal to the output voltage of the bridge minus 2 device drops, remember, 2 device drops.

So, if you assume that in the device, assume that the device are ideal that is average value of the output voltage applied to the load is 2 V_m by pi into cos alpha itself. Otherwise, it is this value minus twice or 2 device drops is the voltage applied to the load.

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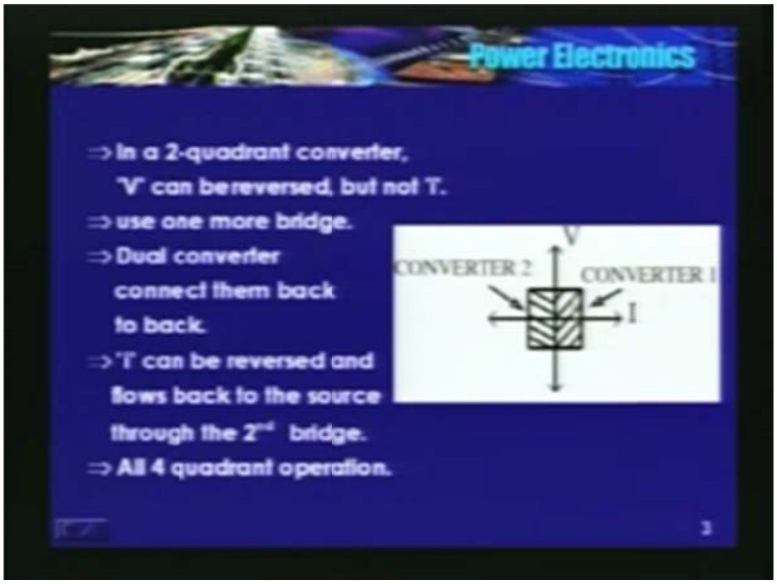

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- ⇒ In a 2-quadrant converter, 'V' can be reversed, but not 'I'.
- ⇒ use one more bridge.
- ⇒ Dual converter connect them back to back.
- ⇒ 'I' can be reversed and flows back to the source through the 2^{nd} bridge.
- ⇒ All 4 quadrant operation.

So, we use only 1 convertor, wherein, voltage is reversing but the current cannot reverse. So, we will use 1 more convertor connected back to back. In the sense, current can flow back to the source with the through the second convertor. So, there are 2 convertors, hence, the name dual convertor. So, if you see a convertor 1, voltage can be positive or negative, current is always positive. So, operation is in quadrant 1 or quadrant 4.

Now, I have connected another bridge in a reverse fashion, wherein, current can flow back to the source. Now, negative current corresponds to with respect to the bridge 1, the direction of current flowing in convertor 2 is in the opposite direction. So, voltage again can be positive or negative. So, operation is either in the quadrant 2 or in quadrant 3. So, in other words, using a dual convertor I can have all 4 quadrant operations, all 4 quadrant operation is possible.

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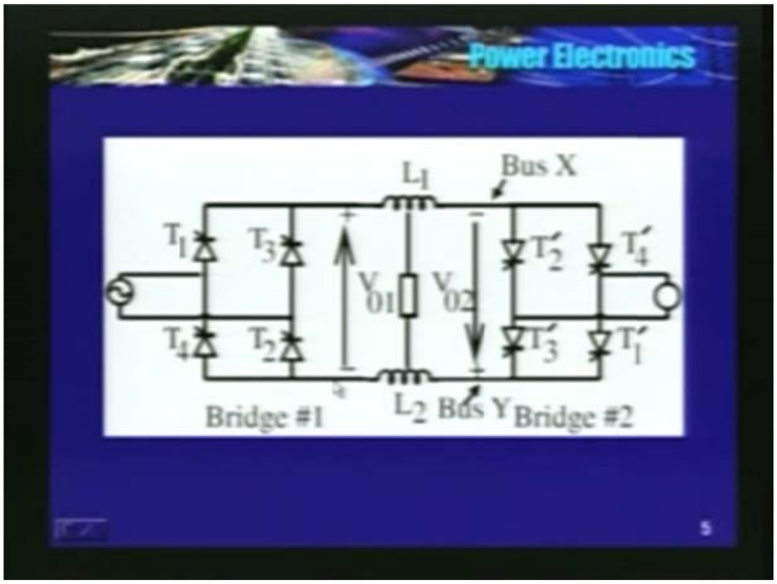

So, here is a circuit, power circuit; single phase bridge, T_1 to T_4. I have another bridge here, T_1 dash to T_4 dash, connected in the reverse fashion. 2 bridges are interconnected by 2 inductors and in the center I am connecting a load. The purpose of this inductor, I will tell you sometime later.

What is the principle of operation of this bridge? Assume that both the convertors are working and let alpha be the trigger angle or alpha$_1$ be the trigger angle for the bridge 1. Now, what is the relationship between alpha$_1$ and the trigger angle of the bridge 2? So, let it be alpha$_2$.

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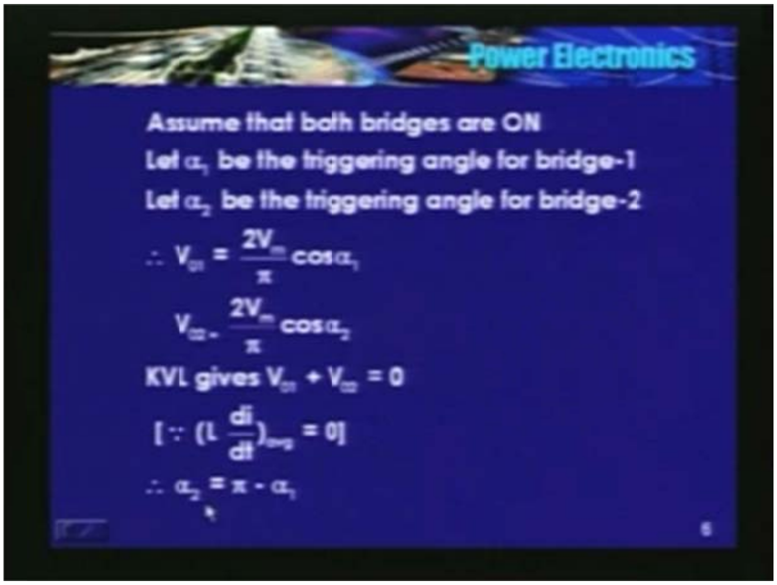

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Assume that both bridges are ON

Let α_1 be the triggering angle for bridge-1

Let α_2 be the triggering angle for bridge-2

$$\therefore V_{01} = \frac{2V_m}{\pi} \cos\alpha_1$$

$$V_{02} = \frac{2V_m}{\pi} \cos\alpha_2$$

KVL gives $V_{01} + V_{02} = 0$

$$[\because (L\frac{di}{dt})_{avg} = 0]$$

$$\therefore \alpha_2 = \pi - \alpha_1$$

We know if the current is continuous, average value of the output voltage of the bridge 1 is given by 2 V_m by pi into cos alpha$_1$. Similarly, for the second bridge it is 2 V_m by pi into cos alpha 2. Remember, both the bridges are being supplied by the same source. What does the KVL gives? Though there is an inductor, average value across this, average value of the voltage across inductor is 0.

So, I have taken V_{01} with respect to bus y, with respect to this $V_{01,}$ potential of this bus is V_{01} and see here, I have connected this region in a opposite direction, back to back. So, T_1 dash is here, T_1 is here, T_4 dash, T_3 dash and T_2 dash and output voltage of this bridge is V_{02} with respect to this bus X, so V_{02}.

So, the KVL gives V_{01} plus V_{02} should be 0 because voltage across this plus this is 0. So, it gives the relationship between alpha$_2$ and alpha$_1$ is this. The trigger angle for the bridge 2 is pi minus alpha$_{1.}$

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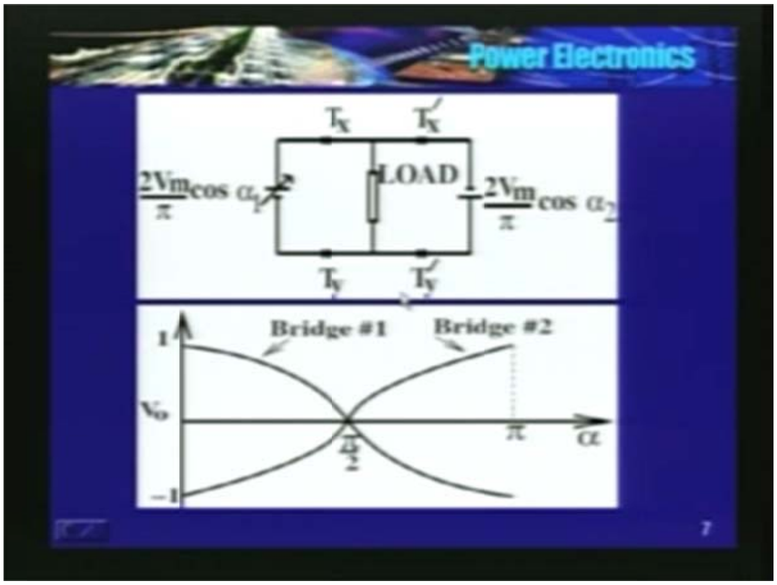

So, here is the equivalent circuit; 2 V_m by pi into cos alpha$_{1,}$ output voltage of the bridge 1, 2 device are conducting at a time. 2 V_m by pi into cos alpha 2 is the output voltage of the bridge 2, again 2 devices are conducting here. I have not shown the inductor, the load is connected in between. Now, if I plot the output voltage, average value of the output voltage with alpha$_1$ and alpha$_{2,}$ how do they look like?

For the bridge 1 it is given by this equation, 0 at pi by 2. This waveform you drew, you have already drawn for single phase fully controlled bridge. So, alpha$_1$ is 0, alpha$_2$ is pi. So, magnitude is the same, it is minus 1. So, I am calling V_m by pi is equal to 1 or 1 per unit. So similarly, therefore, V_m by pi minus V_m by pi is minus 1 per unit. At pi by 2, both are 0s and this is the variation. How does the …

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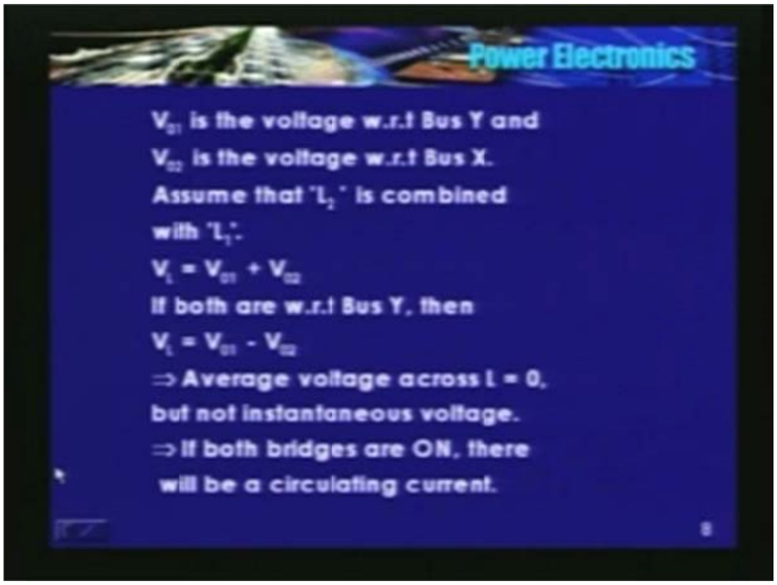

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V_{01} is the voltage w.r.t Bus Y and
V_{02} is the voltage w.r.t Bus X.
Assume that 'L_2' is combined
with 'L_1'.
$V_L = V_{01} + V_{02}$
If both are w.r.t Bus Y, then
$V_L = V_{01} - V_{02}$
⇒ Average voltage across L = 0,
but not instantaneous voltage.
⇒ If both bridges are ON, there
will be a circulating current.

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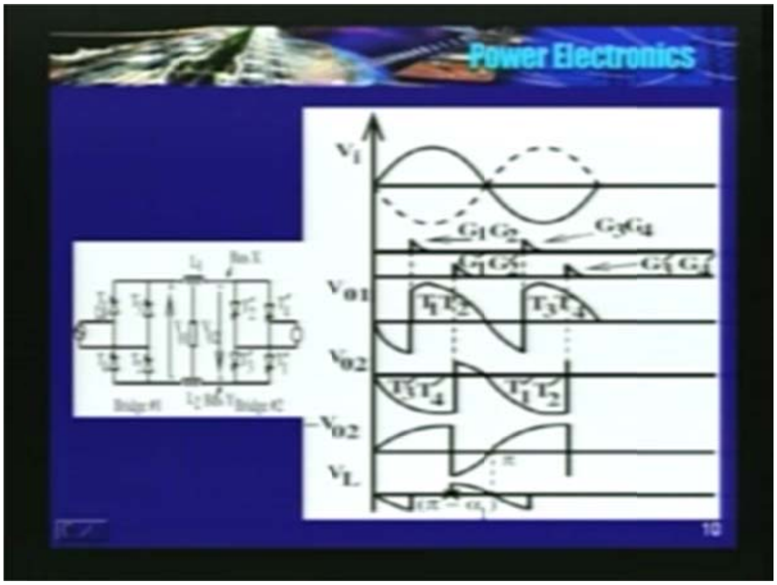

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Let us draw the waveforms, output waveforms. How do they look like? At alpha$_1$ which is less than pi by 2, G$_1$ and G$_2$ or T$_1$ and T 2 are triggered. G$_1$ and G$_2$ are the gates of T$_1$ and T$_2$ and at pi plus alpha$_1$, T$_3$ and T$_4$ are triggered for the bridge 1. At omega t is equal to alpha, alpha is a trigger, alpha$_1$ is a trigger angle for bridge 1 and alpha$_2$ is the trigger angle for bridge 2. So, G$_1$ and G$_2$ are triggered in the positive half at alpha and pi plus alpha$_1$, G$_3$ and G$_4$ or T$_3$ and T$_4$ are triggered.

So, how does the how does V$_{01}$ look like? So, till T$_1$ and T$_2$ are triggered, T$_3$ and T$_4$ were conducting, remember. Recall whatever, all these things we have studied. So, prior to T$_1$ and T$_2$,

T_3 and T_4 were conducting. So, output voltage is negative because from 0 to pi, V_{BA} is negative, this is V_{BA} and this is $V_{AB.}$ V_{BA} is negative, so V_{01} is negative.

At alpha$_{1,}$ T_1 and T_2 are triggered. Now, the output voltage is $V_{AB.}$ So instantaneously, there is a jump. Now, Output voltage is $V_{AB,}$ it will continue till pi plus alpha$_{1.}$ At that instant, T_3 and T_4 are triggered. This waveform we have already studied. How does V_{02} look like? Now, just reverse this bridge, in the sense, take this minus and plus, alpha$_2$ is the trigger angle for the bridge 2 and the relationship between alpha$_1$ and alpha$_2$ is alpha$_2$ is equal to pi minus alpha$_{1.}$

So, somewhere at this instant, G_1 dash and G_2 dash, the gates corresponds to T_1 dash and T_2 dash are triggered. Remember, in the positive half, T_1 and T_2 are triggered. Similarly, here I am triggering, similarly here, T_1 dash and T_2 dash are triggered in the positive half, somewhere here. So, till T_1 dash and T_2 dash are triggered, T_3 dash and T_4 dash were carrying current or they were conducting. So, output voltage is negative, T_3 $T_{4.}$

So, the moment T_1 dash and T_2 dash are triggered, output voltage which is again $V_{AB,}$ it is positive. So, average value, the magnitude of average value that is $V_{0,}$ magnitude of V_{01} is equal to magnitude of $V_{02,}$ if you find. Average value of V_{01} may be equal to average value of V_{02} and let us see what is the voltage waveform appearing across L_1 or what is the voltage waveform that comes across L_1.

Now, V_{01} is this. Now, I will reverse the polarities of V_{02}. Say this is $V_{02,}$ now minus V_{02} looks like this. Same waveform, I am inverting it. Same waveform has to be inverted. So now, with respect to the bus y or this bus, this is V_{01} and with respect to this bus, potential of this is minus $V_{02.}$ What do you observe from these 2 waveforms? I said, mod of V_{01} may be equal to mod of $V_{02.}$ But then instantaneous value of V_{01} is not equal to instantaneous value of $V_{02,}$ remember. Mod of V_{01} maybe equal to mod of V_{02} but then instantaneous value of V_{01} is not equal to the instantaneous value of $V_{02.}$

So therefore, there is a potential difference between the voltage across the ... So, there will be a current flowing from bridge 1 to bridge 2 or in other words, there is a circulating current, hence the name the circulating current type convertor. So, in a dual convertor, if both the convertors are carrying current simultaneously, they are known as circulating current type. If only 1 bridge is carrying current it is known as non circulating type because only 1 bridge is carrying current, only 1 bridge is supplying current to the load. Second bridge is completely off. So, no current can flow through the second bridge. Hence, the name non circulating type.

So, V_L is nothing but V_{01} minus of V_{02}, so here is this. You will find that average value of this waveform is 0. Now, let us see how a dual convertor can be used to control a DC motor? Now, this load will connect a DC machine here. Let us assume that machine is running stably at some constant speed, omega and corresponding $E_{B,}$ back EMF is of the order of 90 volts, let us assume. If back EMF is 90 volts, applied voltage, output voltage of the bridge should be higher than 90 volts only then the current will flow. In other words, output voltage of the bridge should be equal to I_a r_a plus $E_{B.}$

So, let us assume that V_{01}, the magnitude of V_{01} is equal to the magnitude of V_{02} is around 100 volts. The output voltage of the bridge is 100 volts, the magnitudes and E_B is of the order of 90 volts. So, let us assume that corresponding trigger angel for the bridge 1 is around 45 degrees. So therefore, $alpha_2$ is pi minus 45 is equal to 135.

So I will repeat; $alpha_1$ is 45, $alpha_2$ is 135, corresponding $V_{0,}$ magnitude of V_{01} is 100, magnitude of V_{02} is again 100 and E_B is 90, it is possible. Now, I want to feed the, you want to use the regenerative breaking and reverse the speed of operation. Initially, motor was running, as a machine was operating as a motor and was rotating in the clock wise direction. Torque is positive, speed is also positive.

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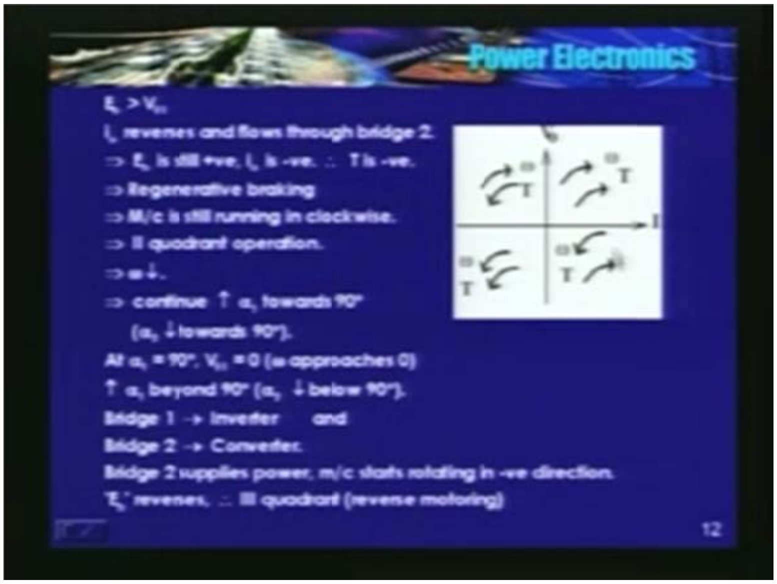

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$E_b > V_{01}$

I_a reverses and flows through bridge 2.

$\Rightarrow E_b$ is still +ve, I_a is -ve. ∴ T is -ve.

⇒ Regenerative braking

⇒ M/c is still running in clockwise.

⇒ II quadrant operation.

$\Rightarrow \omega \downarrow$.

$\Rightarrow$ continue $\uparrow \alpha_1$ towards 90°

($\alpha_2 \downarrow$ towards 90°).

At $\alpha_1 = 90°$, $V_{01} = 0$ (ω approaches 0)

$\uparrow \alpha_1$ beyond 90° ($\alpha_2 \downarrow$ below 90°).

Bridge 1 → Inverter and

Bridge 2 → Converter.

Bridge 2 supplies power, m/c starts rotating in -ve direction.

'E_b' reverses, ∴ III quadrant (reverse motoring)

Quadrant 1 operation, torque is positive, positive torque and direction of rotation, omega is again clock wise.

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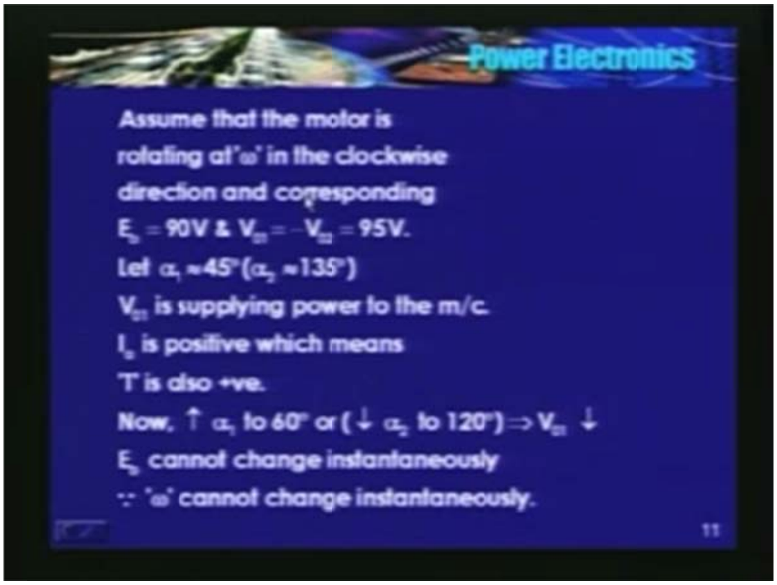

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Assume that the motor is rotating at 'ω' in the clockwise direction and corresponding $E_b = 90V$ & $V_{01} = -V_{02} = 95V$.

Let $\alpha_1 \approx 45^\circ$ ($\alpha_2 \approx 135^\circ$)

V_{01} is supplying power to the m/c.

I_a is positive which means T is also +ve.

Now, $\uparrow \alpha_1$ to 60° or ($\downarrow \alpha_2$ to 120°) $\Rightarrow V_{01} \downarrow$

E_b cannot change instantaneously

$\because$ 'ω' cannot change instantaneously.

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Now, what I will do is, increase alpha$_1$ towards 90 slowly.

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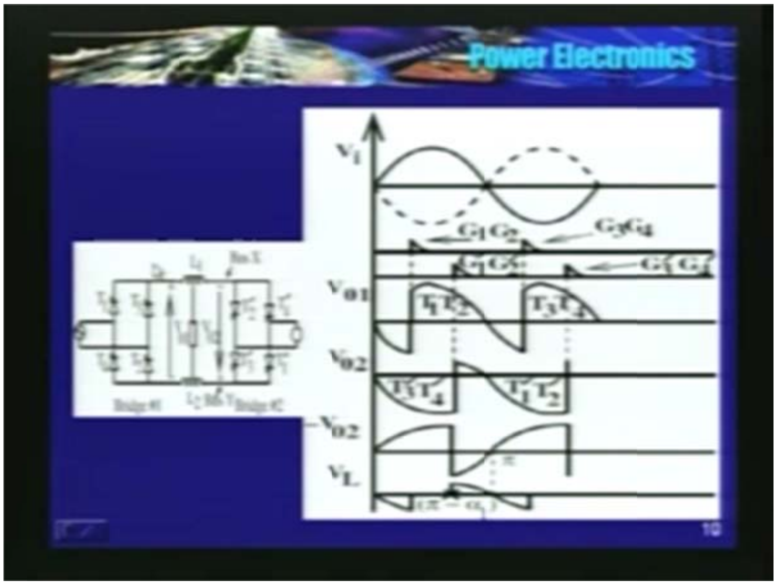

So, V_{01} becomes less than E_B. When I am increasing alpha$_1$ towards 90, simultaneously I have to do or I have to decrease alpha of alpha$_2$ of the bridge 2. So, I am increasing alpha$_1$ towards 90. Similarly, alpha$_2$ is decreased towards 90 of bridge 2. Now, you will find that V_{01} is less than E_B. So, if the terminal voltage is less than the back emf, now, current can the direction of current can reverse.

So now, initially, if the current was entering terminal A of armature, now it will leave the terminal A. How does it will flow? Now, it will flow through the bridge 2.

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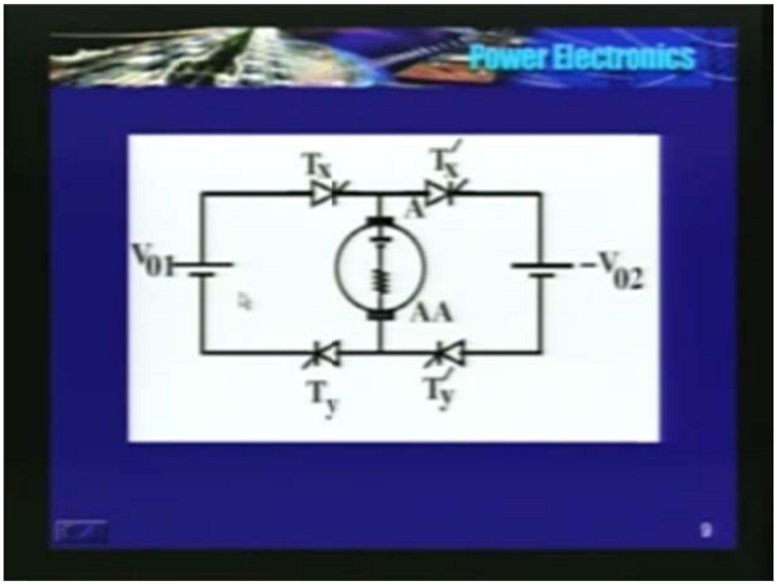

See, in this direction. Initially, the current was flowing in this fashion. Current was flowing in this direction, this was 100 volts, 90, E_B was 90. Magnitude of V_{02} is also 100. See, I have made it, now I will reverse the terminals here. Now, I have reduced V_{01} by increasing alpha$_1$ towards 90.

So, V_{01} has reduced or V_{01} is less than E_B. Now, current can leave this terminal. So, it can flow through T_X back to source. So, this is the path. If this operation is known as the motoring, this is the regenerating action or motor is acting like a generator, feeding energy back to the source. Machine is feeding power back to the source, there is no mechanical input, speed falls.

As the speed falls, I am also reducing V_{01} or in other words, alpha$_1$ is approaching towards 90 degrees, alpha$_2$ is also approaching towards 90 degrees. Speed is falling, assume that speed is approaching 0, at that time V_{01} has also approached 0 and V_{02} has also approached 0, corresponding alpha$_1$ is and alpha$_2$, both are approximately 90 degrees.

Now, continue to increase alpha$_1$ above 90, what will happen? This will, V_{01} will change polarities. Now, this will become minus, V_{02} will become plus. Now, initially quadrant 1 then we went to quadrant 2 operation because speed was, though it was falling, speed was still in the same direction. Direction of rotation is the same, still in the clockwise direction. Torque has reverse because initially current enter the polarity A sorry current will enter terminal A. Now, current is leaving terminal A, torque is negative. So, we are in the quadrant 2 operation.

Power is been feed back to the source through the second bridge. Current is flowing back to the source through the second bridge, regenerative breaking. So, omega falls, continuity increase towards 90 degrees. At alpha$_1$ is equal to 90, V$_1$ is also 0. Omega approaches 0, increase alpha$_1$ beyond 90 degrees, alpha$_2$ below 90 degrees.

Now, bridge 1 is acting like an inverter and bridge 2 is acting like a convertor. Now, bridge 2 supplies power to the machine. Now, machine starts rotating in the negative direction. So, quadrant 1, it is known as forward mortaring, quadrant 3 is known as the reverse mortaring. Direction of rotation is opposite.

Now, increase alpha alpha$_1$ towards 180 degrees, therefore, alpha$_2$ decreases towards 0. So, average value of the output voltage increases. Both the magnitudes are increasing. So, the speed is also increasing. At steady state, machine is running in the reverse direction at some omega. Now, if you want to do again regenerative breaking, follow the same steps. The operation goes to quadrant 4.

So, this is the principal of the operation of dual convertor fed DC motor. Enough of theory, now let see, let us solve 1 or 2 problem in convertor fed DC motor.

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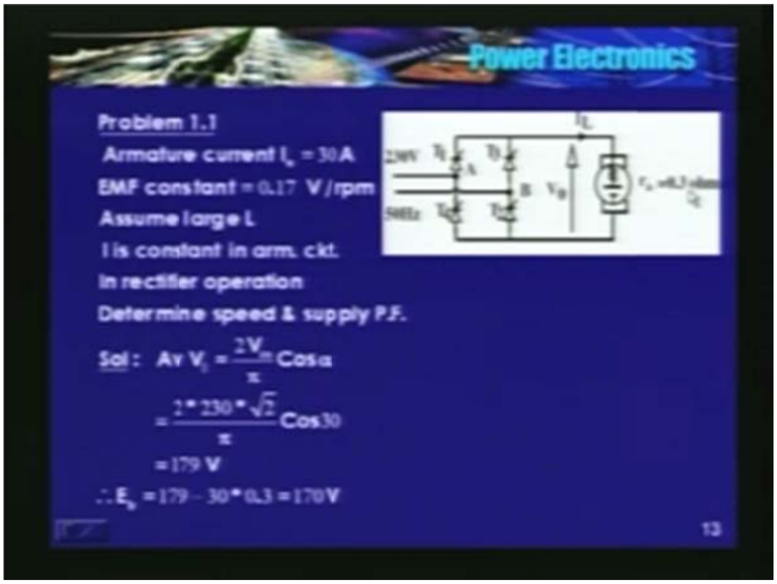

Problem 1.1

Armature current $I_a = 30$A

EMF constant = 0.17 V/rpm

Assume large L

I is constant in arm. ckt.

In rectifier operation

Determine speed & supply P.F.

Sol: $\text{Av } V_0 = \frac{2V_m}{\pi} \text{Cos}\alpha$

$= \frac{2 * 230 * \sqrt{2}}{\pi} \text{Cos}30$

$= 179$ V

$\therefore E_b = 179 - 30 * 0.3 = 170$V

A very simple problem; a fully controlled bridge supplying power to a DC machine, R$_A$ is of the order of 0.3 ohms, EMF constant is of the order of 0.17 volts per rpm. Problem says that assume a large inductor is connected in armature circuit. So, the moment you see this sentence, you need to assume that the armature current is continuous. Determine speed and supply power factor. Alpha is alpha to the bridge 1 is or trigger angel is maintained at 30 degrees.

What is the average value of the output voltage? Since, the current is continuous, it is 2 V$_m$ by pi into cos alpha. I am saying that current is continuous because a large inductor in connected in the armature circuit. So, you can safely assume that current is continuous. So therefore, an average value for alpha is equal to 30 degrees is found to be is 179 volts. So, V minus I$_a$ r$_a$ is equal to E.

So, E_B is of the order of 170 volts. Armature current is 30 amperes, it is given. It is constant and you can assume that I_A is constant and repel free.

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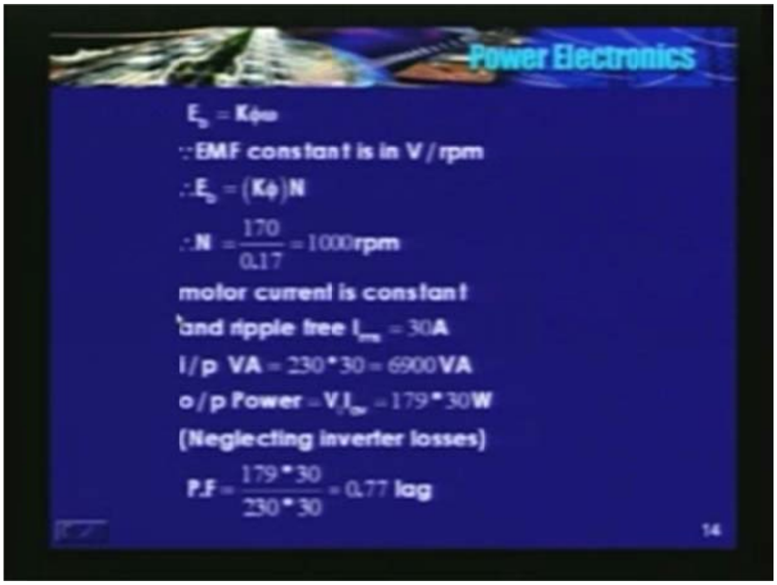

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$E_b = K\phi\omega$

$\because$ EMF constant is in V/rpm

$\therefore E_b = (K\phi)N$

$\therefore N = \frac{170}{0.17} = 1000$ rpm

motor current is constant

and ripple free $I_{rms} = 30A$

I/p VA = 230*30 = 6900VA

o/p Power = $V_0 I_{av}$ = 179*30W

(Neglecting inverter losses)

$P.F = \frac{179*30}{230*30} = 0.77$ lag

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Now, how do I determine the speed? EMF constant is given. EMF constant is volts per rpm. The magnitude of E_B is known. So, I can calculate speed because volts per rpm into rpm is volts. So, E_B divided by EMF constant will give you the speed. It is found to be 1000 rpm. How do I determine the supply power factor?

There are 2 ways. 1 way is we have assumed that armature current is constant and repel free. So, I average is 30 amperes. What is the power supplied to the load? V average into I average is power supplied to the bridge or input power to the bridge is V average into I average. So, V_0 into I average is the power input. What is the input V_A? It is V_{rms} into I_{rms}. V_{rms} is same as 230 volts because we are assuming that input is ideal sinusoid, current is constant and repel free and magnitude is 30 amperes. So, rms value of this current wave form is 30 amperes.

We have found that if the current is constant and repel free, each device is conducting for pi radians. If each device conducts for pi radians, rms value is same as the average value. So, I_{rms} is also 30 ampere here. So, input V_A is 230 into 30 that is 6900 V_A. That V average into I average is 179 into 30 watts.

So therefore, power factor is power divided by volts ampere, is of the so it is found to be 0.77 and it is lagging. Remember, the moment you introduce alpha, power factor lags. Even at alpha is equal to 0, power factor is not unity. Displacement angel may be unity, remember displacement angle is not equal to power factor angle. So, they are different. Displacement angel may be unity sorry displacement angel is equal to 0. In other words, displacement factor may be unity but that does not mean that power factor is unity. So, power factor is 0.77 lakh.

What is the second method? Second method I have already discussed. Source current is a square wave for pi radians. The fundamental component of the square wave is 4 by pi into the magnitude of the current is the peak value. So, rms is divided by root 2. So, the rms value of the fundamental component of source current is 2 root 2 by pi into the current. It is of for this case, it is around 27 amperes.

For a fully controlled bridge, we found that displacement angel is same as trigger angel. In another words, phi 1 is a same as alpha. So, displacement factor is same is equal to cos of the trigger angel. Source current may be a square wave, so therefore, it has fundamental component and it has a higher frequency components. I told you that only the fundamental component of the input voltage and current are responsible for power transfer. The higher frequency component gives rise to I square R heating or additional heating in the machine. The other effect will see some time later.

So, power transferred is V_1 into I_1 into cos pi 1. The fundamental component of the input voltage, the fundamental component of the source current into the cos of the angel between these 2 wave forms divided by V_{rms} into $I_{rms.}$ Since input voltage is sinusoid, fundament component is same as the rms component. So, V_1 cancels with $V_{rms.}$

We found that the fundamental component for the square wave is 2 root 2 by pi into 30 where 30 is magnitude of the current that is flowing in the load which is assumed to be constant and repel free. So, it is of 27 amperes, alpha is 30.

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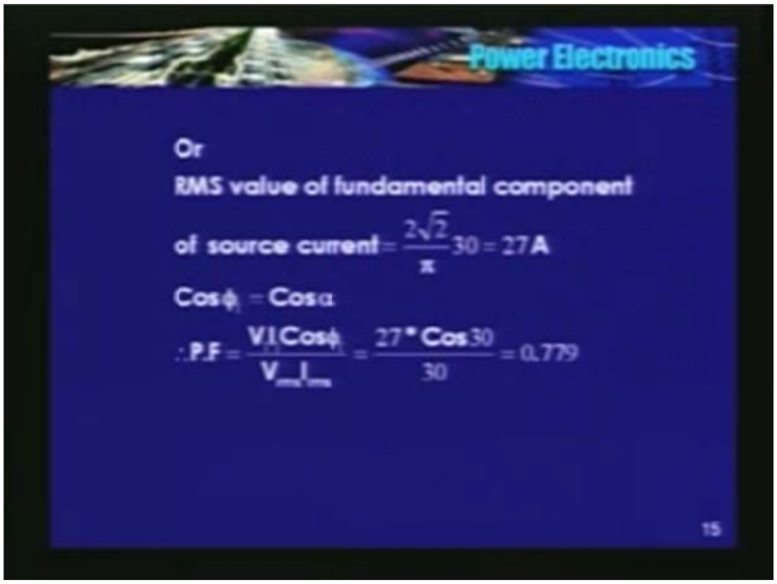

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Or

RMS value of fundamental component

of source current $= \frac{2\sqrt{2}}{\pi} 30 = 27\text{A}$

$\text{Cos}\phi_1 = \text{Cos}\alpha$

$\therefore \text{P.F} = \frac{V_1 I_1 \text{Cos}\phi_1}{V_{rms} I_{rms}} = \frac{27 * \text{Cos}30}{30} = 0.779$

So, cos power factor sorry power factor is given by point, in this case it is found to be 0.779. Both the cases, they have to tally and both the cases, they have to give the same answer. It is up to you to choice which ever method is convenient for you. You do not need to follow the method 2 or method 1, it is up to you.

Part 2 of the problem is regenerating breaking is used. But in this case, problem says, polarity of back EMF is reversed. See, I have not discussed this. I all the time I have discussed, reversing the armature terminals or reversing the armature current. Here the problem says, back EMF, polarities of back EMF is reversed. It is possible by reversing the flux. How flux is reversed, let us not discuss, either they would have used a dual convertor or they would have used a contactor, may can break, interchange the field terminals.

So problem says, calculate alpha and power feedback to the source. Armature current is maintained at the previous value, the same current of 30 ampere is flowing.

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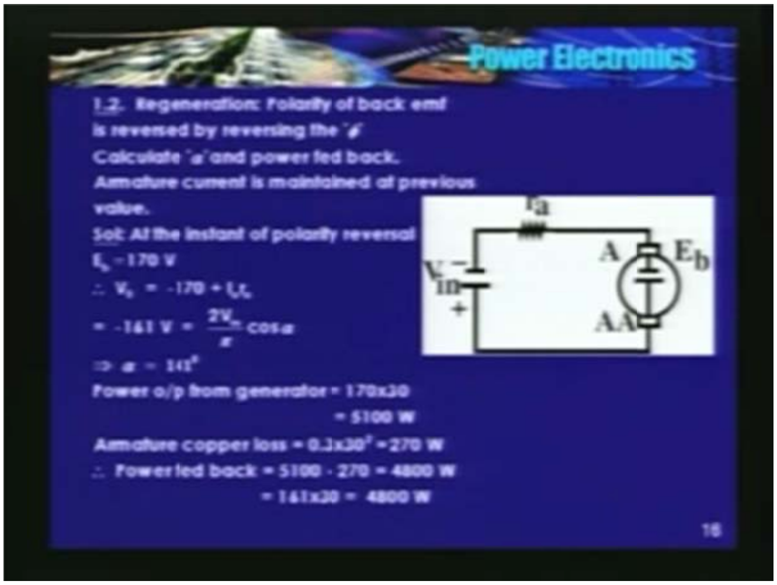

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1.2. Regeneration: Polarity of back emf is reversed by reversing the 'ϕ'

Calculate 'α' and power fed back.

Armature current is maintained at previous value.

Sol: At the instant of polarity reversal

$E_b = -170$ V

$\therefore V_o = -170 + I_a r_a$

$= -161 \text{ V} = \frac{2V_m}{\pi} \cos\alpha$

$\Rightarrow \alpha = 141°$

Power o/p from generator = 170x30

= 5100 W

Armature copper loss = 0.3×30^2 = 270 W

$\therefore$ Power fed back = 5100 - 270 = 4800 W

= 161x30 = 4800 W

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So, here is the equivalent circuit, mind you, he has interchanged, the operator has interchanged the polarities of back EMF. Simultaneously, he has increased alpha greater than 90. I did tell you in my beginning of lecture, increasing alpha alone above 90 degrees in the single convertor will not ensure where the machine or motor will act like a generator.

Similarly, here interchange the terminals alone, not ensure the motor to act like a generator. I have to interchange or I have to interchange the polarities and simultaneously increase alpha above 90 degrees. So, this is the equivalent circuit. Current is still flowing in this direction. Prior to the polarity reversal, E_B was 170 degrees. For alpha is equal to 30 we found that V V_O or the V_{in} is 179. 30 amperes is the current that it is flowing, R_A is 0.3 volts, so 170 is a voltage here.

Now, E_B is minus 170, current is still flowing in this direction of 30 amperes. What is a, what is the value or what is the magnitude of Vin? It should be 161 volts. Ir_a drops, the difference between this should be Ir_a drops. Current is still flowing in this direction. If this is 170, this is 161.

So, current is continuous. Listen, current is still continuous, so therefore, alpha is 141. What is the amount or what is the power feed back to the source? It is nothing but V_{in} into I average or output power of the generator minus I_A square into R_A. What is the power output of the generator? E_B into I_A, 170 into 30 is the output power of the generator minus I square R loses 270 watts. Therefore, power fed back is power output minus I square r losses. This should also be equal to V_1 into I_1 into cos of the angle between V_1 and I_1 we are, because we are assuming that converter is loss less. In other words, efficiency of the converter is 100%. Generally, efficiency is very high. In all the problems solving, we have neglected device drops. Actually, the voltage applied to the load is slightly less than 2 V_m pi into cos alpha because 2 devices are conducting at a time.

If you recall 1 of the assumptions that we made in the very first lecture of converters is that source inductance is 0. But now, let us consider the effect of source inductance because source inductance is always finite because power is fed back, power is being fed through transmission lines or underground cables, there is a transformer at 1 end, it has its own leakage inductance. So, source inductance is finite.

Now, let us see effect of source inductance. If the source inductance is 0, the moment T_3 is triggered, T_1 turns off because current can instantaneously change.

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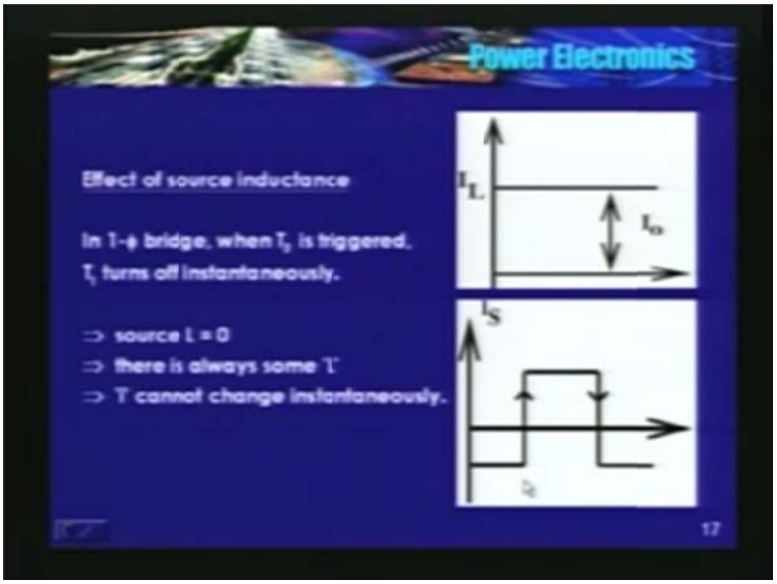

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Effect of source inductance

In 1-φ bridge, when T_3 is triggered, T_1 turns off instantaneously.

⇒ source L = 0
⇒ there is always some 'L'
⇒ 'I' cannot change instantaneously.

See, here is the wave form. I_L is the constant and ripple free. Somewhere at alpha, T_3 might have triggered. So, the moment you trigger T_3, T_1 turns off. T_1 turns off and current reverses. At this instance, T_1 is triggered, T_3 turns off and positive current and here T_3 is triggered, T_1 turns off, negative current. So, current changes instantaneously. This is possible only if the source inductance is 0. If there is a finite source inductance, what will happen now? What will happen to the output voltage? We will see.

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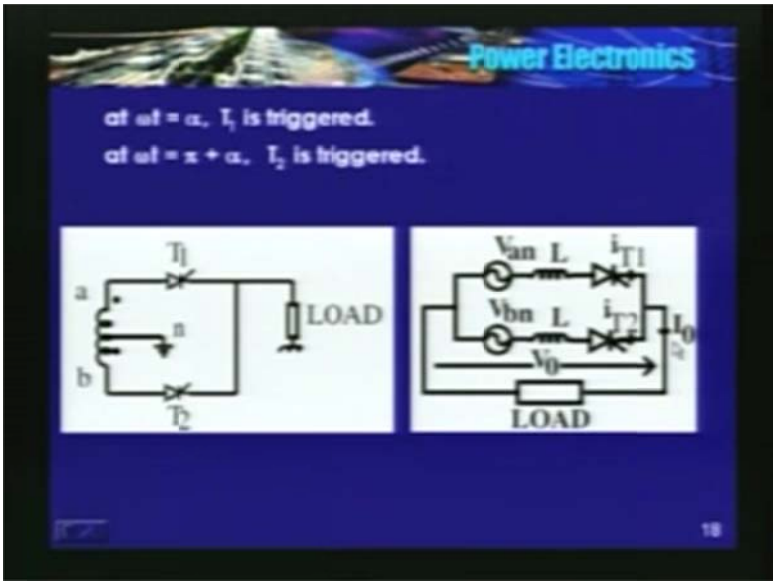

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at $\omega t = \alpha$, T_1 is triggered.

at $\omega t = \pi + \alpha$, T_2 is triggered.

Let us consider a simple case. Now, I am using a center tap transformer, T_1 and T_2. Let me tell you 1 thing, you can do this analysis for a fully controlled bridge also, similar steps. So, V_{an} is the voltage induced in the upper half of the transformer and V_{bn} in the lower half. L is the leakage inductance or inductance of this path. Similarly, L is the leakage inductance of transformer, i_{T1} and i_{T2} are thyristors of the load. At $alpha_{1,}$ at positive half, T_1 is triggered, at some alpha. At pi alpha, T_2 is triggered.

Now, source inductance is finite. Now, how does output voltage look like? Initially, the entire I_0 was flowing through $i_{T1,}$ through $T_{1,}$ entire load current was flowing through $T_{1.}$ T_2 is triggered**,** now, current through T_1 starts decreasing. It cannot come down to 0 instantaneously because of this L. At the same time, current through T_2 starts increasing. Since, we assume as load current is constant and repel free, I_0 is constant. So, i_{T1} is equal to or i_{T1} plus i_{T2} should be equal to $I_{0.}$ So, i_{T1} decreases, i_2 to T increases, so the sum remains $I_{0.}$

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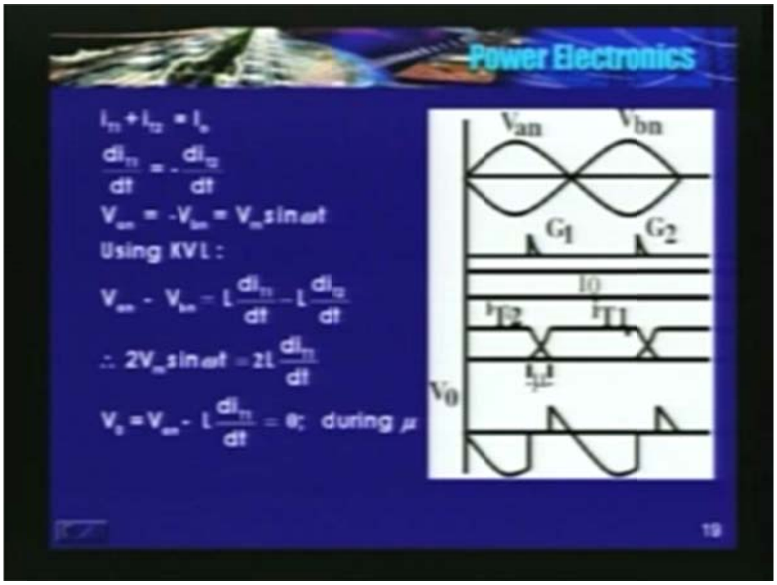

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$i_{T1} + i_{T2} = I_o$

$\frac{di_{T1}}{dt} = -\frac{di_{T2}}{dt}$

$V_{an} = -V_{bn} = V_m \sin\omega t$

Using KVL :

$V_{an} - V_{bn} = L\frac{di_{T1}}{dt} - L\frac{di_{T2}}{dt}$

$\therefore 2V_m \sin\omega t = 2L\frac{di_{T1}}{dt}$

$V_o = V_{an} - L\frac{di_{T1}}{dt} = 0;$ during μ

Now, what does the KVL gives? KVL is V_{an} is equal to minus V_{bn} is V_m sin omega t. For KVL, if I use KVL, V_{an} minus V_{bn} is equal to L d i_{T1} by dt minus L d i_{T2} by dt. See in this circuit, if I use KVL, V_{an} minus V_{bn} is equal to voltage drop across this inductor and voltage drop across this inductor, KVL. Here current is decreasing, this current is increasing. So, d i_{T1} by dt is equal to minus of d i_{T2} by dt. Current slowly decreasing, current slowly increasing.

Similarly here, i_{T2} T, current through this thyristor 2 is decreasing and is increasing in the thyristor T_1 and both the thyristors are conducting for a finite time what is known as mu. Now, substitute this condition in this equation. We will find that V_m sin omega t is equal to L d i_{T1} by dt .

What is V_0? This voltage is nothing but V_{an} minus L d i_{T1} by dt. We found that V_{an} is equal to L di T_1 by dt during this, during mu. So, output voltage is 0 during mu. In other words, when both the thyristors are conducting, output voltage becomes 0 in a single phase. So in this period, output voltage is 0. So, prior to $T_{1,}$ T_2 was conducting, voltage is negative, same wave form. During mu, output voltage is 0. Then $T_{2,}$ current through T_2 becomes 0. In other words, entire current, T_1 is carrying now. Now, V_o is nothing but V_{an} itself, that is V_m sin omega t. Now, this is the wave form.

So, you will find that there is a net reduction in the output voltage. If source inductance is 0, you would have got instantaneous rise here and would have followed this way. Output voltage would have been instantaneous change and would have followed this way. But then here, due to source inductance for a finite time, this output voltage is 0.

So, from observing this wave form, we can conclude that because of the source inductance there is a reduction in the output voltage. What is the magnitude of the reduction in the output voltage? We will find out. We will derive an expression.

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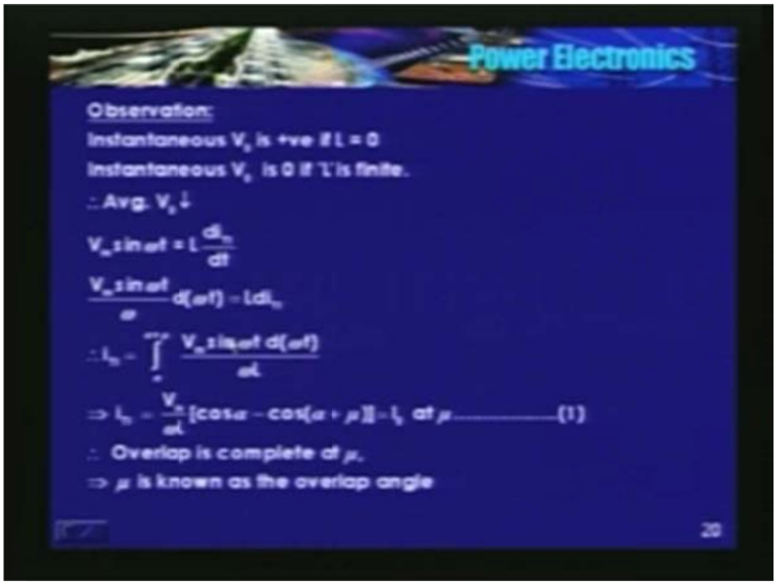

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Observation:

Instantaneous V_0 is +ve if L = 0

Instantaneous V_0 is 0 if 'L' is finite.

$\therefore$ Avg. $V_0 \downarrow$

$V_m \sin \omega t = L \frac{di_{T1}}{dt}$

$\frac{V_m \sin \omega t}{\omega} d(\omega t) = L di_{T1}$

$\therefore i_{T1} = \int_{\alpha}^{\alpha+\mu} \frac{V_m \sin \omega t \, d(\omega t)}{\omega L}$

$\Rightarrow i_{T1} = \frac{V_m}{\omega L}[\cos\alpha - \cos(\alpha+\mu)] = I_0$ at μ ....(1)

$\therefore$ Overlap is complete at μ.

$\Rightarrow$ μ is known as the overlap angle

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So, here is a, where are the various equations? They are very simple and straight forward. At alpha, 2 alpha plus mu, i_{T1} is given by this equation because V_m sin omega t is equal to d i_{T1} by dt. So, I can derive this equation from this. Integrate this and at alpha, at omega t is equal to alpha plus mu, i_{T1} is nothing but I_0.

I will repeat; when omega t is equal to alpha plus mu, this quantity is I_0 itself because entire current, i_{T1} is carrying. So, since both the thyristors were conducting during mu, this period is known as overlap period or overlap angle. Mu is also known as the overlap angle. What is the expression for the average output voltage? because, now there is a 0 voltage period during mu. From alpha to alpha to mu, the average, alpha to alpha plus mu, the instantaneous value of the output voltage is 0. So, expression for average, V_0 is 2 by 2 pi into alpha plus mu into pi plus alpha.

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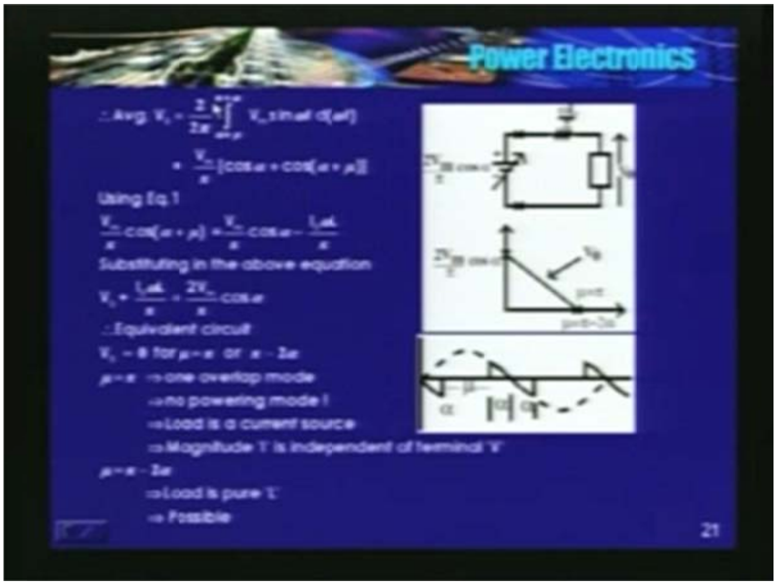

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$\therefore$ Avg. $V_0 = \frac{2}{2\pi}\int_{\alpha+\mu}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)$

$= \frac{V_m}{\pi}[\cos\alpha + \cos(\alpha+\mu)]$

Using Eq.1

$\frac{V_m}{\pi}\cos(\alpha+\mu) = \frac{V_m}{\pi}\cos\alpha - \frac{I_0\omega L}{\pi}$

Substituting in the above equation

$V_0 = -\frac{I_0\omega L}{\pi} + \frac{2V_m}{\pi}\cos\alpha$

$\therefore$ Equivalent circuit

$V_0 = 0$ for $\mu = \pi$ or $\pi - 2\alpha$

$\mu = \pi$ ⇒ one overlap mode

⇒ no powering mode !

⇒ Load is a current source

⇒ Magnitude 'I' is independent of terminal 'V'

$\mu = \pi - 2\alpha$

⇒ Load is pure 'L'

⇒ Possible

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So, here is the expression. From alpha plus mu 2 pi plus alpha, it is V_m sin omega t. It is not that alpha to pi plus alpha it is V_m sin omega t, it is alpha to mu sorry alpha plus mu to pi plus alpha, it is V_m sin omega t. So, you will find that average V_0 is given by this equation.

In our previous expression that was here, cos alpha plus mu, so we will substitute for this factor and solve it. You will get this expression. So, V_m by pi into cos alpha plus mu is equal to V_m by pi into cos alpha minus I_0 into omega by pi. This is from a previous equation, equation number 1. Now, if I substitute this in this, I will get this equation. Now, can I draw an equivalent circuit of this equation? Here is it, 2 V_m by pi into cos alpha which is again varying.

There are 2 thyristors here, at any given time. In this case, there may be 1 but then if I use this bridge, 2 devices are conducting at a time into omega L by pi into I_0 is the voltage drop due to source inductance, mind you. R represented by resistor here, omega L by pi. So, I_0 is the current that is flowing through the load. So, remaining is the voltage across the load, V_0. What is our another observation?

You find this from this expression that average V_0 is 0 for 2 values of mu. One is mu is equal to pi or mu is equal to pi minus 2 alpha. So, both these values, average value of V_0 is 0. Or let us take first condition, mu is equal to pi. First of all, can I have that sort of a condition? In the sense, for entire pi duration, there is a short circuit. In other words, output voltage is 0 for pi radians, both the thyristors starts are conducting, the entire positive half cycle is a overlap period for thyristor 1 and the remaining pi radians in the negative half is the overlap period for another thyristor.

In other words, source does not supply any power to the load. But then we have assumed that load current is constant and repel free and there is no period or in other words, there is source does not supply power to the load at all. How is this possible? This is possible only if the load is an ideal current source. Remember, is an ideal current source. Voltage, terminal voltage is independent of or the current that is flowing is independent of the terminal voltage. Voltage applied during mu to a load is 0 but then constant current is flowing, this is possible only if the load is an ideal current source.

The second condition is mu is equal to pi minus 2 alpha. So, let us draw the wave form. How does it look like? At alpha T_1 is triggered, overlap period is pi minus 2 alpha. So, this is mu, this should be alpha, so this is pi minus 2 alpha. Again at alpha, in the next half, at alpha one more thyristor is triggered that is T_2 is triggered. This is the competition overlap period and at this point overlap commutation overlap, commutation is complete. Entire current, thyristor starts carrying.

So, if you see here, average value of the output voltage is 0, positive half is equal to negative half. So, what sort of a load? It is an ideal inductor. So second case, ideally, it may be possible but for that matter, even the first case if I connect a constant an ideal constant current source, a single phase bridge is feeding. So, mu is pi, it is possible. The second case if I have an ideal inductor, I can have a situation wherein, overlap period is equal to pi minus 2 alpha.