Power Electronics

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Lecture - 33

In my last class I was discussing about the limitation of a hard switched converter. I told you that in a hard switch converter the rate of change of current that is flowing through the device or the voltage across the device are uncontrolled. This quantity is dependent completely on the circuit configuration. I gave the example of a boost converter. The moment you switch the device, whatever the current that was flowing through the inductor starts flowing through the switch.

In other words, di by dt through the device is very high, whereas, in a soft switch converter, the rate of change of current and the voltage are controlled using additional L and C. The size of this L and C is very small. In other words, the resonance frequency of this circuit is very high. So, depending upon the power rating, it could be of the order of 500 kilo hertz. It could be of the order of 500 kilo hertz. So, size becomes very small. Since this rate of change of voltage and current, they are controlled; there is a significant reduction in the device stress. There is a significant reduction in the switching losses. See, I will just give an example here.

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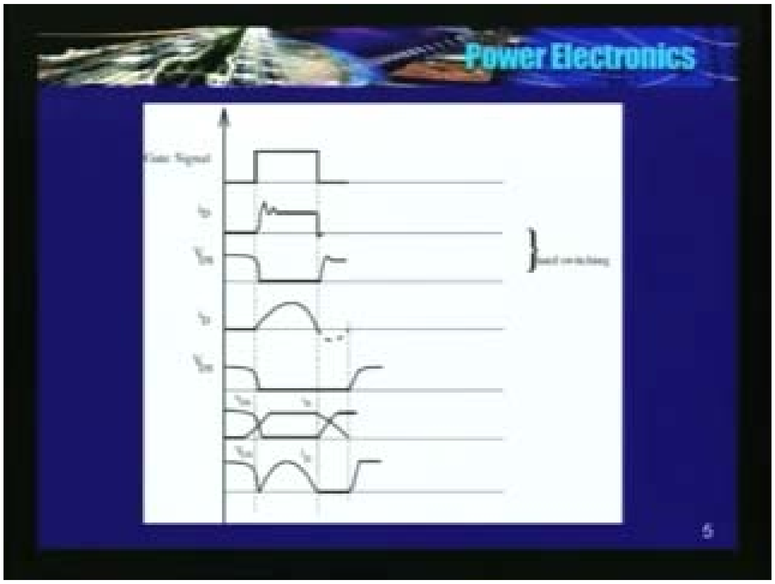

See, this is the slide; this is the current flowing through the device, voltage is falling here. See, this is if I plot in a same graph, intersection takes place at this point. Voltage across the device is relatively high. It has not attained its saturation voltage. Current has result to a significant value, so instantaneous power loss instantaneous power loss that is taking place in the device is quite high quite high.

So, loss the device loss during the switching is high, phase is also high. di by dt is di by dt is see, it is very fast, very high, whereas, in a soft switch converter; see, the voltage has become 0. How, we will see.

I said, we need to use a separate L and C. Voltage across the device has become 0 and then slowly currents starts rising. So, voltage across it has attained its saturation value, current starts rising. In other words, the switching losses are practically eliminated practically eliminated and see this current rise, it is a LC circuit; a resonant, some sort of resonant current. So, there is a significant reduction in the di by dt also here. You compare these 2. This happens both ways, while turn on as well as while turn off.

So, let me repeat; in a soft switch converter, there is a significant reduction in the device stress and the significant reduction in the the switching losses. Since, there is a reduction in the switching losses, now there is an improvement in the inverter efficiency. Losses have reduced. Therefore, operating temperature comes down. The cooling comes a cooling requirement reduces. Now, there is di by dt is controlled. In other words, there is a reduction in the EMI, electromagnetic interference.

Another a very important advantage of soft switch converter is that it is possible to it is possible to increase the switching frequency. Now, you can operate the converter at a very high switching frequency. In a hard switch converter, because switching losses are high, you have to reduce the switching frequency even though the device may be able to operate it at a higher frequency. In other words, you will not be exploit the all the good qualities of a device because of hard switching hard switching.

There are 2 types of soft switch converter. What are they? One is 0 current switching and another one is 0 voltage switching. See, before showing this figure I will just show you and explain this graph. I have explained to you in a previous lecture.

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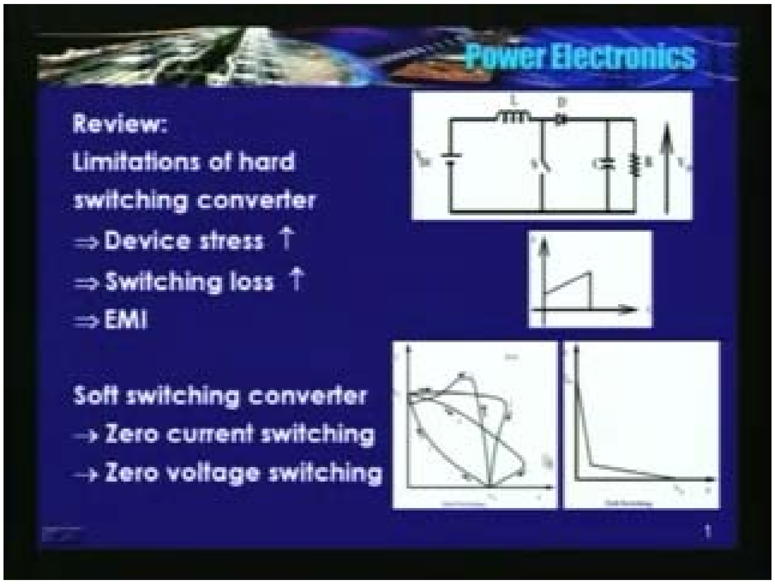

See, the voltage across a device has fallen to a very low value, relatively low and only then current starts increasing only then the current starts increasing and vice versa. Current decreases, it is relatively low value and then voltage across that device increases. So, this is the area, this area is nothing but the losses.

Whereas, in a hard switch converters, see the locus; current increases with fairly a high value, voltage has not reduced and comes down. This is all because of the parasitic elements parasitic elements and this is while turning it off. Now, I had also told that the losses that are taking place in the device can be reduced by using an external snubber. A passive snubber if I use, losses, the switching losses can be reduced. At the time, this is a locus. There is some controllability. In other words, both dv by dt and di by dt are controlled. But then these losses that are taking place in the device, they are transferred to the external circuit and they are dissipated there, they are dissipated there.

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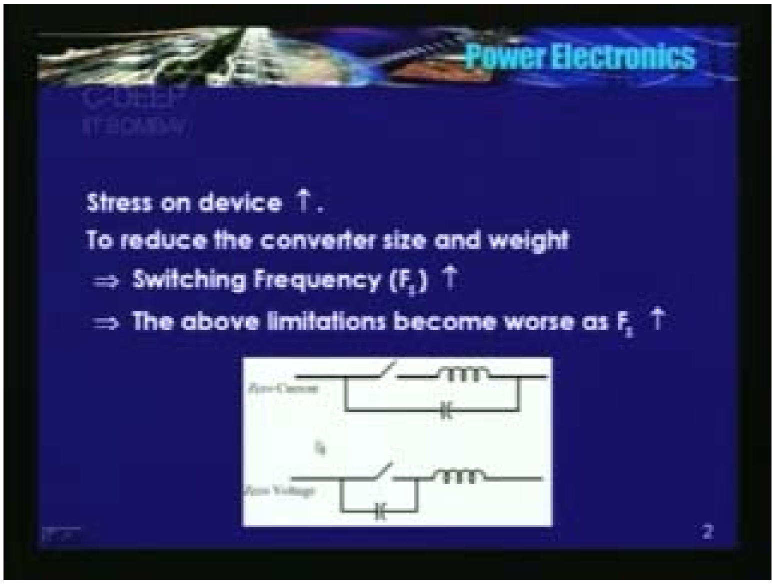

See, the 0 switching 0 current switch converters and a 0 voltage switch converter; basic topology, simple topology. There are various circuit configurations. One such example I have given here, it is a 0 current. Why am I calling this 0 current? Assume that switch is open, more current in this branch, I will close the switch. Because of this inductor, current through the switch cannot change instantaneously. It has to start from 0, slowly rises, slowly increases because of this inductor. Hence the name 0 current switched converter.

I will repeat; I will close the switch, current at T is equal to 0 minus or just prior to closing the switch, it is 0. I closed it; still the current is 0 because of this inductor and now current starts increasing slowly. Come here in a 0 voltage, just see, I have connected a small capacitor, a very small capacitor. We know that voltage across the capacitor cannot change instantaneously. So, assume that switch is closed. So, voltage across it is is approximately 0 or is saturation voltage.

Now, I will open the switch. Since I have connected a capacitor, voltage across it cannot increase instantaneously. It will slowly rise, it will slowly increase slowly increase. In other words, voltage across the device starts from 0 and slowly it will increase. Hence the name 0 voltage switched converter. So, basic topologies; one of the topologies, so, using separate L and C, now it is possible to reduce the switching losses. It is possible to reduce the device stress.

What do I need to do, to do this? The the existing power electronic converter, now should have additional L and C circuits. That is all. Size of this L and C is really very small. So, what are the, if I have to summarize, what are the advantages? See, the advantages are here; Device stress reduces, there is a significant reduction in electromagnetic interference.

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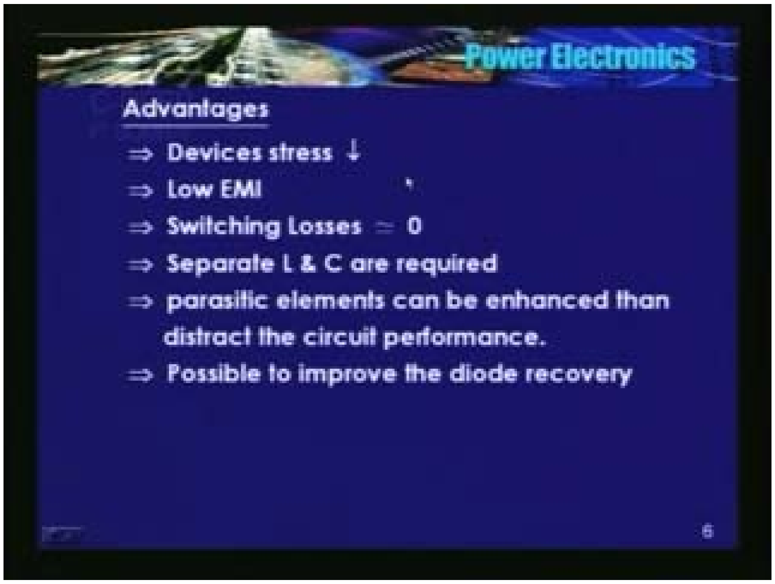

Remember, if you have to sell your product in the international market, for that matter even in India we have our own, our India there is IS standard. So, to sell the product in the market, you have to edit to the standards. So, if the EMI is very high, you will not be able to sell it in the market. So, there is a significant reduction in EMI. Switching losses are practically eliminated. I said, they require separate L and C. Now, this L and C could be the parasitic elements itself parasitic elements itself. So, these parasitic elements created an additional spike in a current or voltage during hard switching.

I showed you the locus of voltage and current. That is either there is a spike in the current or there is a spike in voltage. That is because of the parasitic elements, parasitic L and C. Now, I can or now it is possible to use this parasitic elements for our advantage and last one is it is possible to improve the diode recovery or in other words, it is possible to switch the diode under 0 voltage or 0 current situations. It is possible; you have to modify the circuit.

By the way, I have been talking about the advantages of the soft switch converter. Definitely, there has to be some disadvantages. What are they? They are very obvious. Circuit operation now is bit complex, circuit operation is slightly complex. Second, the peak current is peak current is higher, peak current is higher. See, I will show you. See here, after all power transferred is the product of V and I. See, current is approximately remains constant here, whereas whereas, it starts from 0, slowly rises and it is some is a sinusoid. So, area should be the same for the same power, may be. So therefore, definitely, the peak current should be higher. So, in other words, peak current through the device has increased peak current through the device has increased.

Where is the major application of this soft switch converter? The major application, one of the major applications is in power supplies power supplies. If you have to reduce the size, if you have to reduce the weight, you have to increase the switching frequency and it is possible only using soft switching techniques. It is possible only using soft switching techniques. So, soft switch DC to DC converters are very popular very popular. So, this does not mean that soft switching is not used in AC to DC converter and may be DC to AC converter. I have not covered DC to AC so far.

But then major application or major use of soft switching technique is in DC to DC conversion and second one is in induction heating induction heating. We require a high frequency AC source high frequency AC source. Higher the frequency, the better it is. May be, sometime later, I will I will explain to you the requirements of induction heating. You require a really a high frequency AC source. There also, soft switching technique is used soft switching techniques are used. Another is the lighting ballast choke, power efficient small electronic ballast. Power factor also unity there, the soft switched or resonant technique even is used in electronic ballast.

So, these are the major applications. I will not discuss much on soft switched converters because let me tell you one thing, this is a subject by itself. This is really vast. I just introduced the concept of 0 switching to you. With this I have completed. In fact, I should not be using a word completed; I will stop discussing DC to DC conversion. We did discuss 4 different types of topologies without using a transformer. They are buck converter, boost, buck - boost and chuk converters. Then we started discussing the topologies using a transformer. They are fly back, forward and push - pull. Then I introduced little bit of the concept of soft switch converters. With this I will stop the DC to DC conversion topic.

Now, I will start discussing another important area in power electronics. That is DC to AC conversion, DC to AC conversion. These are also known as inverters. Now, let me clarify one point; recall our discussion in AC to DC conversion, I said that AC to DC conversion or AC to DC converters are also known as converters. In a fully controlled bridge, if alpha is equal to greater than 90, I told that it is known as inverter.

Now I am, again here, I am saying; if the input is DC and output is AC, they are known as inverters. Yes, both are known as inverters. But then the first group or when the input is AC, output is DC and alpha is greater than 90 and if the load is active, power is being fed back to the source, this equipment is known as line commutated inverter line commutated inverter.

So therefore, if someone says inverter; by default you can take it for granted that input is DC output is AC. Now, do not please confuse with the line commutated inverter and DC to AC converter, no. By the way, why is there are need for DC to AC converter? I told you AC to DC conversion; yes, we require because to control the speed of a DC machine, DC to DC conversion may be required in power supply. Now, why DC to AC?

See, the voltage or the power that is generated in the generating station is alternating. Except for solar power or power that is obtained from solar cells, almost all the power is alternating, AC power because if I rotate a conductor in magnetic field, where the magnetic field is AC or DC does not matter, the voltage induced in that conductor is AC. So, power that is generated is AC. Now, I am going to discuss a equipment which converts from DC to AC. Why you require this or why is there a need for this sort of equipment and why they say, it is another very important area in power electronics?

So, let me tell you one thing. If there is an equipment which converts DC to AC, that equipment should also have an AC to DC converter.

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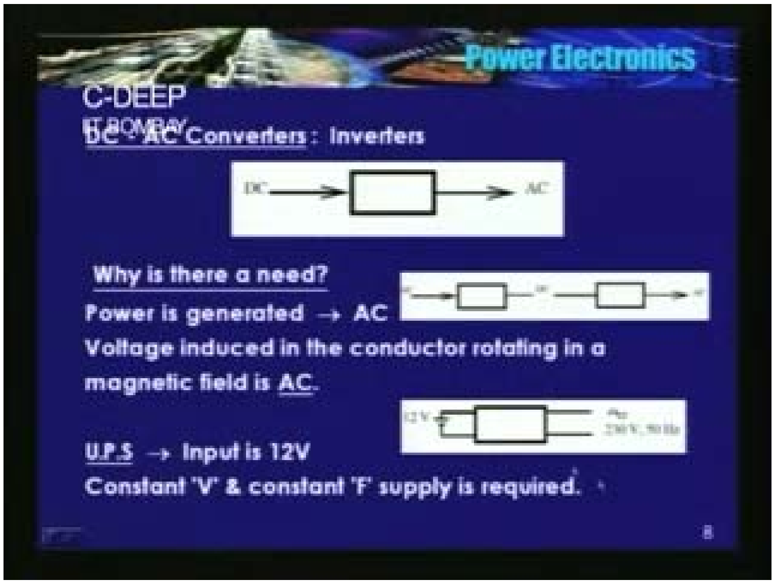

It is like this; I will have I will first convert AC to DC because power that is generated or power that is available is AC except for solar with DC and from this DC to AC. But then, this in this topic we will discuss or we will concentrate only on DC to AC. How to get this DC? We have already studied in AC to DC conversion.

Now, I will give 2 examples 2 or 2 applications. Take for example; the inverter which is used in our home or a UPS which is used in a computer center as a backup. What the inverter which is used in our home does? The moment the utility power supply goes or the moment there is the power shut down, that inverter converts whatever that energy that is stored in the battery. It could be either 12 volts or 24 volts to 230 volts, 50 hertz AC. So, the inverter converts 12 volts DC to 230 volts AC.

So, during normal operation or when there is utility supply available, the battery is getting charged. So, there has to be a small bridge which converts AC to DC and charges the battery. If the battery is discharged, it charges and after wards it is floating in a DC bus. So, that is the reason I said, if any equipment which converts DC to AC should have an AC to DC converter. So, one of the application is 12 volt DC is the input and output is 230 volts, 50 hertz AC. Over here I have drawn a sinusoid. Whether it is a sinusoid or how to get this sinusoid, we will see some time later.

So, one of the applications is output should be constant voltage and constant frequency. Remember, from a DC, output should be a constant 230 volts and a constant 50 hertz supply is required.

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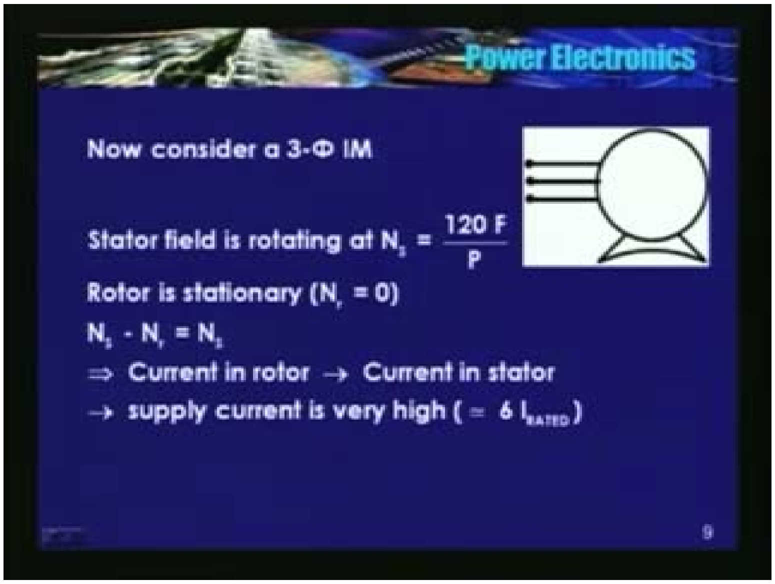

Now, I will just take a small diversion. Go back to an AC machine theory. Please, for a half an hour or so I will discuss the principle of operation of induction machine. You might have already studied this in your machines course, let me briefly revise this.

So, we all know that when a 3 phase sinusoidally distributed winding which is excited by a 3 phase current, the stator field is rotating. In other words, when I connect a 3 phase stator to 3 phase AC supply, the field produced by the stator is rotating at synchronous speed and that synchronous speed is 120 F by P, where F is the supply frequency.

Initially, rotor is stationery. N_r is equal to 0. Stator field is rotating at N_S. So, N_S minus N_r is nothing but the relative speed between the stator field and the rotor is N_S itself because rotor is stationery. Since, the relative speed is maximum, a large current will flow in the rotor. This current has to come from the stator, so there will be an equivalent current flowing in the stator. This current, the stator current has to come back or has to come from the source.

So, in other words, when you switch on the 3 phase induction machine to the source, a large current will flow and this current could be of the order of 6 times the rated current. It could be of the order of 6 times the rated current. I am emphasizing this because we need this when we are discussing in detail about the inverter operation. So, current carrying conductor placed in a magnetic field experience a force, this all we know. So, stator has established a field that is the current flowing in the rotor conductor. So therefore, rotor starts accelerating.

So, N_r increases. As N_r increases, N_S minus N_r decreases. In other words, relative speed falls. If the relative speed falls, current in the conductor also falls. Rotor starts accelerating and it will attain a steady speed which is less than the synchronous speed and at that speed the torque produced by the motor is equal to the electro is equal to a load torque. So, so here is the speed torque characteristic of an induction machine which you have already studied in the machines course.

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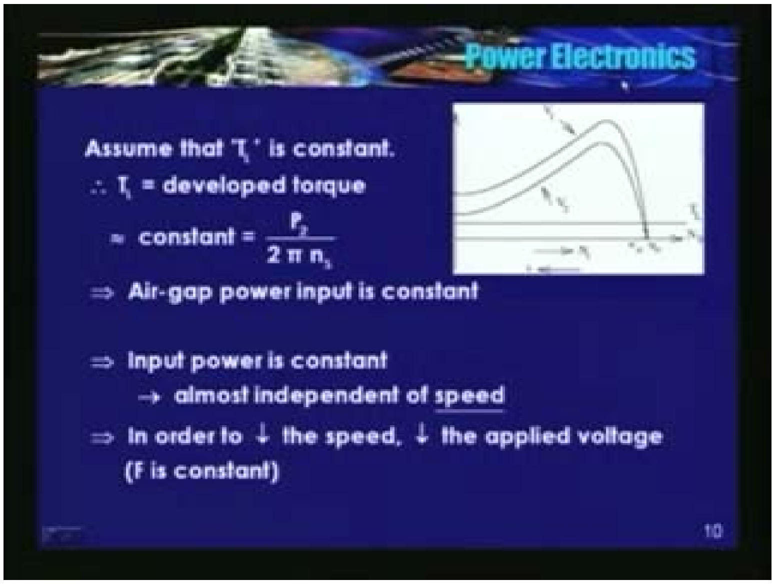

Now, assume that a constant load is being applied to the shaft. In other words, the rotor is driving a load whose torque is independent of the speed. See here, I have represented that characteristic by a straight line. Load torque remains the same. Since, load torque has remained the same, the electromagnetic torque also will remain constant and it is independent of the speed.

So, what is electromagnetic torque or developed torque? It is nothing but air gap power input P_2 divided by 2 pi n_S. So, this is the expression, a very popular expression; P_2 divided by 2 pi n_S. This is nothing but the developed torque. The P_2 is the air gap power input. Now, N_S is constant because or N_S depends only on the frequency of the stator supply. Therefore, if N_S is held constant and the machine is driving a constant torque load, T_L remains constants, P_2 or the air gap power input remains constant.

Now, this air gap power input is approximately equal to the input power itself. So therefore, what I can conclude is that the input power is almost independent of the speed if the machine is driving a constant torque load. I will repeat; the input power to the machine is almost independent of the speed of rotation, provided, the machine is driving a constant torque load.

So, what happens if you want to try, if you want to reduce the speed of the rotation? I am saying, frequency is held constant; so, if you have tried to reduce a speed of rotation by reducing the applied voltage, I will keep frequency constant, am just trying to reduce the applied voltage. May be, using an auto transformer or so. That is what we have done in machines course or machines lab. Since, synchronous speed is held constant, the input will remain constant. Speed of rotation has come down.

Assuming that speed has speed of rotation has reduced, the slip has increased slip has increased. N_S minus N_r divided by N_S. N_r is reduced, N_S is constant, slip has increased. If slip has increased, S times the air gap power input is dissipated as heat in the rotor, rotor copper losses. So, rotor there is an increase in the rotor copper loss. If there is an increase in rotor copper loss, the temperature rise increases. Since, there is an increase in the rotor current and I told you, this current has to come from the stator, there is an increase in stator copper loss also.

In other words, there is a reduction in the efficiency of the motor. See in this plot, a … characteristic for one supply voltage V_1. I will try to reduce the stator applied voltage to V_2. All these points will remain the same; a peak torque or speed at which the peak torque occurs will remain the same, this synchronous speed also will remain the same. The intersection of the load characteristics with the motor characteristics is the operating point.

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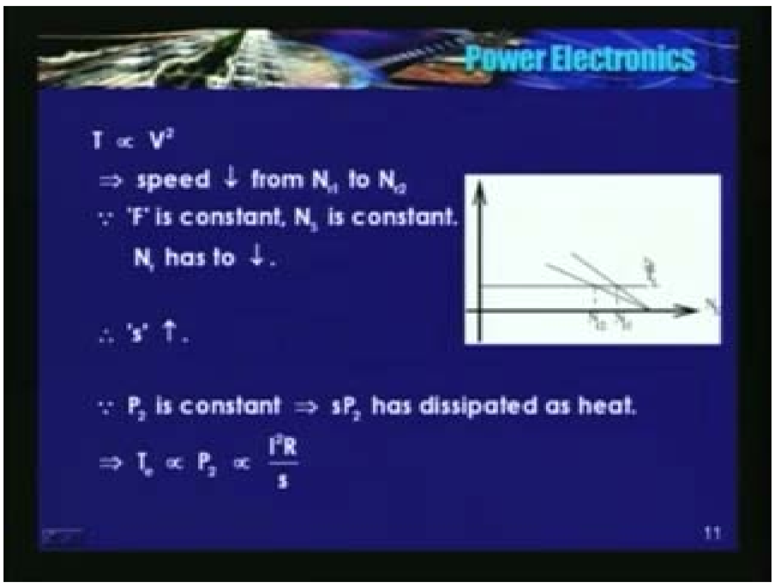

Now, if I expand this region, it looks like this. I have expanded, I have exaggerated. Initially, it is operating at N_{r1}. When I try to reduce the voltage, it started operating at N_{r2}. N_S is constant here, synchronous speed. Now, the machine is operating at N_{r2}. So, there is an increase in the slip compared to the previous case. So, there is an increase in the slip. P_2 is constant and it is independent of the speed of rotation. That is what you have proved. So, S times P_2 is dissipated as heat.

Now, what is the relationship between electromagnetic torque and the slip? See here, P_2 is nothing but I square R by S. This is again, we are we have studied again in the machines class. So, that is nothing but T_e. So, what is the relationship between this I and S?

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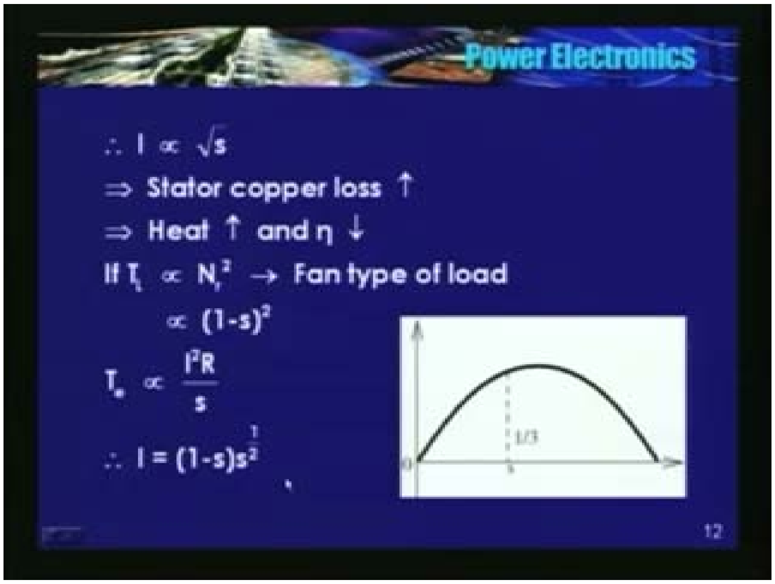

I is proportional to square root of S. I is proportional to square root of S. So, as S increases, stator current also increases and therefore, stator copper loss increases. So, there is an increase in the stator copper loss, there is an increase in rotor copper loss; therefore, there is an increase in the heat developed and there is a reduction in efficiency.

Now, take for example the second case; a very popular type of load, a fan type of load or a pump. What are the characteristics, load characteristics of a fan? T_L is proportional to the square of the speed. T_L is proportional to the square of the speed. That is N_r. T_L is proportional to N_r square. So, what is N_r? 1 minus S into N_S. So therefore, T_L is proportional to 1 minus S square. Just now I showed you that T_e is proportional to I square R by S. This is nothing but nothing but air gap power input air gap power input. So, T_e is proportional to I square R by S. So, at steady state and if I neglect the friction or windage losses, these 2 should be equal; IR square by S should be equal to or should be proportional to 1 minus S square.

So, therefore, what is the relationship? I is equal to or I is proportional to I is proportional to this. Now, if I plot the magnitude of I verses the slip, I will get some this sort of a characteristics. You will find that current is maximum at S is equal to 1 by 3. It is very simple. You need to differentiate this equation with respect to S and equate it to 0. 1 minus S into square root of S; you differentiate it with respect to S and equate it to 0, you will find that at S is equal to 0.333, I is maximum. Whereas, if the torque remains constant, I is proportional to square root of S, which is not the case if the if the load is of a fan type.

So, please remember, characteristics or the operation changes and it depends on the nature of load. Machine may be the same machine may be the same. So, what do we conclude? We can conclude that if the process requires wide variation in speed, N_S should be changed especially for constant torque applications. If the process requires wide variation in speed, synchronous speed should be changed especially for load torque remains constant. And, please remember, in principle in principle this may not be required.

In other words, you do not need to operate this. You do not need to change the synchronous speed for fan type of loads in principle. Why? It is because in constant torque type of load, the input power is independent of the speed of rotation. That is what I told you in the beginning. If the load torque remains constant, input power will remain constant and it is independent of speed of rotation, whereas, if the load torque depends on the speed and for a fan type of load, load torque varies with the … in the speed. So, as the speed of rotation decreases or changes, input also changes.

So see, here is it. Stator current attains a peak at S is equal to 1 3 and again it comes down again its comes down. It attains a peak at 1 third and it comes down.

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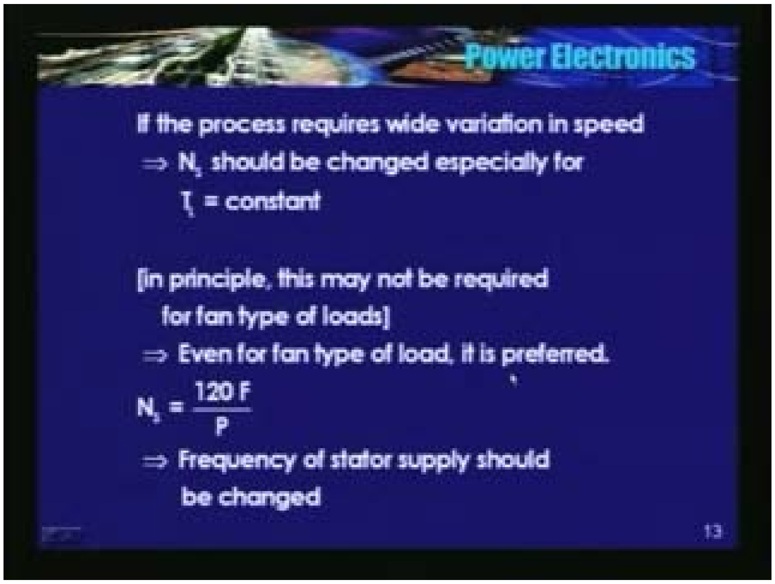

So, in principle, you can vary the speed of a fan type of load by varying by varying this applied voltage to the motor, keeping the frequency of the stator supply constant in principle. But then, for a high power fan, say especially in a power plant especially in a power plant in a cooling tower, the the rating of the fan could be a fraction of a mega watt, could be of 1.2 mega watt or so, is that high. Cooling torque fans or or if you have a pump, a boiler feed pump; say, HP rating could be could be of the order of 2000 or so. Say, 235 mega watt power plant, the boiler feed pump kilo watt rating could be of the order of 2000 or so and cooling tower fan could be of the order of 1.2 mega watt or so.

So there, if you want to vary the speed over a wide range, in case, if you want to vary the speed over a wide range or if you want to change the or vary the discharge over a wide range, it is preferred to vary the synchronous speed. So therefore, if you want to vary the speed of rotation of an induction machine and if you want to maintain a very good efficiency, what do we need to do? You have to change the frequency of the stator supply.

So, I will repeat; for a wide variation in speed of an induction machine, stator frequency has to be varied. So far I have not told you the relationship between the stator frequency and the magnitude of voltage that is applied to the induction machine. I just concluded that to vary the speed over a wide range, you change the frequency of the stator supply. What should happen to the magnitude of voltage? We will see.

Again, go back to induction machine theory. See, here is the equivalent circuit, a very popular equivalent circuit; stator parameters, rotor parameters, equivalent load, magnetizing inductance.

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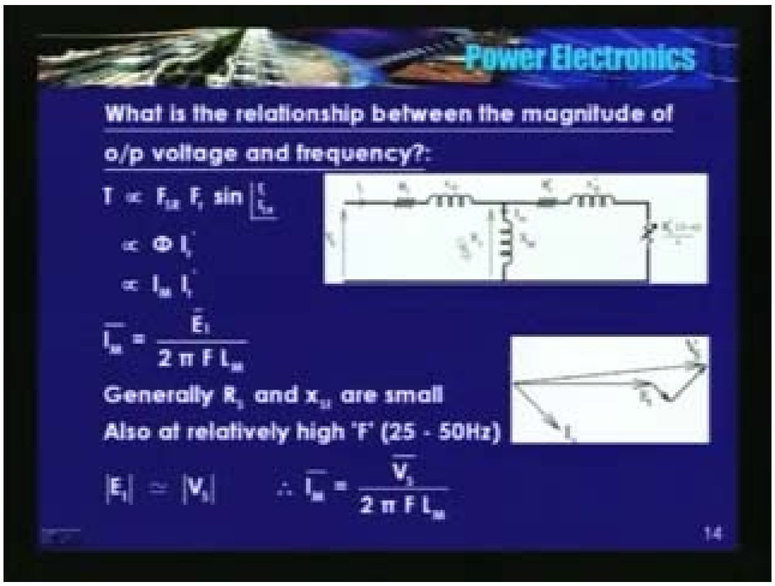

And, what is torque? We all know, very popular torque expression; torque is proportional to F_S F_R, sine of the angle between F_S and F_R or torque is proportional to F_{SR} and F_S, sine of the angle between F_{SR} and F_S and the third expression is torque is proportional to F_{SR} and F_R, sine of the angle between F_{SR} and F_R. These might have studied in the, again in the machine course, basic equations.

So, if I use the same expressions here, one of them, F_{SR} is nothing but the air gap flux, phi. F_{SR} is a resultant magnetic field that is nothing but the air gap flux here, phi. F_R is a rotor MMF that is nothing but or it is proportional to I_R prime, current that is flowing in the rotor circuit. Now, this flux phi is produced by the current that is flowing in the magnetizing branch. So therefore, phi is proportional to I_M.

Now, what is I_M? I_M is given by E_1 divided by 2 pi F into L_M. 2 pi F L_M. Generally, if the HP rating of the motor is high or high power machines, stator resistance is very stator resistance is very small. In other words, see, this is the equivalent circuit. All the series elements, all these elements should be as small as possible because this is the main path of the power flow, power flows in this direction. So, this should be as small as possible this should be as small as possible. For invariably they are: for a for a high HP machines. Which may not be true for a low HP or a fraction HP machines; for high HP machines, these parameters are very small.

If these parameters are very small and at relatively high frequency, high frequency in the sense, may be may be of the order of 25 to 50 hertz, these are; approximately I have drawn, please, so from 25 to 50 hertz or so, I am calling this as high frequency. I can say that magnitude of E_1 is approximately equal to V_S.

See, while doing, I will recall the transformer equivalent circuit, transfer approximate equivalent circuit. What did we do? We shifted that magnetizing branch and connected across the supply and we called that circuit as an approximate equivalent circuit. Same thing I am doing. I am shifting that magnetizing branch to the supply and this circuit is and I am saying that this is valid at relatively at high frequency. We concentrated or we used a 50 hertz supply, rated frequency. So, there the change of frequency did not arise.

Here, before coming to this topic, I concluded that stator frequency should be changed or should be varied in order to vary the stator frequency, in order to vary the speed of rotation. So, I am shifting this branch to the input and I am saying that V_1 is approximately equal to V_S and this assumption is valid only at relatively at high frequency. Why? I will tell you sometime later.

So, at relatively at high frequency, V_1 is approximately equal to V_S. See, I have just drawn a vector diagram, just to tell you. May be, this is a bit exaggerated again. I am I am taking E_1 as reference and some I_S, lagging current because current has to be lagging in induction machine. I_S R_S, I_S into XSN, this is V_S.

So, the magnitude of V_1 could be approximately equal to magnitude of V_S because these parameters are again very small. So therefore, I_M is equal to V_S divided by 2 pi F into L_M. I_M is equal to the supply, the magnitude of the supply voltage divided by 2 pi F into $L_{M.}$

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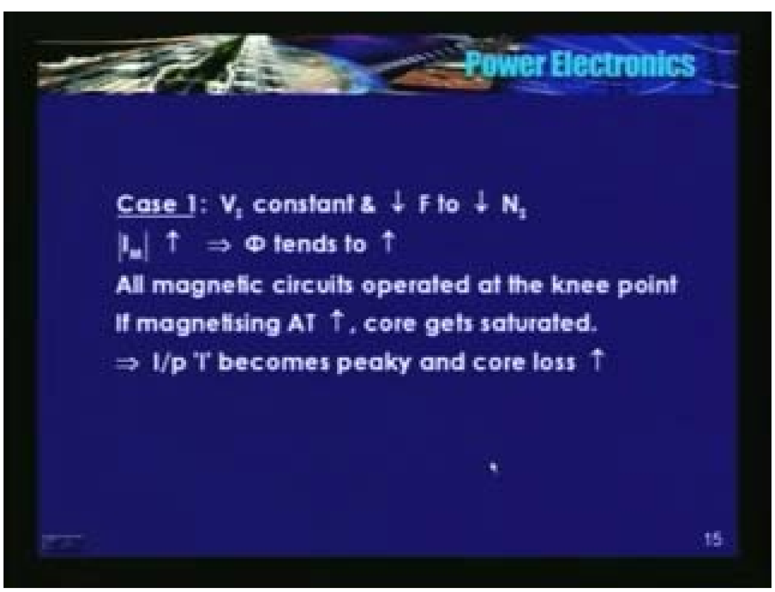

Now, we will discuss various cases. Case 1; I will keep V_S constant and I will try to reduce the frequency because I have to reduce the speed of rotation. So, frequency should be reduced. So, what happens? See in this equation. I will keep V_S constant and try to reduce the frequency. So, this equation says that I_M tries to increase, I_M increases. In an actual machine whether it increases or not, we will see later. I_M increases. If I_M increases, flux increases. I told you that or it is known that machines or the magnetic circuit that is used in the in machines or in transformer; always operated at the knee point. The magnetic circuit is generally operated at the knee point.

A knee point is a point, wherein the saturation begins to start. Till the knee point, magnetic circuit is linear and above the knee point, it starts saturating. It is going to be non linear. In this equation, I am keeping V_S constant, trying to reduce F, I_M increases. Therefore, flux tries to increase. If flux tries to increase, magnetic circuit starts getting saturated and if the circuit saturates, the source current is going to be peaky. Source current becomes peaky, harmonic content increases plus core loss increases.

So therefore, keeping V_S constant or keeping the magnitude of voltage constant and decreasing the frequency in order to decrease the speed of rotation is not a solution. I will repeat; keeping the magnitude of voltage constant and trying to reduce the frequency in order to reduce the speed of rotation is not a possible solution because machine may or machine will get saturated. The remaining cases we will see in the next class.

Thank you.