Electrical Machines
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Lecture # 32
3 Phase Induction Machine: Starting Methods

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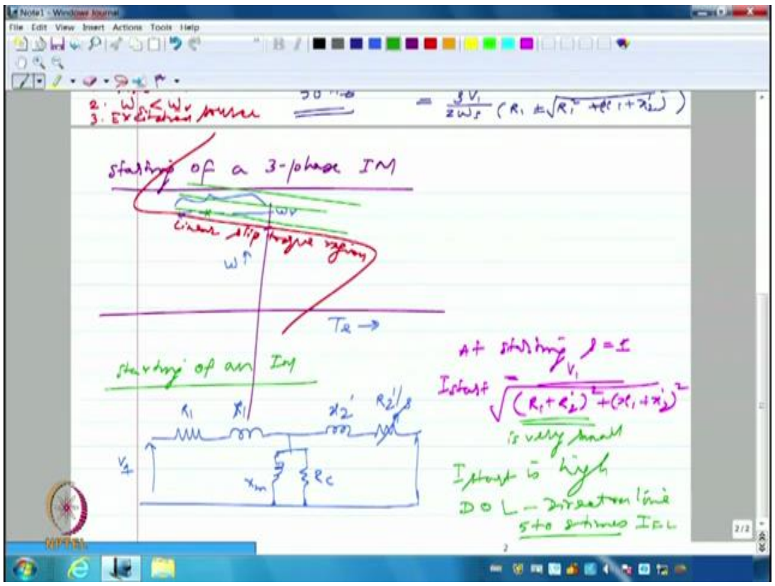

Starting of an induction machine, please recall the equivalent circuit we drew, we said if I neglect whatever is my parallel parameter. This was R_1, X_1 if I if I include the parallel, of course, this will be X_m this can be R_c which I have not included almost until now, but nevertheless if I want to include the ion losses, this should be included, then I am going to have X_2^l, I am going to have R_2^l/s which has two components clearly. One is inherent loss that takes place which is R_2^l and the other portion is the mechanical output which is $\frac{R_2^l}{s(1-s)}$.

And then this going to be short circuited. This is the normal equivalent circuit of the induction machine with V_1 being the input voltage or Vs stator per phase voltage. Then I am going to start a machine, speed is zero, so the slip will be one. So at starting flip is 1, because slip is 1 I am going to have the starting current if I try to write neglecting even the magnetizing current I should be able to say $I_{start} = \frac{V_1}{\sqrt{(R_1 + R_2^l)^2 + (X_1 + X_2^l)^2}}$.

So, I eliminate s completely here because s is 1, when s was not 1 I had this s to be 0.01, 0.02, 0.03 whatever, so if I assume R_2^l is 1 ohm, for example, it will be multiplied by the factor of 33 or 50 or 100 as the case maybe depending on whatever the slip is, so this entire rotor impedance is going to look bloated up because of which automatically the current will get decreased. The rotor current will get decreased once; the slip becomes really-really a small value.

But when the slip is 1 this impedance, whatever impedance I am looking at is very small. Because this is very small I_{start} is high, this going to be really-really high. So, it is definitely not a good option to start the machine directly by applying the three phase voltages which we call as DOL direct online starting. So, direct online starting of an induction motor is definitely not a good option, it is a self-starting machine agreed, but is not going to really help us, if we are trying to start, let us say 100 kilo watt induction motor directly by applying the 3 phase supply.

Because that current that I am going to draw will be as high as 5 to 8 times, the T_I full load, if I say I_{FL} 10 ampere I might draw as high as 70 to 80 amperes when I am connecting directly to a 3 phase supply, so normally power system power system authority is put a limit on what is the rating of the induction motor, you can directly start. Generally, beyond 10 kilo watt we are not allowed to start, at the most 50 kilo watt. If you go beyond 50 kilo watt and then try to do direct online starting, may in all probability or all power supply will be removed. Power system authorities will take a pretty stern action because it affects all the other people.

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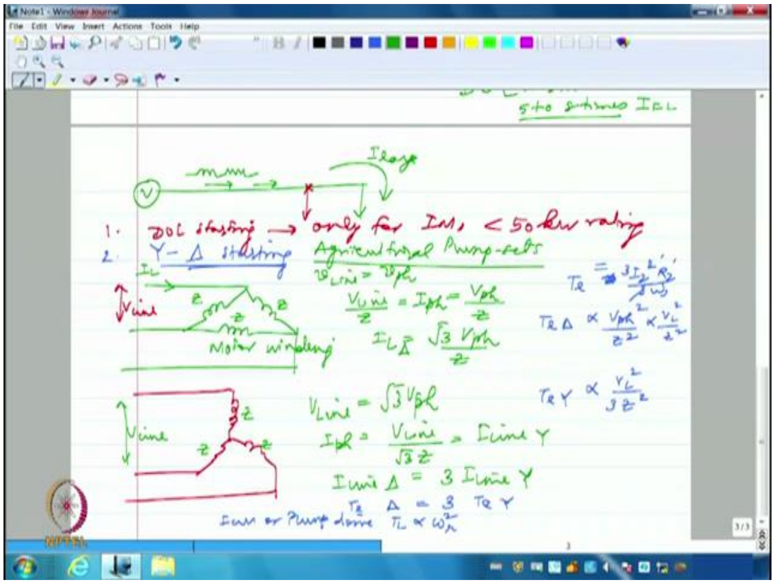

I am going to have a transmission line maybe here is my source and I am going to have a long transmission line like this. The transmission line has certain value of resistance and inductance definitely. So, if my factory is located somewhere here and I am going to draw a huge current. Then I am going to have lot of drop taking place all over in all this R and l, everywhere there will be drop taking place, so a next floor neighbour who has another factory probably, if they are looking at the voltage at this point, I am going to have really much lower voltage when I am starting the machine.

So, normally it may be 400 volts, now it may be 380 volts or 360 volts, so it is definitely not good for the equipment that are connected in the same line closer to my industry premises. So, generally, there is kind of an understanding existing between the electricity supply provider and the consumer saying that you cannot use this loads. Welding, for example, if you try to weld directly from the power supply, what will happen is, because it is a short circuit, most the times welding happens when there is an arch struck and you are going to put the electrode right there.

So, it is a short circuit, so you will see that the current drawn is very high, the voltage will dip, so it is really-really dangerous for the other equipment which require constant voltage, so you cannot connect that equipment in the same line or you should put a restriction on the equipment that can be used or it cannot be used, so DOL starting normally is used only for motors less than strictly 50 kilowatt rating. In fact, even for 10 kilowatt rating maybe until 10 kilowatt rating it is okay to use it.

But definitely not for greater than 50 kilowatt rating, so I should have some other method of starting a machine, so another method of starting which is very commonly used is star delta starting. So, in star delta starting, normally we assume that the motor stator winding is connected in delta. So, if I am connecting the motor winding in delta and let us say I am applying certain voltage, I am going to have in this case $V_{line} = V_{ph}$ and let us say the impedance of each of this phase is Z.

So, I am going to have whatever is the current that is being drawn in terms of RMS value, if I try to do I should say $\frac{V_{line}}{Z} = I_{ph} = \frac{V_{ph}}{Z}$. Whereas, if I try to look at line currents, what is drawn from the supply, what is the motor drawing is different, what is actually drawn from the power supply is root 3 times that motor current, phase current and for power system authorities are going to look at only this root 3 times the phase current.

So, I am going to have this $I_{Ls} = \frac{\sqrt{3}V_{ph}}{Z}$. Rather than this, if I try to make initially the winding get connected in star, I do not want it in delta, I want the same thing in star, so I will still have the impedance to be Z, Z and Z nothing has changed, the same winding I am reconnecting in star and I am going to have essentially the voltage, the same voltage is going to be applied, so here we called this as V_{line}, so I am going to again call this as V_{line}, I am not changing anything the same power I am connecting to the motor but am going to connect the motor windings in star format.

So, in this particular case I can say $V_{line} = \sqrt{3}V_{ph}$. So, what I am applying across each of the phases is only $V_{ph} = \frac{V_{line}}{\sqrt{3}}$, so I can say $I_{ph} = \frac{V_{line}}{\sqrt{3}Z} = I_{line}$. So, if try to look at the ratio of $I_{line\ delta}$ and this is $I_{linestar}$, I can say $I_{line}(\Delta) = 3I_{line}(Y)$. So, I am going to have three times, so by doing this I am essentially reducing the starting current, but what happens to the starting torque?

We said that the torque is proportional to current square. We know that the electromagnetic torque $T_e = \frac{3I_2^2 R_2^l}{s\omega_s}$. So, I can say simply whatever is the current that is being drawn square of that will be corresponding to torque, so I can say $T_e(\Delta)\ \alpha\ \frac{V_{ph}^2}{Z^2} \alpha\ \frac{V_L^2}{Z^2}$, because $V_{ph} = V_{line}$ for delta is concerned.

Whereas if I try to look at what is $T_e(Y)\ \alpha\ \frac{V_L^2}{3Z^2}$, so I am going to have a gain $T_e(\Delta) = 3T_e(Y)$. So, the torque is also going to get decreased by a factor of one third, when I look at the delta torque will be much higher, so we are taking a hit on the torque generated by the machine, but we are also reducing the current.

So it is not a great option if I am trying to start an induction motor which is probably coupled to a hoist, coupled to an electric vehicle or coupled to an elevator because those things require a high starting torque, whereas here the torque is going to be very-very limited, I am not going to get a good amount of torque. So if I had started it in delta maybe my machine would have started, my system would have started.

But if I try looking at it after connecting delta a star I am not going to get a good amount of torque. So, these are applicable mainly in those applications where I do not require a large starting torque, typically fans, pumps, if you look at fans, torque is proportional to omega square, low torque is proportional to omega square, so if I look at fan or pump drive $T_L\ \alpha\ \omega_r^2$.

So, if ω_r is really-really small initially it does not have to displace a large amount of air surrounding it, so obviously when I start I will require very small torque and as I go up the speed, I will require more and more torque. So, this is very much applicable to fan or pump drive and this torque delta starting is very commonly used in agricultural pump sets.

So, star delta starters are very commonly used in agricultural pump sets because, most of them require very-very small torque during the time of starting not a big deal and generally, there will be a time delay, it will be in star for probably 0.5 seconds, 0.7 seconds and after that automatically it will switch over to delta, so when that happens both ends of the winding should be brought out.

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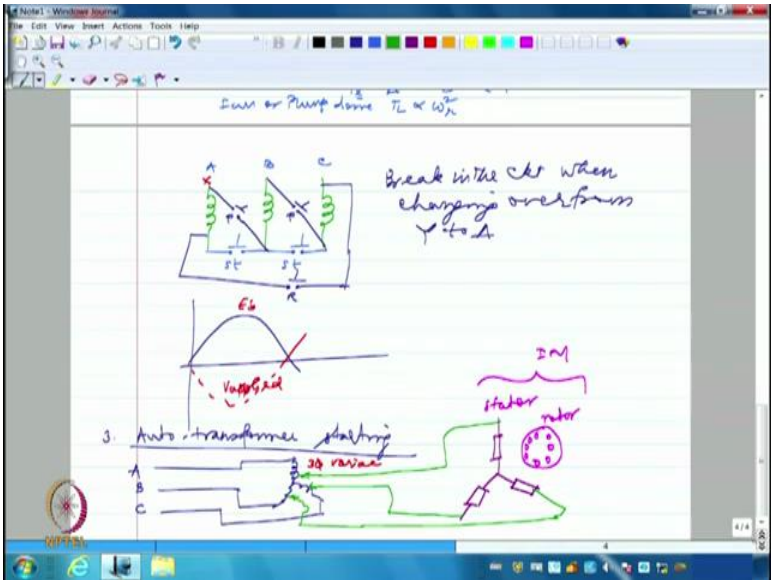

If I am going to have A, B, C three phase windings, I am going to have this as A this as B and this as C. So, if I want star I have to actually have contactors here, and contactors here, this two have to be, so this are starting contactors, they will be closed and I am going to have A, B, C three phase supply applied here. So this will be the starting contactor which will be closed and if I want really this to be connected in delta, I will have something like this from here I will have one contactor, so this will be during running.

One more I should have like this, so this will be again running contactor and the third one has to be connected basically between this and this. This will be the another running contactor. So starting contactors will be opened out, running contactors will be closed and then it will become connected automatically in delta and then it will pick up a higher torque after that. So star delta starting is very-very commonly used in agricultural pump sets, but please note, when I am opening the starting contactors and later on connecting it in for running contactor format, there is break in the circuit for a very short while, so your load should be able to withstand that.

Because it is pump it is alright, it is just delivering water, for a short while if little bit of reduction happens heavens will not fall, so these are okay where very great accuracy is not really demanded. So, this will have a break in the circuit, definitely when it is changing over from star to delta and one more problem also can be., I have some back EMF always. Like a transformer, I will definitely have back EMF. Flux may not collapse right away, so I will have some amount of back EMF definitely, when I break the circuit and reconnect the circuit.

Whether the voltages that were induced and whatever is the voltage that is coming from the supply line, if they are incomplete opposition, I will have a huge amount of current, they can 180 degrees out of phase. if I am going to have the back EMF somewhat like this, whereas I am going to have the applied voltage somewhat like this. That is being applied between this point and whatever is the induced EMF.

So, each of this windings have to limit a very-very large current if the two back EMF's, that is the back EMF and the applied voltage are completely opposing each other. They are 180 degree out of phase, if they are actually in phase roughly, then I will not have so much of voltage being withstood by the motor winding. So these are generally inherent problems that are face in such application where I am going to break the circuit and reconnect the circuit.

So this breaking the circuit and reconnecting the circuit once again. So, this is one of the problems normally we may face in star delta starting, so one is E_b the other one will be $V_{applied}$, so if they are completely out of phase, then I am going to have a major issue. So there are more methods of starting which will also give me somewhat accurate starting that is possible within certain duration of time and so on. So we looked at DOL, we looked at star delta starting.

The third method of starting that we are going to discuss is auto transformer starting. Which you used in the laboratory, in electro mechanics lab generally what we were using is with an auto transformer, we always had a three phase auto transformer, so what we are actually looking at is, here is the three phase supply that I have and I am going to have three phase variac, I am showing it as though it is start connected, so this is how it is connected.

So, this A, B, C and this is the three phase variac. Now, I am going to have my induction motor here just to differentiate between these two, let me probably draw the induction motor winding, again I have showing it in star it need not be in star it can be in delta as well, so this how it is going to be, so this is actually the stator and here is the rotor. I am showing squirrel cage rotor, so this is the rotor, this is the stator, so overall this is the induction motor.

Now, from here I am connecting this probably to one of the phases, I am again connecting this to another phase and I am connecting it to the third phase. Please note I am applying a very small portion of the voltage because, this is the jockey point or the variable point. So, I am applying if there are hundred turns, I am probably applying only corresponding to 10 turns, nothing more than that. So, I am applying very-very small amount of voltage in a balanced manner, all three phases are balanced, because the three phase variac jockey is moving, in a balanced manner.

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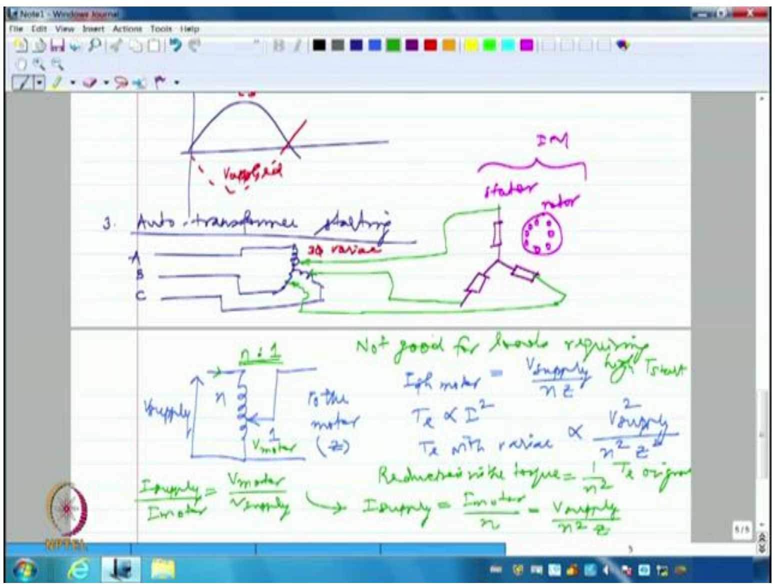

if I try to look at just one single phase winding, here is my variac, this is the power supply V_{supply} and what I am doing is to connect a jockey point and then I am going to have this applied to the motor. So, if I say that there are n number of turns here whereas I just applying only one turn, for example, n:1 is the ratio of the voltage of the supply to the voltage applied to the induction motor, so I am going to have actually the current through the motor $I_{phmotor} = \frac{V_{\sup ply}}{nZ}$.

If I say this is Z impedance is Z, this is how it is going to be, so obviously, if I try to look at the torque because the $T_r \; \alpha \; I^2$, I am going to have T_r with variac $\alpha \; \frac{V_{\sup ply}^2}{n^2 Z^2}$. If I had not had the variac I would have got the torque to be $T_r = \frac{V_{\sup ply}^2}{Z^2}$. So, the torque has decremented or decreased by a factor of $\frac{1}{n^2}$, so I am going to have reduction in the torque is by a factor of $\frac{1}{n^2}$ of Te original.

If I try to look at what is the original torque compared to that it is going to become $\frac{1}{n^2}$. But if I actually look at the current here, because I am going to have n:1 as the voltage ratio, the current would become 1:n, because I am going to have $V_1 I_1 = V_2 I_2$. So I can say in this case, if I just say this $V_{primary}$ or V_{supply} and this is V_{motor}, so I should say $\frac{I_{\sup ply}}{I_{motor}} = \frac{V_{motor}}{V_{\sup ply}}$. This is valid always, so I am going to have essentially $I_{\sup ply} = \frac{I_{motor}}{n} = \frac{V_{\sup ply}}{n^2 Z}$.

So, the current as well as the torque both are actually decremented or reduced by a factor of $\frac{1}{n^2}$, when I am using n:1 as the turns ratio of the primary side to the secondary side in a variac. So, it is very-very similar to star delta starting, if I assume that instead of n is to 1 I have $\sqrt{3}$: 1, you would not see any difference between the star delta starting and this auto transformer starting.

If I assume that I still have the motor winding connected in delta itself, but I am going to have $\sqrt{3}$:1 as a variac which is inserted, it will behave exactly similar to a star delta starting. So, this method is also really not good for loads requiring high starting torque. So this essentially tells us about the third method of starting which auto transformer starting.

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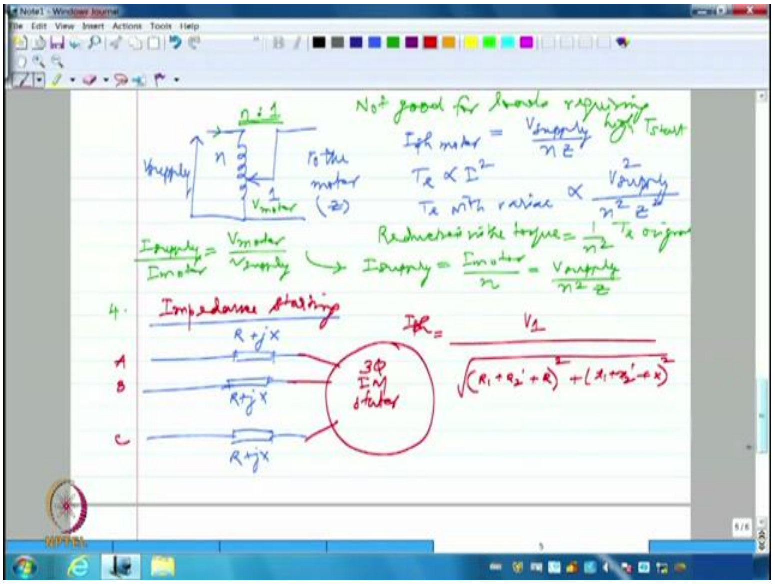

There is one more method of starting, the next method of starting that we would like to look at is impedance starting, which is very similar to what we did in the case of DC motor. In DC motor we inserted a large armature resistance; similar to that I will insert a large impedance in series with my power supply. Let us say here is the three phase supply I am getting, so I am going to insert one external impedance like this, so these are the three phase impedances, so I would say R+jX this is also some R+jX and this also some R+jX.

And then this is connected to my three phase induction motors stator. So this is my three phase induction motor, so I have just connected it like this, so these are the three phase supplies A B C. So, the overall current drawn will get decreased because originally we wrote the expression to be $R_1 + R_2^l + R$, this will be the total impedance.

Similarly, I will have $X_1 + X_2^l + X$. And V_1 is the voltage that is being applied. So this will be I phase, $I_{ph} = \dfrac{V_1}{\sqrt{(R_1 + R_2^l + R)^2 + (X_1 + X_2^l + X)^2}}$. So the per phase current will get decreased because of the inclusion of R and X from the external to the motor. So, I will have the reduction in the current, but definitely I will have the reduction in the torque as well.

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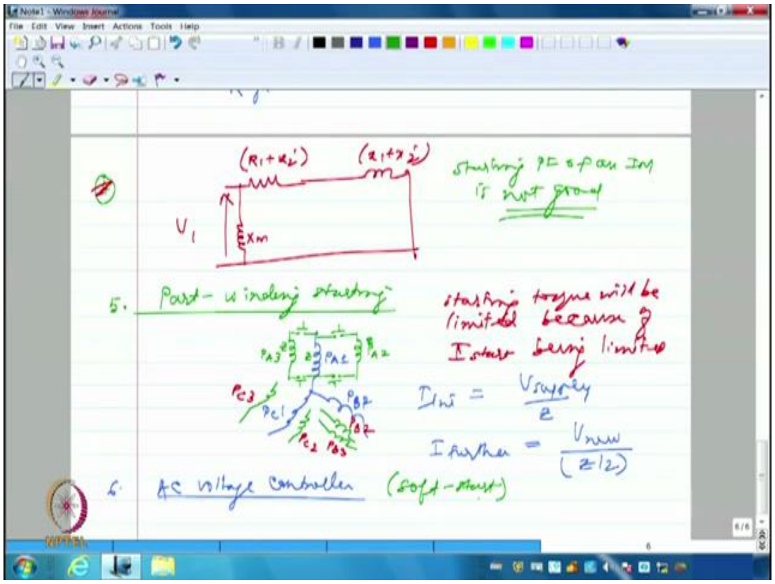

If you actually look at the induction motor during starting, you are essentially looking at the equivalent circuit like this I told you, this will be R_1+R_2^l and I am going to have X_1+X_2^l and I am going to apply a V_1, this is what is my starting condition of the induction motor. I do have definitely a magnetizing reactance because I have to establish the flux, so the magnetizing reactance as well approximation I can show it here.

It is an approximation clearly, so this is my X_m, so if I look at the power factor of the motor, it will not be very good during starting condition also, because you have R_1+R_2^l, R_2^l is generally small squirrel cage induction motors, thick rotor bars, so I will not have much resistance R_1 might have some amount of value and X_1 and X_2^l if I am looking at I am really not going to have very small value because there is air gap, leakage is going to be somewhat pronounced.

So, X_1 and X_2^l actually are going to be leakage values which are somewhat large. X_m actually is also going to draw a good amount of current because I have air gap, I cannot help it, so we will see normally that the starting power factor is not good. So, if it is not good in that case, if I include R and jX they will also medal with whatever is the power factor that I am going to get, if I include more X rather than R then I will have very bad power factor, but I will not have much of heat loses.

If I include more resistance but less X then the power factor maybe fairly good, but I will have a good amount of heat loses, so I have to decide what really I want, if I have a good cooling arrangement but I am going to take care of the power factor much better then I might try to include a larger resistance and smaller reactance. But nevertheless this is a lossy method it is not going to really give you a good performance in terms of good amount of starting torque.

The starting torque is going to be still limited that is one of the problems that we are going to face with respect to this particular method of starting. So, the impedance starting can include large R less X, less R large X or all of them almost equal to each other, depending upon what is kind of requirement you have. Can we have an AC voltage controller to start the induction motor? We had looked at AC voltage controller earlier in power electronics course. This is also generally termed as soft start, so you are essentially trying to look at changing the voltage that is being applied to the induction motor.

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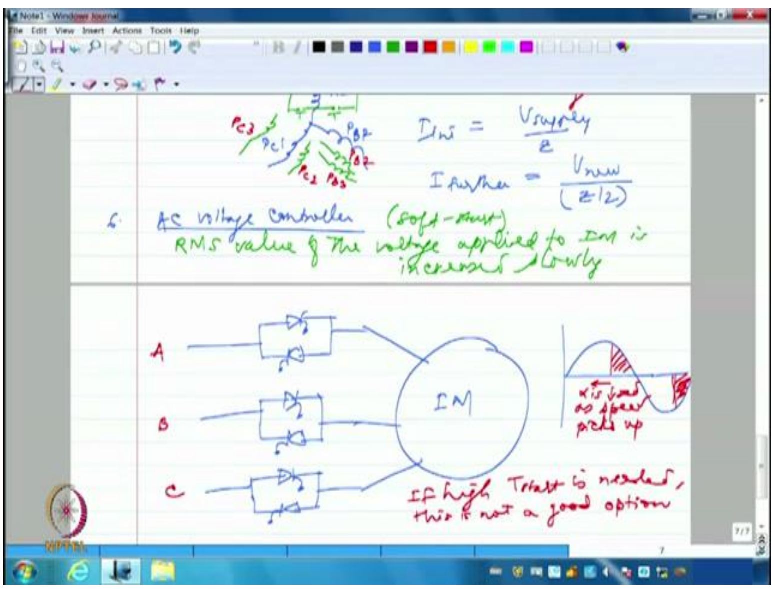

So, I can just have the RMS value, so RMS value of the voltage applied to the induction motor is increased slowly. So, this is done with the help of one thyristor in this direction and another thyristor in this direction. Similarly, I am going to have three pairs. This is the second pair and I am going to have the third pair like this. These are the three phase power supplies A B C and I am going to connect this to the induction motor.

So, let us say this is connected like this, so I can start with the firing angle of 100 degrees or 120 degrees, I can start off with a large firing angle, so I am going to look at it as though if I just look at one particular phase, if this is my applied voltage, if I look at the firing angle of 100 degrees or something I am going to apply only this much of voltage and this much of voltage, nothing more than that.

And slowly I can vary the firing angle such that it decreases as the machine picks up speed, as the machine picks up speed, I will have more back EMF generated, so that will automatically bring down the current, at that point I can try to reduce the firing angle, so α is decreased as speed picks up, so this will essentially vary the RMS value of voltage that is being applied to the motor and I can have a complete control because I am looking at the firing angle being changed at my own will, so I should be able to definitely adjust the amount of voltage that is being applied as per the requirement of the motor and the load system.

So this sounds like a good option provided again the starting torque requirement is not so high, the starting torque requirement if it is high, again I am applying only lower value of voltage, then how will I get really a good amount of current or good amount of torque, so this also definitely not good for, if high torque is required. If high starting torque is needed this not a good option.

One more major problem is harmonics, we definitely not looking at sinusoidal voltage or sinusoidal current, everything is non-sinusoidal, so the motor can have third harmonic, fifth harmonic, seventh harmonic and so on and so fourth and which can really interfere with the proper working of the motor. We will look at how the induction motor behaves when I am actually feeding it with harmonic rich supplies.

As we going to inverter fed induction motor, at that point we will talk about that in greater detail. But it definitely not a good option to feed the induction motor with unnecessary harmonics that is not a good option at all.

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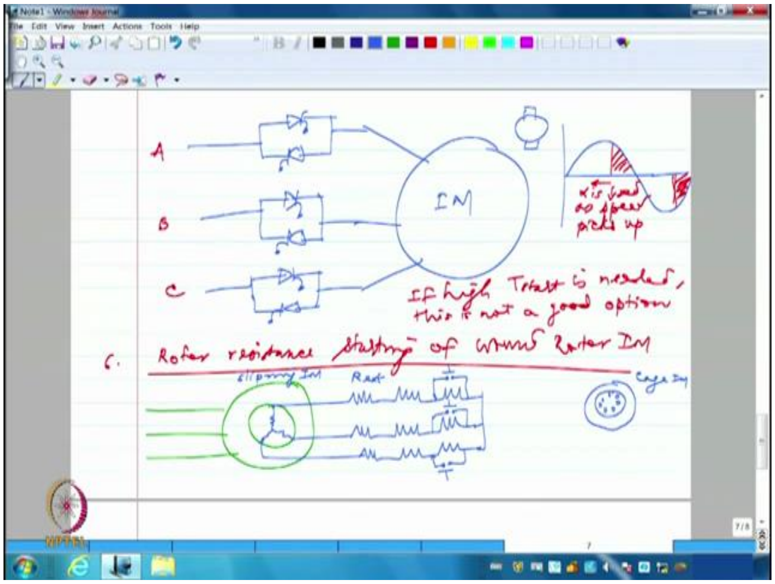

So, this actually whatever we discussed so far all of them are applicable to both squirrel cage as well as wound rotor induction motor because I am interfering with the working of the induction motor from the stator side, whatever we so far is from the stator side, so that definitely can work for both wound induction motor as well as the squirrel cage induction motor, so if we are looking at another method which is only applicable to the wound rotor induction motor.

This is rotor resistance starting of wound rotor induction motor. So we are actually looking at if you actually draw the wound rotor induction motor I should show somewhat like this, this is my stator, stator is essentially the same, so as far as the rotor is concerned, in wound rotor normally we show it with three windings like this, they are connected to the slip ring, the difference between squirrel cage, squirrel cage normally we show it like this, I have the stator here, this is the rotor, rotor we show it this.

This is essentially showing the rotor bars, so this the representation of cage induction motor, whereas this is the slip ring induction motor representation. You guys know DC motor, DC motor is always represented like this with two brushes because I see still some kids drawing the induction motor and showing two brushes, please do not ever do that. If it is a three phase induction motor, you cannot have brushes. You know protruding from two ends, definitely not representation is extremely important when you draw a diagram. So, now these are three terminals of the rotor that are brought out.

I can have additional resistances connected here but off course they maybe three phase resistance. So, if I have multiple number of resistances connected like this I can short circuit them as the speed increases further and further, so I will have normally contactors connected across each of these resistances like this which can be closed as the machines gains speed further and further, so I am just showing contactors for each of these resistances, so similarly, I will have contactors for the next resistances as well they will be closed as the motor gains velocity further and further.

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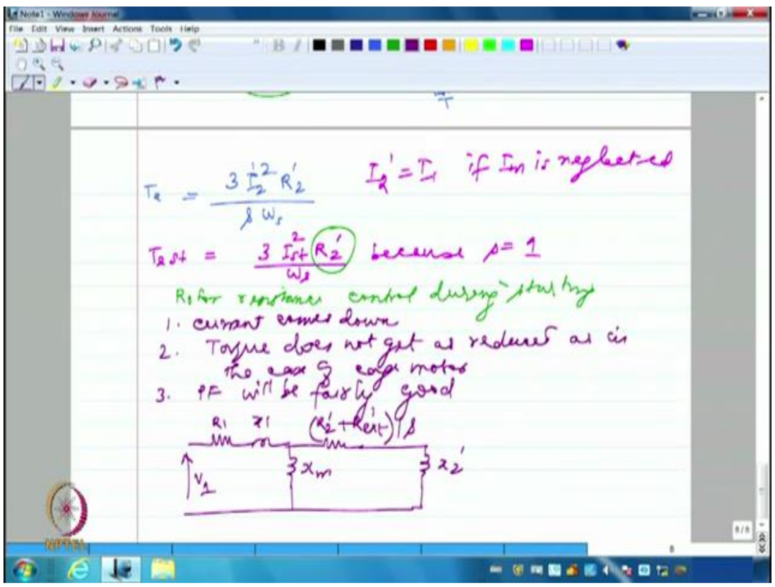

So, if I say that this is R external together, we wrote for induction motor $T_e = \frac{3I_2^2 R_2^l}{s\omega_s}$. If we are neglecting the magnetizing current I_m, I should say $I_2^l = I_1$. So I can simply say if I am looking at $T_{e\ starting}$ I should be able to write $T_{est} = \frac{3I_{st}^2 R_2^l}{\omega_s}$ because s=1.

So, if I try to look at this expression, I am having R_2^l coming into picture, so if I am able to increase the rotor resistance not only do I reduce the starting current but I also give an increment to the starting torque, so if I somehow temper with rotor the resistance that will give me two advantages during starting I will bring down the starting current alright but the reduction in the starting torque what I got in squirrel cage there I had to tamper it only from the stator side, I cannot even tamper anything in the rotor side I cannot touch the rotor side, whereas here I will be able to touch definitely the rotor resistance, I will be able to modify the rotor resistance.

So, I would be able to get good amount of starting torque as compare to squirrel cage. The same thing if I am not able to bring down the current I would have gotten better torque, no doubt, but my soul purposes to bring down starting current as well. So, when I am bringing down the starting current am I reducing the starting torque also drastically, if I look at it that way I would not be really reducing it drastically as compared to squirrel cage induction motor, so rotor resistance control actually will be advantageous in several ways.

One is definitely the current comes down, and torque does not get as reduced as in the case of cage motor because I am going to have this resistance parameter even coming up in the numerator. I am going to have $R_2^l + R_{external}$ whatever is the external resistance that I am including, and obviously power factor will also not come down, power factor will be fairly good, I would not say very good, but fairly good because I am going to have this recall the equivalent circuit I will have R_1, X_1, X_m then I am going to have $(R_2^l+R_{external}^l)/s$.

And I am going to have X_2^l, this becomes my equivalent circuit during the time of rotor resistance starting. So, basically we looked at all these methods of starting common to both the motors except for the last method where I am going to tamper with the rotor resistance alone.