Electrical Machines
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Lecture 39
Synchronous Machines: Power Angle Relationship, V and Inverted V Curves

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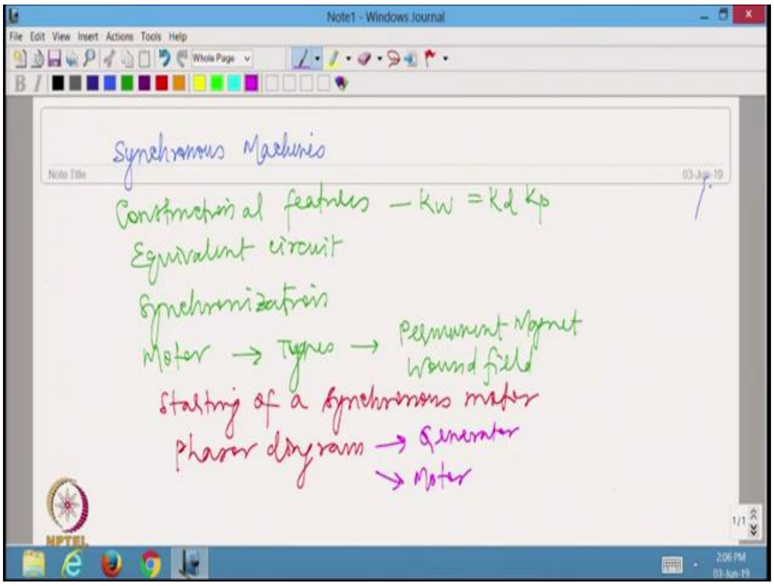

Synchronous Machines

Constructional features – $K_w = K_d K_p$

Equivalent circuit

Synchronization

Motor → Types → Permanent Magnet
Wound field

Starting of a Synchronous motor

Phasor diagram → Generator
→ Motor

We had looked at synchronous machines in terms of their constructional features in which we had talked about winding factor which is consisting of distribution factor and pitch factor, then we had looked at equivalent circuit then we had also looked at when a generator is synchronized with the bus bar, so how synchronization is done.

Then, we also talked about how a synchronous machine can work as a motor? What are all the different types? like permanent magnet synchronous motor or wound field synchronous motor, so we had looked at these two mainly, then I had also talked about starting of a synchronous motor then ultimately we had also talked about phasor diagram of a synchronous motor, this is where we stand in fact phasor diagram we discussed for both generator operation and motor operation.

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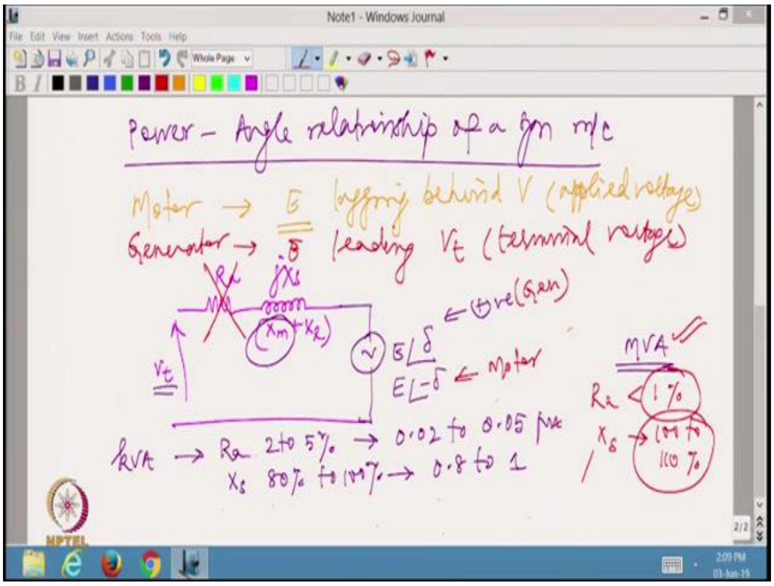

Now, the next topic that we are going to take up will be on power angle relationship of a synchronous machine. I think we already said that if it is motor we are going to have invariably E lagging behind V that is the rotor side flux because of that whatever is the induced EMF E that is going to lag behind V which is the applied voltage, whereas if we are looking at generator we are going to have E leading because this is the induced EMF which is the root cause for any voltage that is appearing at the terminal.

So, this will be leading whatever is the terminal voltage V. So if we try to draw the overall equivalent circuit we should be normally drawing a resistance which is actually the resistance of the armature winding or stator winding and then we are going to have an inductance which is actually known as the synchronous reactance which will consist of the mutual inductance between the armature and field plus whatever is the leakage.

If I may call that as the leakage, so X_l and X_m put together will be X_s and I am going to have on one side may be the terminal voltage that is appearing if it is a generator or the terminal voltage that I am applying if I am looking at it as a motor and I am going to have the induced EMF here, on this side which is $E\angle\delta$ if I may call this as generator where δ will be positive, if I am going to talk about this as $E\angle-\delta$ in which case this is going to be a corresponding to motor. So, this is for generator whereas this is for motor.

Normal values if you look at even if it is a kVA rated synchronous machine I am normally going to have R_a about 2 to 5 percent, what I mean is 0.02 to 0.05 per unit is going to be the normal resistance value and if I look at X_s it will be anywhere between 80 to 100 percent, please note this is very-very high because X_m is also part of this X_s, so I am going to have essentially this to be 0.8 to 1 whereas, if I look at MVA rating of the machine normally we will have this R_a to be less than 1 percent, it can be 0.005 something like that it is going to be really-really small, whereas if I look at what is X_s?

X_s will be 100 to 110 percent or 120 percent, so you can imagine this is really-really small as compared to this. In both the cases it is even more so in MVA rating, so we can afford to neglect this, there is nothing wrong in neglecting the resistance.

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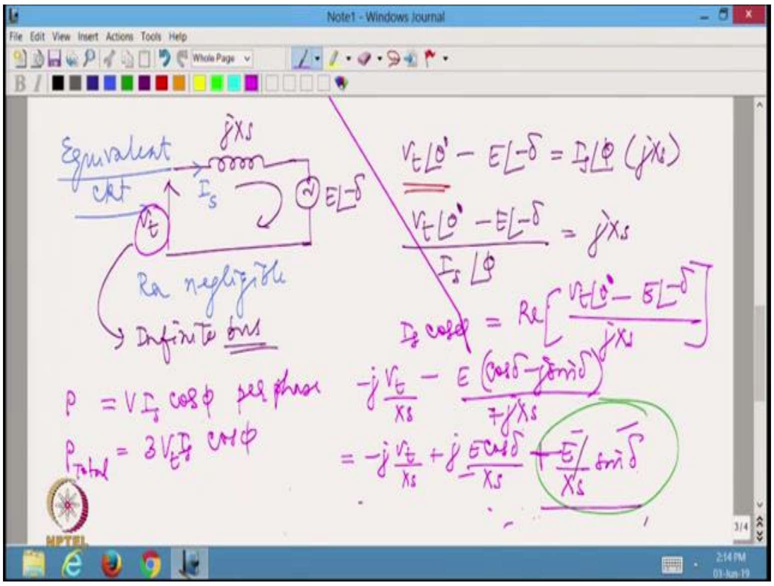

$V_t\angle 0^\circ - E\angle -\delta = I_s\angle\phi\,(jX_s)$

$\frac{V_t\angle 0^\circ - E\angle -\delta}{I_s\angle\phi} = jX_s$

$I_s\cos\phi = Re\left[\frac{V_t\angle 0^\circ - E\angle -\delta}{jX_s}\right]$

$-j\frac{V_t}{X_s} - \frac{E(\cos\delta - j\sin\delta)}{jX_s}$

$= -j\frac{V_t}{X_s} + j\frac{E\cos\delta}{X_s} - \frac{E}{X_s}\sin\delta$

$P = VI_s\cos\phi$ per phase

$P_{Total} = 3V_tI_s\cos\phi$

So, if we are actually drawing the equivalent circuit without the resistance, I am simply going to have this jX_s and I am going to have a voltage V_t on this side and if it is a motor for example I am going to have this as $E\angle-\delta$, this is the equivalent circuit for the synchronous machine where we have neglected R_a, so we are assuming R_a is negligible which is justified. Now if it is a motor I am going to have the current flowing from here towards the induced EMF side.

So, this is stator current I_s, so If I try to write the equation I should write $V_t\angle 0$ specially if I am assuming that this is connected to an infinite bus I am going to assume that the voltage is going to be my reference vector, so I can write that as $V_t\angle 0$ without any problem. Now $V_t\angle 0 - E\angle -\delta = I_s\angle\phi\,(jX_s)$.

So this is going to be the equation which is essentially the KVL I have written for this particular loop, so I can write $\frac{V_t\angle 0 - E\angle -\delta}{I_s\angle \phi} = \mathrm{jX}_s$ but when I write the power per phase $P = VI_s \cos\phi$, this is going to be the power that is being absorbed by the machine, so this is transported from the infinite bus towards the machine if it is a motor and it is going to deliver it in the form of mechanical power.

So let me write this as P per phase, but for 3-phases when I write, I should write $P_{total} = 3V_t I_s \cos\phi$ this is going to be the 3-phase power, so I can say $I_s \cos\phi_s$ will be the real part of $\frac{V_t\angle 0 - E\angle -\delta}{\mathrm{jX}_s}$.

Now I should be able to let me write this as $\cos\phi$ itself not $\cos\phi_s$, so let me write this as $\cos\phi$ because I have used only $\cos\phi$ as the power factor. Now I can write $V_t\angle 0 - E\angle -\delta$ I should be able to write this as $\frac{V_t}{X_s}$ and this is $\frac{1}{j}$ this will be essentially -j and I am going to have $E\angle -\delta$.

So E this can be written as $\frac{\cos\delta - j\sin\delta}{jX_s}$, so this will be $\frac{E\cos\delta}{jX_s}$ so I can write $-\frac{E\cos\delta}{jX_s}$ because of which I should be able to write this as $-j\frac{V_t}{X_s} + j\frac{E\cos\delta}{X_s} + \frac{E}{X_s}\sin\delta$. So if I want to look at the real part alone this is the only real part that is percent. So this is going to be the real part that is available.

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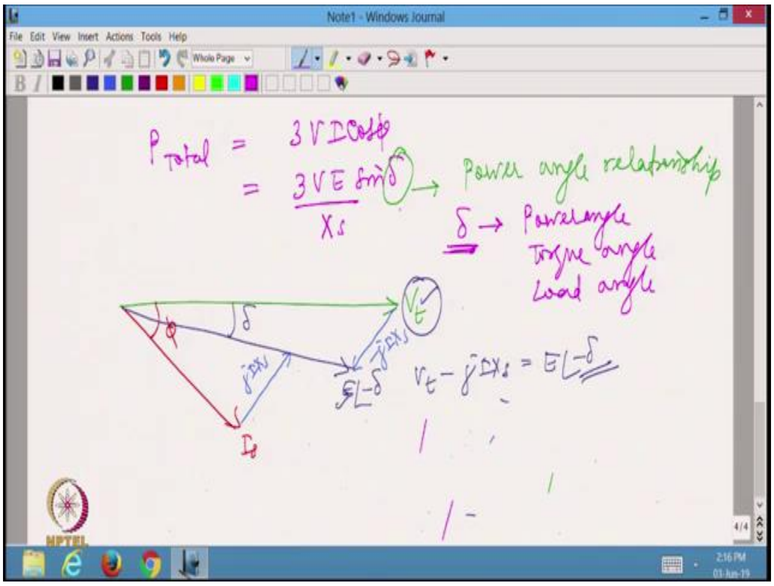

So, let me write the power what I have written as the total power $P_{total} = 3VI\cos\phi = \frac{3VE\sin\delta}{X_s}$. So this is essentially known as the power angle relationship for a synchronous machine. So this δ which is the angle between if I say this is actually my V or V_t and let us say I am going to draw a current which is I_s and which is having a phase angle of Φ I should be able to write that IX_s will be somewhat like this, this is what will be jIX_s.

So I have essentially write the same thing in the opposite direction which will become $-jIX_s$, so $V_t - jIX_s = E\angle-\delta$. Please note E is lagging behind V_t in a motor, so I am essentially having the relationship $V_t - jIX_s = E\angle-\delta$ and this particular δ which is the phase angle between V_t and E plays a very vital role in deciding how much power is being delivered by the machine.

So this δ is generally known as power angle or torque angle or load angle all of them are synonymous with each other, so this plays a very vital role in deciding how much is the power delivered either by the synchronous motor in the form of mechanical power or by the synchronous generator in the form of electrical power.

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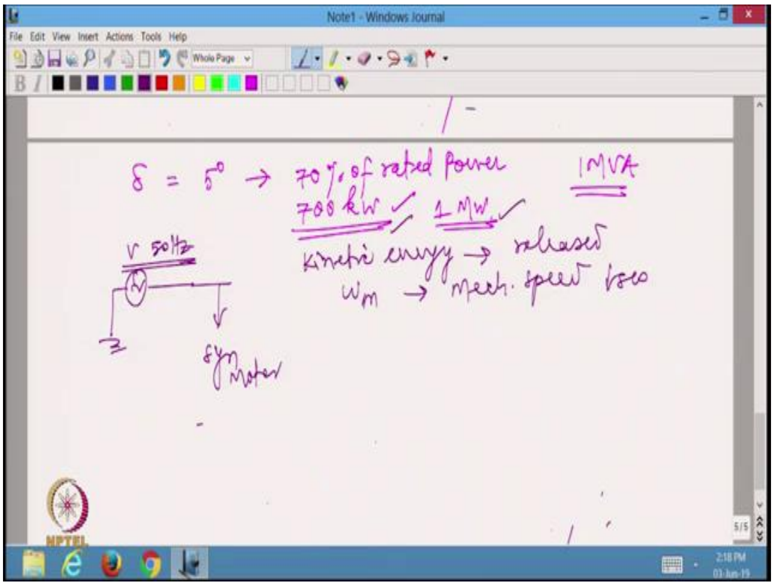

Now, when I have actually let us say a motor which is working at a particular δ let me take some value may be delta is 5 degrees, currently may be the machine is delivering 70 percent of rated power, let me assume it is 1 MVA or 1 MVA generator or motor and it is generating only 700 KVA or kilowatt that is all it is generating. Now if suddenly if it is a motor and I have increased the load to full value may be I have just increased it to 1 megawatt suddenly, now what will happen is instantaneously I am not going to be able to increase the current or increase the voltage nothing can be done.

Actually assume that the machine is connected to the infinite bus, so this is the infinite bus and here is where my synchronous motor is connected. So this voltage and 50 hertz both are set in stone I cannot change them. Now when I increase the power delivering capacity from 700 kilowatts to 1 megawatt I have increased the load, immediate response of the machine will be to release the kinetic energy, so I am going to see that the kinetic energy stored in the rotating parts will be released, when this is released speed is going to decrease. So ω_m, so mechanical speed this is going to decrease because the speed decreases.

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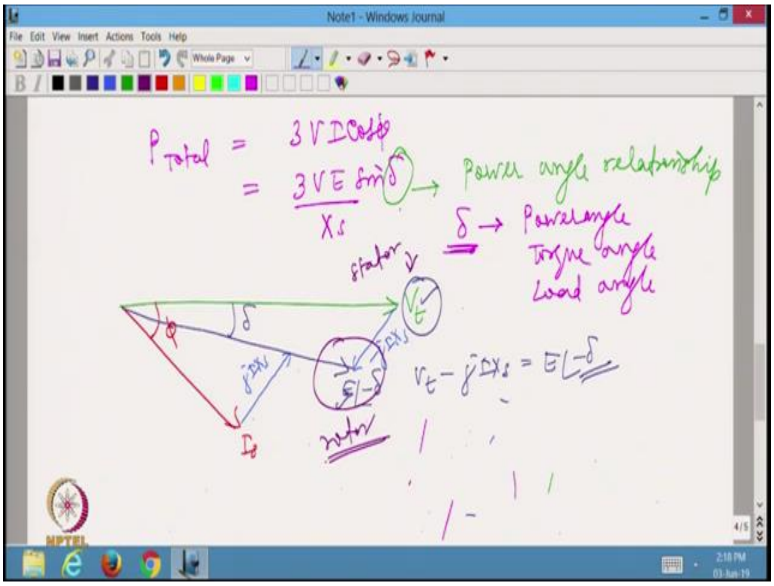

Now, please look at the phasor diagram this corresponds to the rotor whereas this corresponds to the stator. The stator frequency is set in stone that is 50 hertz whereas the rotor speed is not set in stone that depends up on at what velocity the rotor is rotating.

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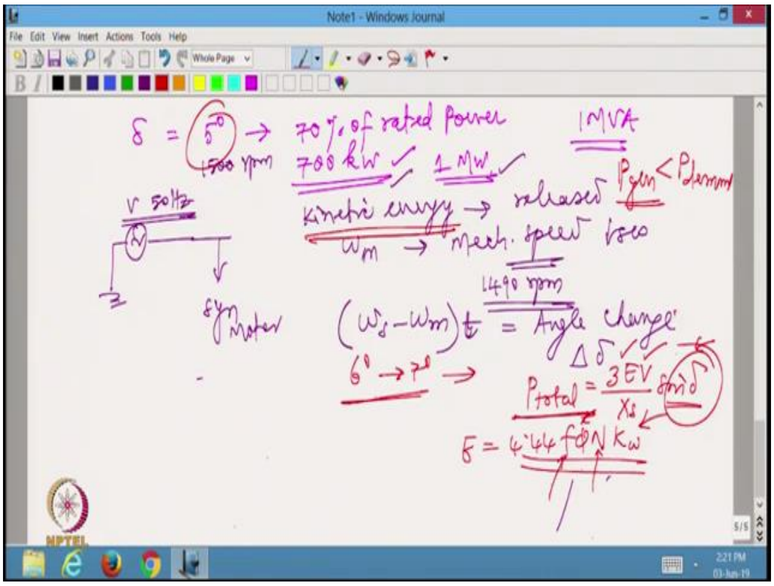

We said that the rotor speed has come down may be originally it was rotating at 1500 rpm now may be it has come down to 1490 rpm. Now between $(\omega_s - \omega_m)t$ is going to be the angle change or change in δ, so $\Delta\delta$ is going to this.

So, what will happen is originally my δ was 5 degrees, now slowly it will start increasing it will go to 6 degree, 7 degrees and so on and so forth it will be increasing, so what we wrote as P total which is $P_{total} = \frac{3VE\sin\delta}{X_s}$ if you look at V that is a constant may be E is also a constant because I have not change the frequency, I have not change the excitation please note $E = 4.44 f\phi N k_w$.

The flux will not change if I do not change the excitation, frequency cannot change because it is connected to infinite bus, number of turns cannot change because it is the structure of the machine, same is the case with the winding factor of the machine as well. So I am going to have essentially only things the P_{total} can change with this with δ and δ has increased, so P_{total} will definitely increase.

Please understand the kinetic energy was released because what was the P generated by the machine was less than P demanded from the load side. Now P generated from the machine is slowly increasing because δ is increasing.

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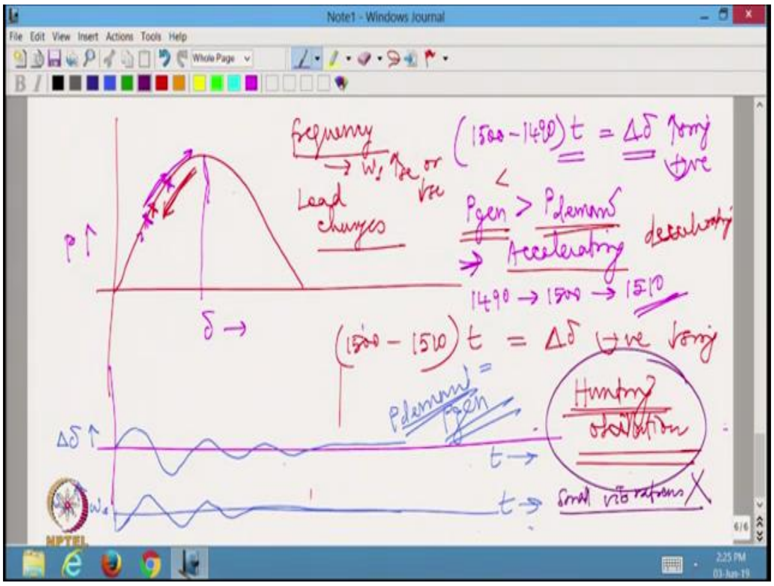

So, if I look at actually how the power is changing I should draw the variations somewhat like this, if this is δ and this power I am going to have increase in the power as δ increases, there is no doubt about that and the maximum power probably is somewhere here which will be much higher than even 1 megawatt. So probably originally it was operating somewhere here and it is moving in this direction.

Now the angle δ is increasing further and further because $(1500 - 1490)t = \Delta\delta$ and as time progress I am going to have increase in δ further and further. So if it is started from here and if it is 1 megawatt point is somewhere here it will even over shoot that and reach a point where may be it is generating 1.2 megawatt or something and at that point because $P_{gen} > P_{demand}$ I am going to have the machine accelerating or accumulating some kinetic energy.

So, from 1490 it will go to 1500 and it might go to even 1510, when it goes to 1510 what will happen is, now here $\Delta\delta$ was increasing or positive whereas now when the speed becomes 1510, 1510 subtracted from 1500 is going to be negative velocity which will make actually $\Delta\delta$ negative or decreasing, when it is decreasing now again the machine will start moving in this direction.

So I am going to have reduction in the power that is being generated, so it might reach a point where it reaches here, at this point again the machine will realize that P generated is smaller as compared to P demand, so again the machine will be decelerating or retarding. So what will happen is you will see that under this condition δ probably was at 5 degrees it increased then it will decrease, then increased, decreased and increase and settle at a particular value, whatever is the value at which $P_{demand} = P_{gen}$, so this is essentially δ variation versus t.

You can even call it as $\Delta\delta$ versus t that is also fine but when you actually look at the speed the speed will also actually it would have started from less than synchronous speed it would have increase, decreased, increased, decreased and ultimately settle at synchronous speed itself this is ω_s, so we are talking about ω_m how it is changing with respect to time, so also will be the torque, torque will also go from positive to negative or power will also go from if I want P demand, initially P generated was less, then it would have gone in increasing, decreasing and so on and ultimately it will settle down at P demand itself.

Now, this oscillation is generally known as hunting oscillation. Hunting is a very-very common phenomenon that is seen in any synchronous machine if there is a variation in the frequency. So if the frequency changes I am going to have simultaneously ω_s changing, this will also increase or decrease depending upon frequency change. Either frequency changes or load changes, in either case you would see hunting oscillations always occurring in a synchronous machine and this hunting oscillations is not good especially if I am looking at very critical loads where even small vibrations cannot be tolerated.

Even small vibrations cannot be tolerated then I would like to eliminate this hunting oscillation.

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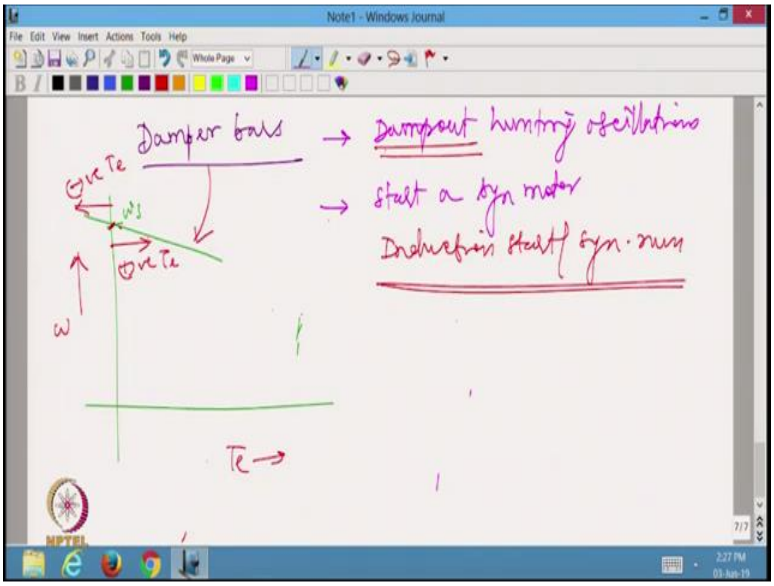

That is why we use something called damper bars. The damper bars have two purposes one is to damp out hunting oscillations, in this particular case because the damper bars are very similar to induction motor winding if I look at the induction motor torque please note if I am looking at this speed as ω_s and I am drawing this as ω and this as torque, I am going to have anything below synchronous speed I will have a positive torque, anything above synchronous speed I will have a negative torque.

So the torque, that is generated by the damper bars which is very similar to the squirrel cage bar that will always be pushing the motor or rotor to reach synchronous speed, so its major job is to push the rotor always to attain synchronous speed. So damping out the hunting oscillations is very effectively done by the damper bars. The second purpose of the damper bars which we discussed already is to start a synchronous motor, this we talked about earlier as induction start synchronous run motor. So this is another purpose of damper bars present in the case of a synchronous machine.

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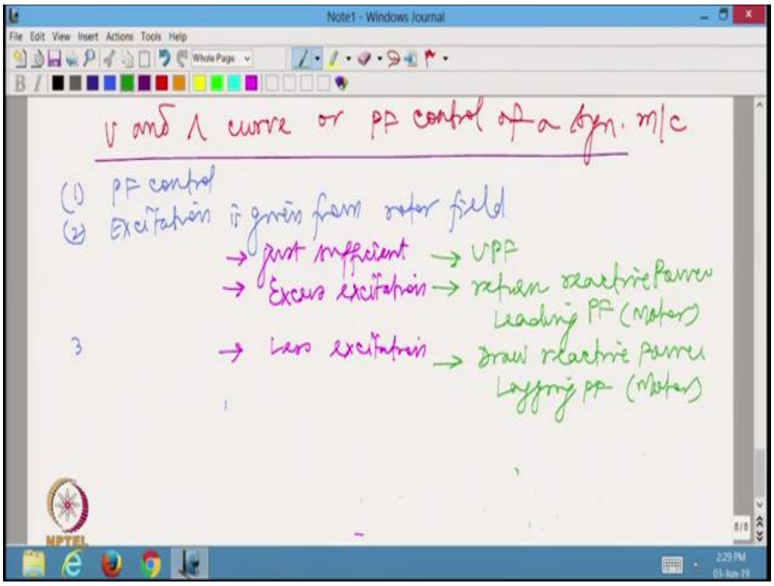

V and Λ curve or PF control of a Syn. m/c

(1) PF control
(2) Excitation is given from rotor field
→ just sufficient → UPF
→ Excess excitation → return reactive Power
Leading PF (Motor)
3 → Less excitation → Draw reactive power
Lagging PF (Motor)

One last topic I would like to take up before I finish synchronous machine is that V and inverted V curve or power factor control of a synchronous machine, we said that one of the major advantages of the synchronous machine is to have a power factor control what we meant was because excitation is given from the field side or rotor side, I can make it in X_S, I can make that less or I can make exactly whatever is needed.

So, we said if this is just sufficient then the machine is going to work at unity power factor. If I am going to give excess excitation which means I am giving excessive amount of reactive power, in that case we will return some reactive power to the mains, which means it is going to act like a capacitor so it will be a leading power factor machine, especially when it is functioning as a motor.

And if I am going to have the excitation slightly less or there is a short fall then I might have to draw some amount of reactive power from actually the grid which means I will have to make the machine function as an inductance. So we are going to see a lagging power factor for the motoring operation of the machine.

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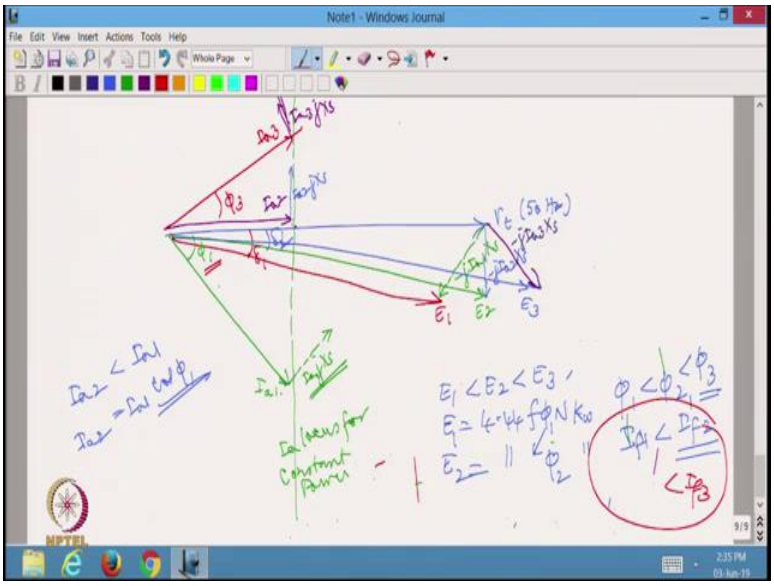

Let us try to analyze this with the help of a phasor diagram, so let me first draw may be the machine is connected to infinite bus, so I am going to have essentially this as my voltage. Please note this is connected to infinite bus so it has to have the same magnitude of voltage and same 50 hertz frequency, it cannot change. Under this condition let us say I have a current like this I am going to show this as I_{a1}, I am talking about the first condition of the current and I am showing a lagging power factor current.

Now, I am talking about V and inverted V curve, so I have to talk about this at the given power. So I am showing the locus of constant power locus for the current, so I_a locus for constant power. So what I mean is $I_a \cos\phi$ is somewhere here, if I draw $I_a \cos\phi$ this is have it. So $3V_t I_a \cos\phi$ is my real power, so irrespective of anything the real component of current the length has to be only this much that is what we are trying to say.

Now this is lagging power factor condition let me call this condition as I_{a2} which is unity power factor condition and I may have one more which is actually leading power factor condition which I am calling as I_3, so which is actually ϕ_3. Let me first of all complete the phasor diagram corresponding to this I_{a1}, so if I_{a1} if I have to draw the drop it is going to be $I_a jX_s$ corresponding to this I_{a1} here, if I subtract this quantity from V_t which I have to draw it like this which is actually parallel to this, so let me draw it like this, this is what is $-jI_{a1}X_s$ then I should be able to draw this particular point as E_1.

This is the excitation voltage corresponding to the first condition where I am having a lagging power factor ϕ_1. Let me try to draw this corresponding to I_{a2} now, if I try to look at I_{a2} I have to draw a perpendicular to this which will be actually $I_{a2} jX_s$, I want you to notice that I_{a1} is much longer than I_{a2} because this is like hypotenuse of this right angle triangle whereas this is the adjacent side of this right angle triangle.

Obviously I am going to have I_{a2} much less than I_{a1} because I_{a2} happens to be $I_{a1} \cos\phi_1$, $\cos\phi_1$ definitely has to be less than 1, so I will have I_{a2} less than 1. Now, If I draw this I_{a2} I have to draw it like this this is what it is, so this will be $-jI_{a2}X_s$, now if I draw the resultant $V_t - jI_{a2}X_s$ I will have it like this and this is E_2 and E_2 is definitely longer than E_1 and I can also draw the angles this is δ_1 whereas this is going to be δ_2 corresponding to the second condition.

Now, E_1 and E_2 if I compare I said E_1 is smaller than E_2 but any $E = 4.44 f \phi N k_w$, only thing that could have changed is ϕ, so if I write about E_1 this will be ϕ_1 whereas if I write about E_2 this will be ϕ_2 rest of the things being same, if $E_1 < E_2$ then I should have $\phi_1 < \phi_2$ which means the field current in the first case must have been smaller than the field current in the second case.

So as I increase the field current the machine moved from lagging power factor zone to unity power factor zone, let me look at the leading power factor zone as well. In the leading power factor zone I should have had $I_{a3}jX_s$, so I should have had it like this it should have been longer actually, so correspondingly I should have drawn this particular quantity which is

$-jI_{a3}X_s$ this is that quantity.

Now, if I have to join this I have to join it like this, this is what is E_3. So I should say $E_1 < E_2 < E_3$, so clearly I am going to have $\phi_1 < \phi_2 < \phi_3$. So as I increase the field current from I_{f1} to I_{f2} to I_{f3} the power factor moved from the lagging zone to the unity power factor zone to the leading zone.

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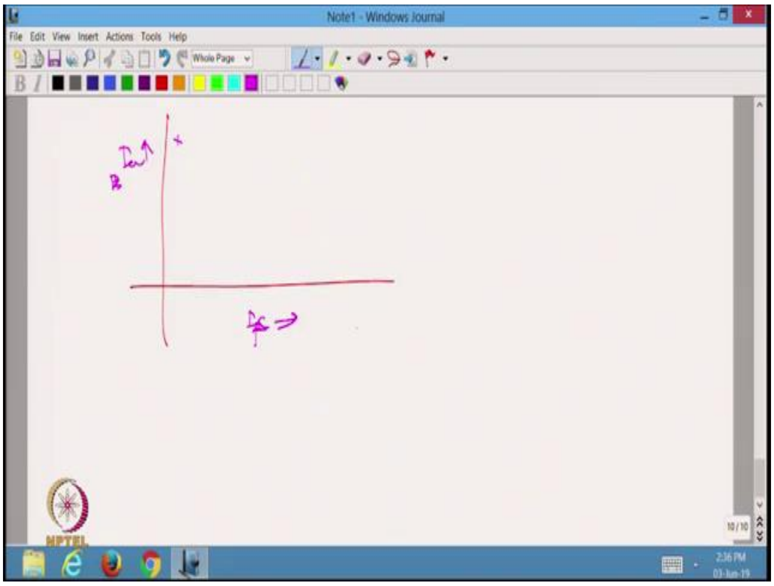

And this if I try to plot in the form of how I_a varies with respect to I_f, so I am trying to look at the field current.

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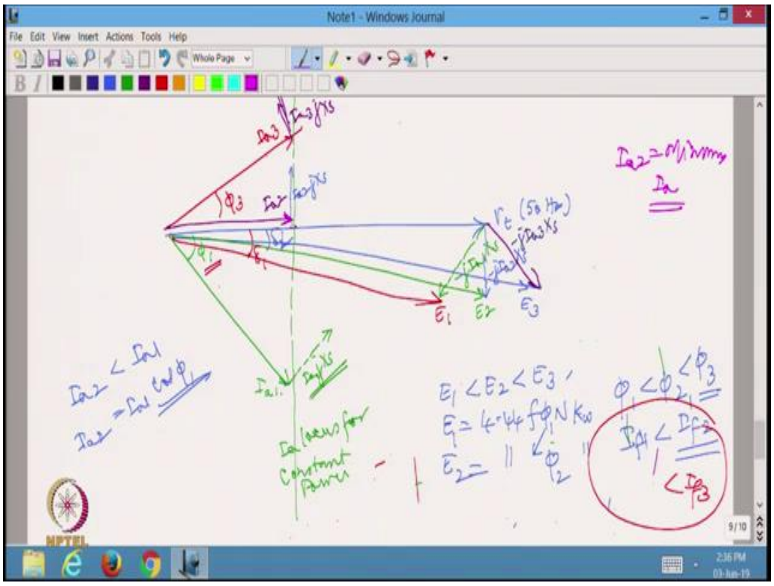

So initially it was at lagging power factor condition but it was drawing a longer or bigger current. When it was a unity power factor condition it was drawing minimum current when again it moves to leading power factor condition it drew a current which is higher, so would say I_{a2} is the minimum armature current.

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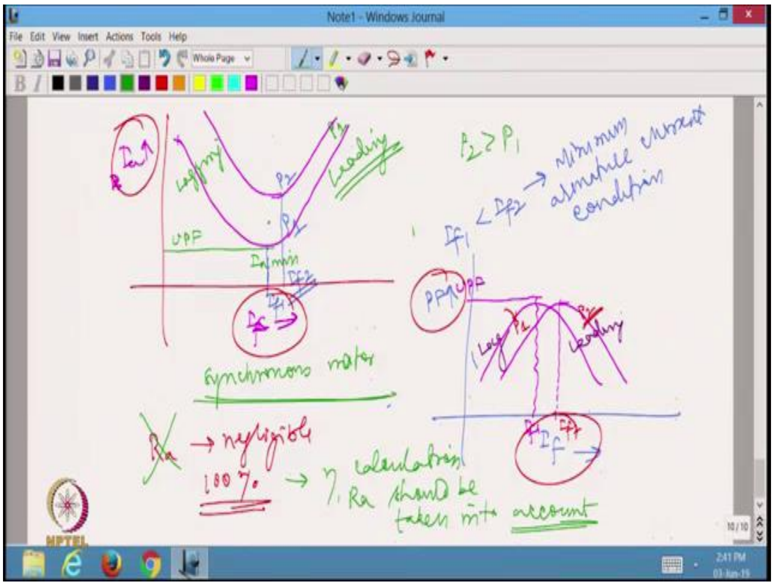

So when I draw I should show it as though at a particular point it becomes minimum armature current and in either of the field current side it is going to be higher than the minimum armature current. So, if this is my minimum armature current this is I_{amin} this will also correspond to UPF condition, unity power factor condition whereas this will be lagging and this will be leading, this is corresponding to a synchronous motor. So the overexcited or excessive excitation condition of a synchronous motor will always result in leading current.

Let us say this correspond to a particular power P_1, if I increase the power further I will again get some other armature current corresponding to that higher power condition, so I_{amin} for P_1 will be definitely smaller as compared to P_2 if $P_2 > P_1$, so I should draw one more graph which is probably like this. So this is corresponding to P_2 whereas this corresponds to P_1. But if this is the field current corresponding to let us say this is I_{f1} for P_2 I would have the minimum armature current corresponding to I_{f2} because to generate P_2 power which is greater than P_1 in all probability I will require a higher flux.

So, normally I would say I_{f1} is going to be smaller than I_{f2} which is actually minimum armature current condition, so they are not going to happen at the same I_f it would rather attract the larger flux or larger field current whenever I am demanding a higher power. On the other hand, I should be able to draw how the power factor changes again with field current, this is pretty clear I suppose because unity power factor occurs at optimum value of filed current.

So I can draw it somewhat like this, so this field current is the one or I_{f1} which is corresponding to unity power factor condition. Whereas this will be lagging and this will be leading. Let us say this corresponds to P_1 a particular power, if I am talking about P_2 we said I_{f2} will the optimum current corresponding to the higher power condition then correspondingly please note the power factor cannot be greater than unity.

So I have to essentially draw it corresponding to this as though this is the way the other curve is and this curve corresponds to P_2. The first curve corresponded to P_1 and this curve corresponds to P_2, so the V curves for the synchronous motor or the synchronous generator are always drawn between I_a and I_f, if in the X axis which is the excitation current, I_a is the armature current drawn from the stator side and inverted V curve are always drawn between the power factor on the Y axis and field current on the X axis.

What is kept as constant is the delivered power, be it motor or generator it does not matter we are essentially talking about the power to be held as a constant. Now because we said resistance is negligible there is hardly any real power loss that we are talking about then we will call almost the efficiency to be 100 percent, which defines the second law of thermodynamics, no machine can have 100 percent efficiency.

So, whenever we do the efficiency calculation we will normally consider R_a or R_a should be taken into account. Whereas whenever I am not doing efficiency calculation most of the times we may neglect R_a, so much so for the V and inverted V curve and hunting oscillations of the synchronous machine.

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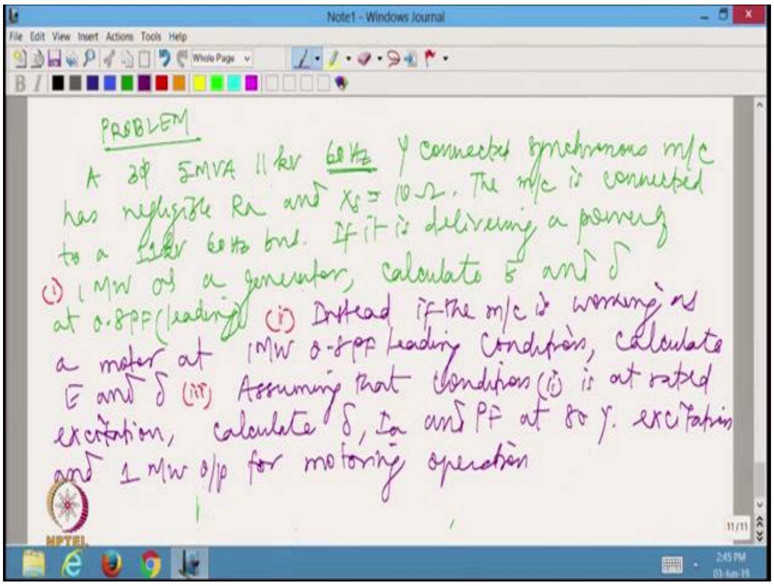

PROBLEM

A 3ϕ 5MVA 11kV 60Hz Y connected synchronous m/c has negligible R_a and $X_s = 10\,\Omega$. The m/c is connected to a 11kV 60Hz bus. If it is delivering a power

(i) 1MW as a generator, calculate E and δ at 0.8PF (leading) (ii) Instead if the m/c is working as a motor at 1MW 0.8PF leading condition, calculate E and δ (iii) Assuming that condition (ii) is at rated excitation, calculate δ, I_a and PF at 80 % excitation and 1 MW o/p for motoring operation

Let me try to work out one problem on synchronous machine, which will also give you a feel for what is actually regulation and so on and so forth. So let me take up the problem statement, so this problem statement is somewhat like this, a 3-phase 5 MVA, 11 kV, 60 hertz Y connected synchronous machine has negligible R_a and X_s =10 ohm and we have said it is already connected to a 60 hertz bus, so we do not have to take a variation of X_s at all, the machine is connected to a 11 kV, 60 hertz bus or grid.

If it is delivering a power of 1 megawatt as a generator calculate E and δ, ofcourse I have said 1 megawatt at 0.8 power factor leading this is the first question that is being asked. There is a second question, instead if the machine is working as a motor at 1 megawatt 0.8 power factor leading condition, calculate E and δ. Third portion is assuming that condition 2 is at rated excitation, calculate δ, I_a and power factor at 80 percent excitation and 1 megawatt output for motoring operation.

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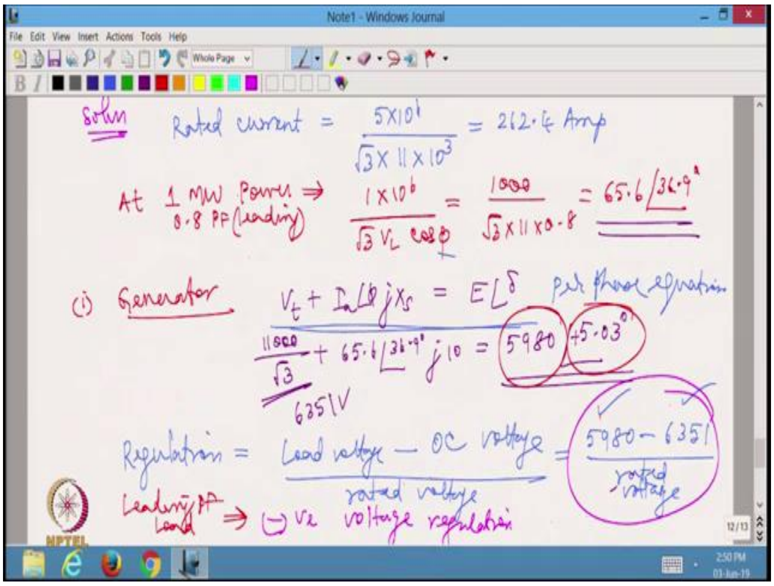

Soln

Rated current $= \frac{5\times10^6}{\sqrt{3}\times11\times10^3} = 262.4$ Amp

At 1 MW Power 0.8 PF (leading) $\Rightarrow \frac{1\times10^6}{\sqrt{3}V_L\cos\phi} = \frac{1000}{\sqrt{3}\times11\times0.8} = 65.6\angle36.9^{\circ}$

(i) Generator $V_t + I_a\angle\phi\, jX_s = E\angle\delta$ per phase equation

$\frac{11000}{\sqrt{3}} + 65.6\angle36.9^{\circ}\, j10 = 5980\angle+5.03^{0}$

6351V

Regulation $= \frac{\text{Load voltage} - \text{OC voltage}}{\text{rated voltage}} = \frac{5980-6351}{\text{rated voltage}}$

Leading PF Load $\Rightarrow$ (−) ve voltage regulation

Let us try to work out the solution, so let me start with first of all calculating the rated current, so rated current is $\frac{5*10^6}{\sqrt{3}*11*10^3} = 262.4A$.

Now let us try to look at what is the condition at 1 megawatt power and this is also given 0.8 power factor leading, please note whenever you are calculating the power weather it is lagging or leading it is not going to matter, so $\frac{1*10^6}{\sqrt{3}V_L\cos\phi} = \frac{1000}{\sqrt{3}*11*0.8} = 65.6\angle36.9^0$.

This current is leading the voltage that is what is given, so when this is functioning as a generator. I have to write $V_t + I_a\angle\phi\, jX_s = E\angle\delta$, please note V_t because it is star connected I have to write $\frac{11000}{\sqrt{3}} + (65.6\angle36.9^0)\, j10 = 5980\angle+5.03^0$.

Please note δ is positive, so it is clearly generator operation 5980 is smaller than this V_t whatever we got this $\frac{11000}{\sqrt{3}}$ is 6351 volts.

So I am going to have actually under this condition I can calculate regulation all though this is not asked I am just calculating it, $\text{Re}\,gulation = \frac{Load\ voltage - OC\ voltage}{Rated\ voltage} = \frac{5980-6351}{Rated\ voltage}$.

Please note that the terminal voltage happens to be higher than the generated voltage which will happen under leading power factor condition, normally any leading power factor condition is going to give rise to a higher voltage at the terminal.

You had seen this in transformers as well, so this is essentially negative voltage regulation this is because of leading power factor condition, this is an additional point I just wanted to mention. Now let us try to work out, so from whatever we got we can say E is 5980, δ is 5.03 degrees, so these two have been solved.

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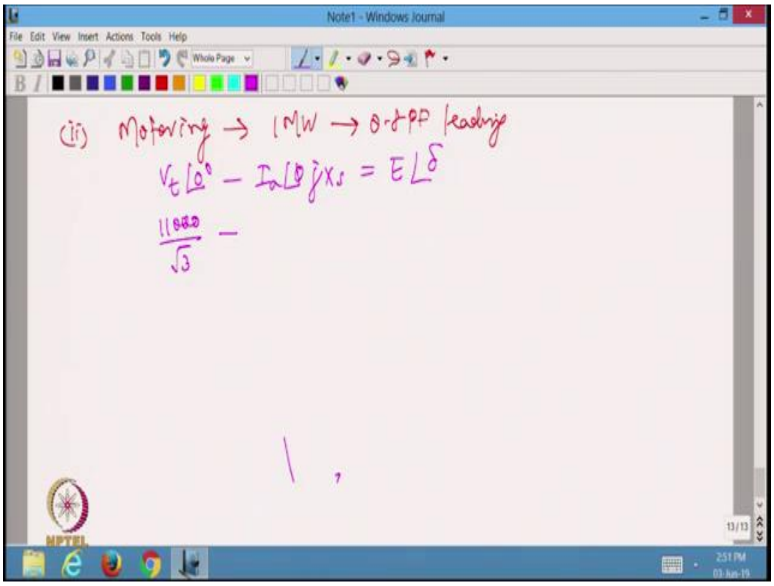

(ii) Motoring → 1MW → 0.8 PF leading

$V_t\angle 0^\circ - I_a\angle\phi\, jX_s = E\angle\delta$

$\frac{11000}{\sqrt{3}} -$

Now, let us try to go to point number 2, where the same 1 megawatt is delivered under motoring condition, under 0.8 power factor leading. All you need to do is you have to say $V_t\angle 0 - I_a\angle\phi\ \mathrm{j}X_s = E\angle\delta$, here δ will automatically come out to be negative.

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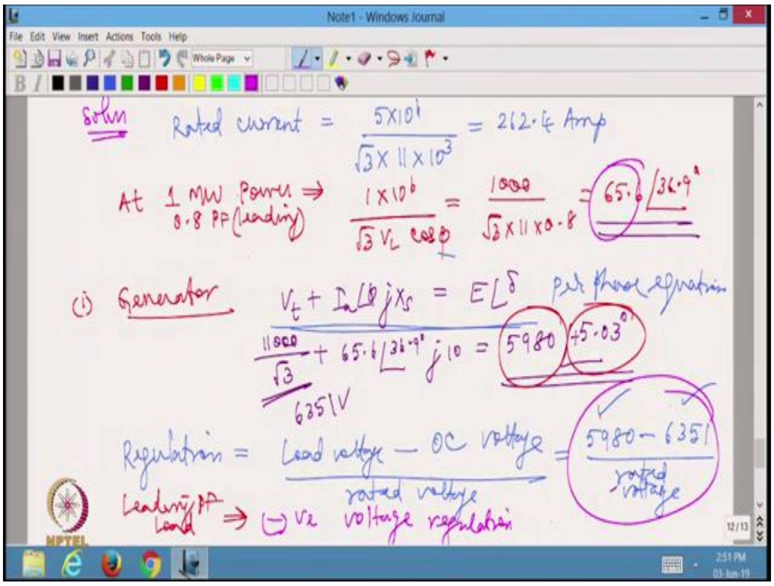

Soln Rated current $= \frac{5\times10^6}{\sqrt{3}\times 11\times10^3} = 262.4$ Amp

At 1 MW Power 0.8 PF (leading) $\Rightarrow \frac{1\times10^6}{\sqrt{3}V_L\cos\phi} = \frac{1000}{\sqrt{3}\times11\times0.8} = 65.6\angle36.9^\circ$

(i) Generator $V_t + I_a\angle\theta\, jX_s = E\angle\delta$ per phase equation

$\frac{11000}{\sqrt{3}} + 65.6\angle36.9^\circ\, j10 = 5980\angle+5.03^\circ$

6351V

Regulation $= \frac{\text{Load voltage} - \text{OC voltage}}{\text{rated voltage}} = \frac{5980-6351}{\text{rated voltage}}$

Leading PF Load $\Rightarrow$ (−)ve voltage regulation

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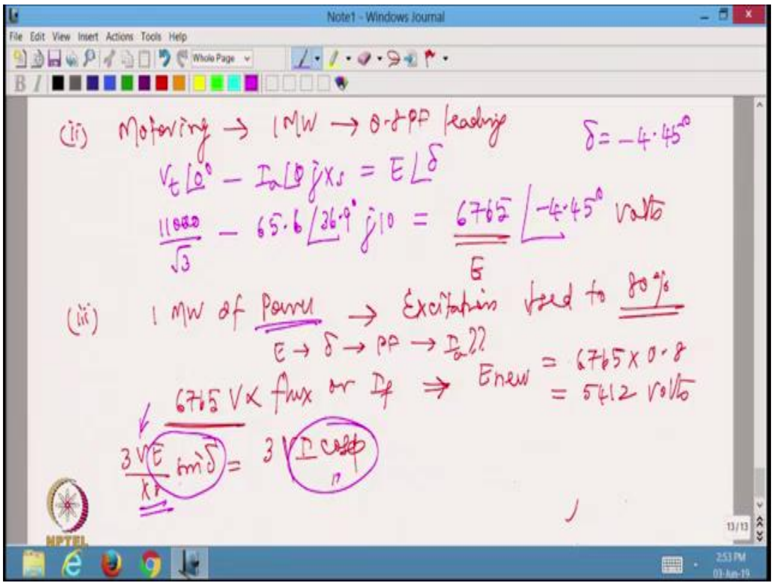

(ii) Motoring → 1MW → 0.8 PF leading $\delta = -4.45^\circ$

$V_t\angle0^\circ - I_a\angle\theta\, jX_s = E\angle\delta$

$\frac{11000}{\sqrt{3}} - 65.6\angle36.9^\circ\, j10 = \underset{E}{6765}\angle-4.45^\circ$ volts

(iii) 1 MW of Power → Excitation reduced to 80%

$E \to \delta \to PF \to I_a$??

6765 V $\propto$ flux or I_f $\Rightarrow$ $E_{new} = 6765\times0.8 = 5412$ volts

$\frac{3VE}{X_s}\sin\delta = 3VI\cos\phi$

$\frac{11000}{\sqrt{3}} - 65.6\angle 36.9^0\ j10 = 6765\angle - 4.45^0$. Please note in the previous case, δ was +5.03 degrees, whereas in this case δ happens to be -4.45 degrees and similarly this happens to be E whereas in the previous case the E was only 5980. Now in this case only these two are asked, in the third case still we are going to have 1 megawatt of power but excitation is decreased to 80 percent. Previously excitation was 100 percent, now excitation is 80 percent.

Now what is being asked is what is E? What is δ? What is the power factor? What is I? Everything is being asked. Now here we got E to be 6765 volts and this is proportional to the flux or I_f when it was 100 percent flux I had 6765 volts, when it is 80 percent I am going to have $E_{new} = 6765 * 0.8 = 5412V$.

Now, one more thing we said was $\frac{3VE\sin\delta}{X_s}$ which is also equal to $3VI\cos\phi$, we said normally $I\cos\phi$ is a constant whenever power is constant, similar thing we should be able to say $E\sin\delta$ is constant because X_s is dependent up on the frequency, infinite bus X_s will be a constant, V is connected to infinite bus so that is also constant, so only thing is $E\sin\delta$ is dependent up on the power, so if power is a constant $E\sin\delta$ is a constant.

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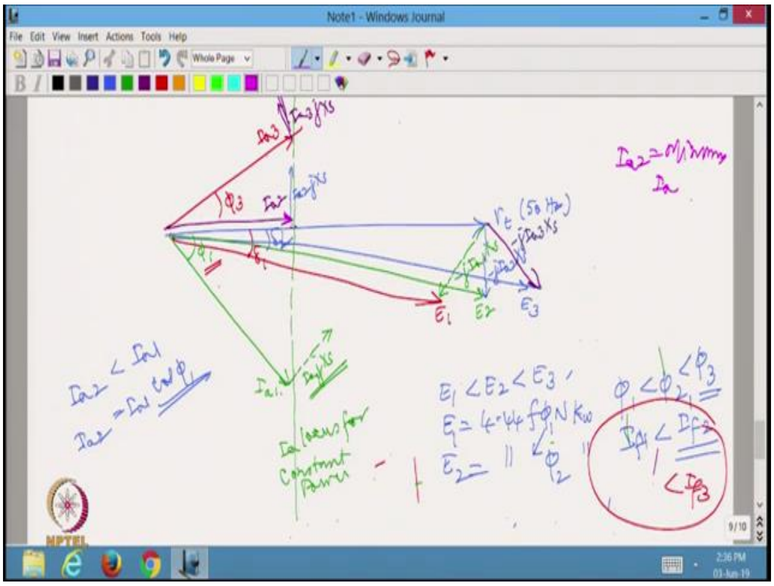

I would like to emphasis that from the phasor diagram what we do earlier, if I try to look at what is $E\sin\delta$ this vertical distance this will be $E\sin\delta$, this $E\sin\delta$ will be a constant as long as power is a constant.

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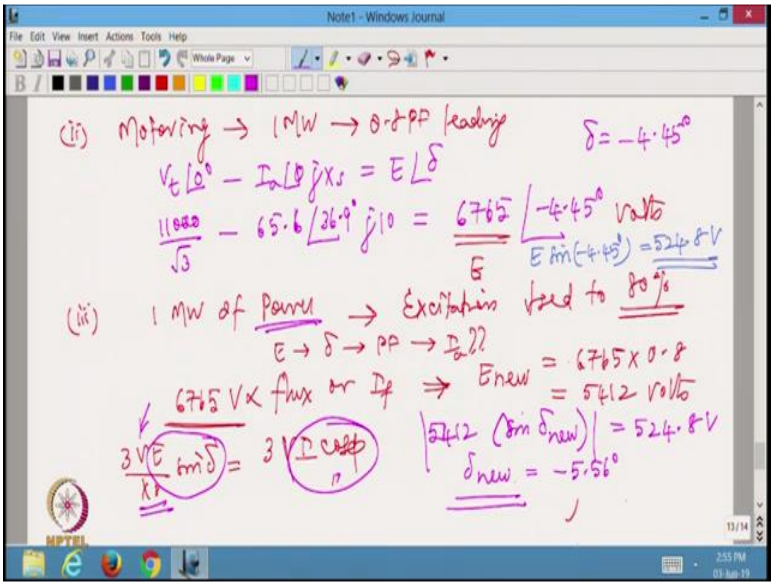

(ii) Motoring → 1MW → 0.8 PF leading $\delta = -4.45^\circ$

$V_t\angle 0^\circ - I_a\angle\phi\, jX_s = E\angle\delta$

$\frac{11000}{\sqrt{3}} - 65.6\angle 36.9^\circ\, j10 = \underbrace{6765}_{E}\angle -4.45^\circ$ volts

$E\sin(-4.45^\circ) = 524.8\,V$

(iii) 1 MW of Power → Excitation reduced to 80%

$E \rightarrow \delta \rightarrow PF \rightarrow I_a$??

$6765\,V \propto$ flux or I_f ⇒ $E_{new} = 6765 \times 0.8 = 5412$ volts

$\frac{3VE}{X_s}\sin\delta = 3VI\cos\phi$

$|5412(\sin\delta_{new})| = 524.8\,V$

$\delta_{new} = -5.56^\circ$

So, let us try to look at what had been $E\sin\delta$ in the previous case, this is $E\delta$. So $E\sin\delta$ will be $E\sin(-4.45^0)$. This came out to be something 524.8 volts, so I should say in this case also $|5412\sin(\delta_{new})| = 524.8$, because $E\sin\delta$ has to remain as a constant. So δ_{new} happens to be now -5.56 degrees from here you should be able to solve for this.

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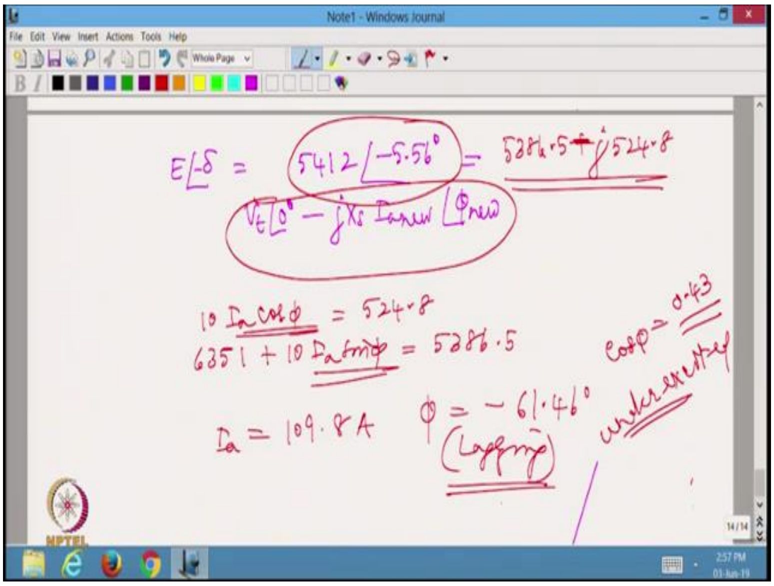

$E\angle-\delta = 5412\angle -5.56^\circ = 5386.5 + j524.8$

$V_t\angle 0^\circ - jX_s I_{anew}\angle\phi_{new}$

$10 I_a\cos\phi = 524.8$

$6351 + 10 I_a\sin\phi = 5386.5$

$I_a = 109.8\,A$ $\phi = -61.46^\circ$ (Lagging)

$\cos\phi = 0.43$ underexcited

Once you have got delta new this is pretty simple now, because I know, I should be able to say $E\angle\delta$ in the new condition which is $E\angle-\delta = 5412\angle-5.56^0 = V_t\angle 0 - jX_s I_{anew}\angle\phi_{new} = 5386.5 - j524.8$. So you would get basically there is one real part and one imaginary part, similarly you will be able to get one real part and one imaginary part here. So I would say $10I_a \cos\phi = 524.8$ and $6351 + 10I_a \sin\phi = 5386.5$.

Now from this I should be able to solve for $\cos\phi$ as well as I_a, so I_a happens to be 109.8 ampere and ϕ happens to be -61.46 degrees, this is lagging clearly, please note by reducing the excitation the machine has moved from leading power factor condition to a lagging power factor condition, this $\cos\phi$ may be something like 0.45 or 0.43 or something like that. So, it has really come to a very-very low value of lagging power factor condition, this tells that this is under excited condition whereas that was overexcited condition.

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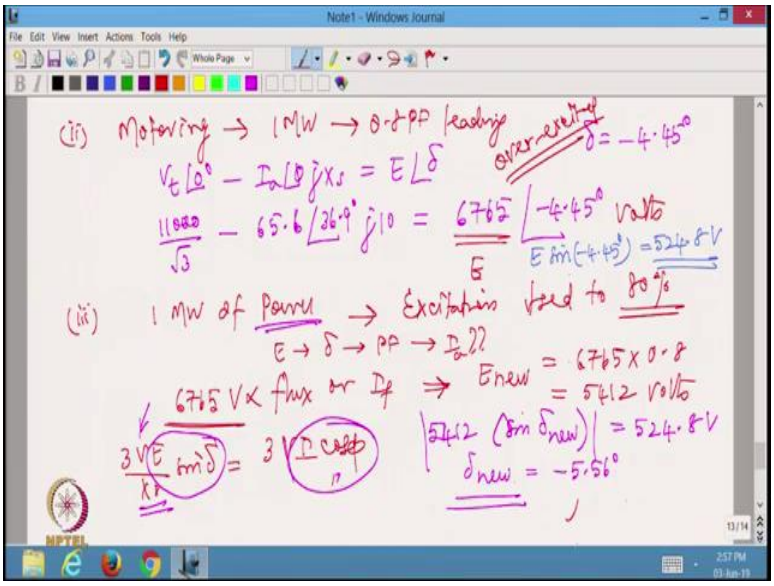

(ii) Motoring → 1MW → 0.8 PF leading

$V_t\angle 0^\circ - I_a\angle\theta\, jX_s = E\angle\delta$ overexcited $\delta = -4.45^\circ$

$\frac{11000}{\sqrt{3}} - 65.6\angle 36.9^\circ\, j10 = \underbrace{6765}_{E}\angle -4.45^\circ$ volts

$E\sin(-4.45^\circ) = 524.8\,V$

(iii) 1 MW of Power → Excitation red to 80%

$E \to \delta \to PF \to I_a$??

$6765\,V \propto$ flux or I_f ⇒ $E_{new} = 6765 \times 0.8 = 5412$ volts

$\frac{3VE}{X_s}\sin\delta = 3VI\cos\phi$

$|5412\,(\sin\delta_{new})| = 524.8\,V$

$\delta_{new} = -5.56^\circ$

The original one what we saw was overexcited condition, so this is indirectly showing how V or inverted V curves works.

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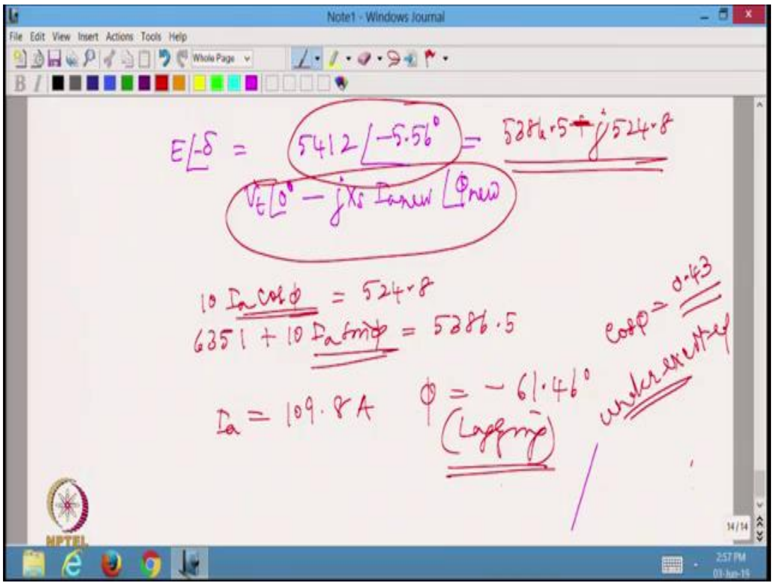

$$E\angle{-\delta} = \boxed{5412\angle{-5.56^\circ}} = \underline{\underline{5286.5 + j524.8}}$$

$$\boxed{V_t\angle{0^\circ} - jX_s I_{a\,new}\angle{\phi_{new}}}$$

$$10\,\underline{\underline{I_a\cos\phi}} = 524.8$$

$$6351 + 10\,\underline{\underline{I_a\sin\phi}} = 5286.5$$

$$I_a = 109.8\,A \qquad \phi = -61.46^\circ$$

(Lagging)

$\cos\phi = \underline{\underline{0.43}}$

underexcited

So on the whole we have completed whatever we had to do in terms of synchronous machine. we had started off with its constructional features, we had looked at its equivalent circuit, we had looked at winding factors and so on then we had looked at synchronization, then we had derived the power angle equation, hunting oscillation. We had also looked at V and inverted V curve and on the top of that we had also looked at one of the problems, how to work out. Thank you so much for your attention.