Electrical machines

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Lecture 38

Synchronous Machines: OC and SC test

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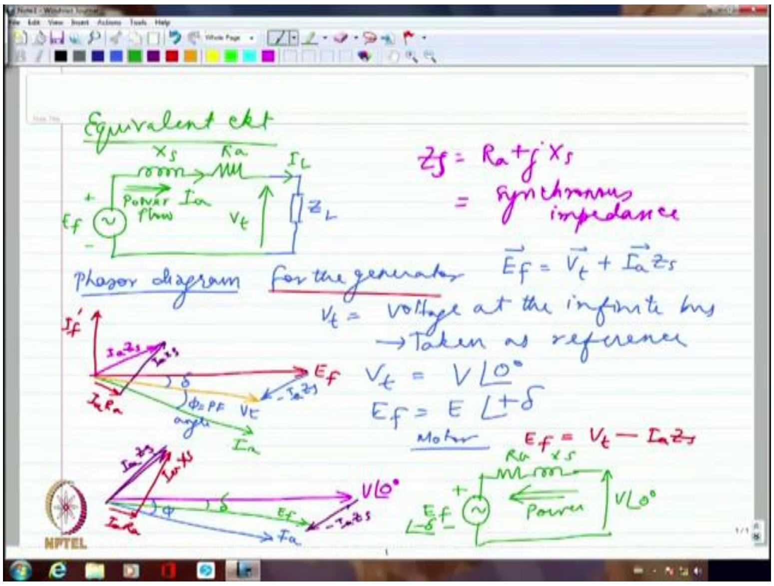

We said that we are going to have a huge reactant, as the series reactant itself in the equivalent circuit model. Because I am going to have the summation of the magnetizing reaction plus leakage to together as the overall reactants. So, if it is a generator I am going to have the induced EMF E_f which is due to the main field flux or the rotor flux that is essentially E_f. Which is going to have a frequency, which is decided by the rotational speed of machine.

Then, we are going to have a value which is X_s which is actually a large reactance value. Which has two portions, one corresponding to the magnetizing reactance, the other one corresponding to leakage. So both of them are going to be there. Then, we will have an armature resistance which is the resistance of the copper winding, which is sitting in the armature. Then finally what is available, this is going to be manifested as the terminal voltage V_t. And, here is where I am going to connect the load.

So, this is going to be my electrical load as far as the generator is concerned. So I may have called this as Z_l. So depending upon whether Z_l is going to be inductive or capacitive or resistive, it is going to decide the power factor. When we actually drew the current in the phasor diagram, we specified as though the power factor with respect to E. Which is not really true because we generally look at the power factor as the angle which is between the load current and load voltage, not really the excitation voltage.

But just for simplicity I started drawing like that. So let us try to look at the phasor diagram once again. So we drew the phasor diagram for the generator, which I want to specify once again. So this is going to be probably my E_f, if I say I_f is somewhere here. I should not specify this as I_f rather it is I_f^l. So, I am going to have this as I_f^l which is the equivalent current on the AC side which would have actually created a similar flux as that of what as actually is the rotating flux of the rotor.

The rotor is not having rotating flux electrically; it is because the physically rotating poles. So physically rotating poles creates a revolving magnetic field. If I had injected a 3-phase current to produce a similar revolving magnetic field what would I have been the magnitude of the 3-phase current on a per phase basis that is what is I_f^l. So I_f^l is the equivalent AC current that I am visualizing such that the strength of the magnetic field would be the same as that of the rotor magnetic field.

So this is E_f and I am probably going to have my current which is somewhat like this. This is going to be I_a, if I may call this as I_a or I_l same as the load current. And I am going to have clearly with respect to load current. If I draw a similar vector in phase with that, that is going to be I_aR_a. And perpendicular to that I should draw as I_aX_s. So when i add these two I am going to get I_aZ_s, Z_s is the synchronous impedance. So I would say $Z_s = R_a + jX_s$. So we call this as synchronous impedance.

Now, this particular I_aZ_s has to be subtracted from E_f only then I will get what is known as V_t. So I can say that I have to just draw a vector, which is probably in the opposite direction. So this is I_aZ_s with a negative sign, this is going to be I_aZ_s. So when I am looking at the resultant this is going to be the resultant. Then I $E_f - I_aZ_s = V_t$. So this is the case when I am talking about the generator.

So now if I now look at it between Ef and Vt that is the angle of δ, I call this as δ this is the very-very significant parameter in the case of a synchronous machine. And I am going to have this as the power factor angle. Because this is the phase shift between V_t and I_a. And this is what is the power factor angle originally what we wrote at the power factor angle is not correct. It is rather $\delta + \phi$, what we got originally, what we mentioned as the phase shift between E_f and I_a that is actually $\delta + \phi$.

Whereas, ϕ is the power factor angle and this V_t in variably will be to the infinite bus, it will be connected to the infinite bus. When we synchronous the generator V_t will be actually connected to the infinite bus. So I would say rather V_t is kind of certain stone, you cannot change its frequency, you cannot change its phase angle. If you may magnitude, if you may take as that as a reference then I may say that $V_t = V\angle 0^0$ whereas $E_f = E\angle +\delta$. So normally V_t is the voltage at the infinite bus.

Because of which this is taken as reference, so normally we write $V_t = V\angle 0^0$. So $E_f = E\angle +\delta$ for a generator. Please clearly note that E is leading, it is going to lead the voltage V_t in the case of a generator. On the other hand, if I try to draw similar thing for the motor. I am going to have basically, again let me draw may be this is what is my $V\angle 0^0$ I am starting with $V\angle 0^0$. If I have $V\angle 0^0$ like this, may be the current drawn by the armature is going to be somewhere here.

Which is I_a and this going to be my power factor angle ϕ. And in the case of generator we said that $E_f = V_t + I_a Z_s$. All these things are vectors, whatever we are writing all of them are vectors phasors rather. Whereas, in the case of motor when we talk about motor, we said that we are going to have $E_f = V_t - I_a Z_s$. So let us try to again draw what is the value of I_aR_a, probably I_aR_a is like this. Now I am going to have I_aX_s like this.

Student: Why Z_i is not represented in the phasor diagram?

Professor: Please note that the load impudence is the power that is been developed. We are talking about the drop within the machine. It can be a resistance, it can be a reactance, it can be a capacitance, it can be a simply feeding the power to the infinite bus. It can be a motor 3-phase induction motor may be drawing a power from the generator. So I do not know what sort of load it is. So we are just not including the load impudence because we are assuming that, that is the bulk power that is been transmitted to may be infinite bus, may be to the load, may be whatever, whichever is the load system.

Now this is going to be, I am sorry this is going to be my I_aZ_s again. So I have to draw the same I_aZ_s in the opposite sense. So maybe this is $-I_aZ_s$ in which case I am going to get the resultant E_f somewhere here. That is when I try look at $E_f = V_t - I_a Z_s$. Now this angle I may call as δ again, but please not E_f is lagging behind the terminal voltage V_t. So generator and motor have this distinctive feature.

This will distinct whether it is the functioning as a motor or whether it is functioning as a generator. So if I am going to have E_f leading, I can say the power is flowing from E_f towards this side, this is the direction of power flow. Whereas, if it is a motor I am going to have actually here is where my $V\angle 0^0$ is. And I am going have R and X as here. So this is R_a, this is X_s and here is where my back EMF is, which is E_f. So the power is flowing in this direction.

So in the case of a motor, the power is flowing from the 3-phase infinite bus into the machine. Whereas in the case of the generator it is flowing from the machine back to the bus. So, whichever is having a leading angle that pushes the power in. Whichever is having the leading angle, in this case E_f is having the leading angle. So, E_f pushes the power back to the mains or 3-phase supply, 3-phase finite bus. Whereas in the case of motor I am going to have this as the leading thing, whereas this is lagging.

So I will be able to write this as $E_f \angle -\delta$. If I say $V\angle 0^0$, in one case E_f becomes E_f +δ which is in the case of generator. Whereas $E_f \angle -\delta$ happens to be the phase angle, in the case of motor for the excitation voltage. So, whichever has the lagging angle that is going to absorb the power. Whichever has the leading angle that is going to supply the power. This is very-very important characteristic in AC systems. In DC systems the current will flow from a higher magnitude to the lower magnitude.

Whereas, in AC systems always the power will try to flow from a leading angle to the lagging angle that is the way the power flow occurs. So, if I am having some power requirement for exampling in Delhi, I may be I have local power generating stations Badarpur and so on so forth. But if I consider Delhi as a node and I want to take a power from somewhere else, I have to make sure that the power angle of the other side, from where want to guzzle up power that has to be at a leading power factor angle.

So, generally we have to make sure of this in the case of AC power transmission, so many of the times the control of AC power transmission is through the phase angle control. Very often we try to adjust the phase angle and then make sure that sufficient amount of power flows. So, this is one of the major differences between the generator and motor. If this is clear, let us know try to look at how to determine the parameters of the synchronous machine by making use of open circuit test and short circuit test.

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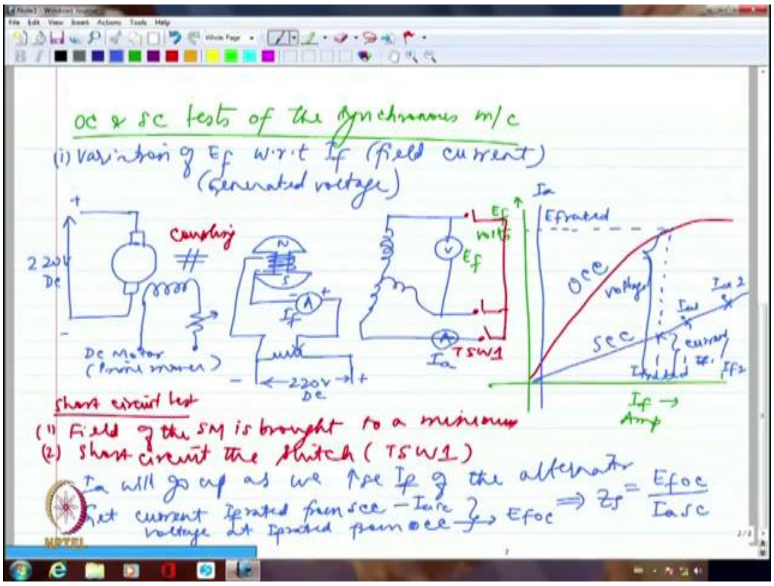

So, let us try to look at that and what is the power expression, these are the two things that I am going to do. So let us try to look at open circuit and short circuit test of the synchronous machine. Open circuit test I think I have already told I do not need to specify it once again. Because what we get from here is the open circuit characteristics. So what we try to get is variation of E_f, I just changed E_g to E_f. Because now i am calling it E_f throughout.

So variation of E_f with respect to I_f, that is the field current. This is the generated voltage in the armature under open circuit condition ofcourse. So I am not connecting any load to the armature, there is no question of any armature reaction and so on and so forth. So what I am going to do is something like this. I have a prime mover, I am showing it to the form of DC motor, because this is what we use in the laboratory so I am exactly showing it like what we do.

So, maybe it will be a separately exited DC motor it does not matter and I am going to apply the voltage say 220 volts DC, ofcourse I will have a stator, I may have a rectifier, I may have large resistance whatever. But I will have a stator along with the DC machine. And I do have a field, so field will also have a resistance. So that I can adjust the speed to exactly 1500 rpm if it is 4 pole machine. I can adjust it to 3000 rpm if it is a 2 pole machine. So this is going to be my prime mover. So, this is the DC motor which is acting like a prime mover.

Only thing what I will measure here, is to make sure that the speed is 1500 rpm if it is a 4 pole machine. Nothing else is needed, I do not need really the field current or anything here. Because I am not concerned about the DC machines characteristics. Now this is going to be coupled to a synchronous machine which is having the rotor. So let me show the rotor somewhat like this. So this is the rotor of the synchronous machine and maybe I have the field here, this is the field.

Now this field also has to be connected to a DC supply along with an ammeter. So that I am able to exactly measure how much is the field current that is flowing through the field of the synchronous machine. So I am going to have, let us say this is my DC supply which is 220 volts DC and I am going to have say plus here and minus here. And then I am having a potential divider so this I am connecting here and this I am connecting here. So I am applying a variable potential to the field.

This enables me get either 0 field current or I can go to maximum field current. So I will put obviously a DC ammeter here. Now this is actually going to have the armature now. So this is the armature and it is open circuited and I am going to put a voltmeter here. And I have to only make sure that I run it at a particular speed which is corresponding to synchronous speed that is about it nothing more than that. So I keep on increasing the flow of current of the synchronous machine and then I note down, what is the voltage generated.

So, I am going to get essentially a characteristic somewhat like this. So this is E_f, so I am measuring E_f and I am going to have I_f. So this is in amperes ofcourse this in volts and then I am going to have a characteristic somewhat like this. So this is what is my OCC. The next test that we are going to conduct is the short circuit test.

This is the coupling; how will you drive the synchronous machine otherwise? You have to rotate it, I do not have a turbine, I am using the DC motor as my prime mover. So it is providing the mechanical powering input so that the synchronous machine works as a generator. They can reverse the role very well, if they have to reverse the role they will do that very nicely. So if provide 3-phase supply to the synchronous machine, it will work very beautifully as a motor, there is no problem. In that case DC machine will work as a generator and then I can connect a load. That is not a problem rather than connecting a DC supply 220 volts DC I can remove that and connect a load, resistance load.

Rotor will have to get definitely a DC supply no matter what, whether it is functioning as a motor or generator. The field has to be excited I do not know whether I answered your question. But, the speed is decided by the frequency now. If it is working as a motor, if it is a synchronous motor, the speed is decided by the frequency. So if I connect it to 50 Hertz no matter what, if it is a 4 pole machine it is going to run at 1500 rpm. You cannot make it run at any other speed, its certain stone.

If you are changing the frequency you will get a different speed. So synchronous motors are essentially constant speed motors. They will not even have the small variation what is seen in an induction machine, no way there will not be any change. So, if I want to have a speed control, I have to have frequency control. No wonder we have become a very important commodity, power electronic engineer, who make inverters, who basically generate variable frequency.

So, all the synchronous motors are now able to run at variable speed. If I am able to generate variable frequency, that is the reason. So in short circuit test what we are going to do is everything else remain the same only thing is I will make sure that first of all field of the synchronous machine is brought to a minimum. I will have to bring it to a minimum because with full voltage I would not like to short circuit the machine. And generally what we try to do is to have a switch connected here.

Because we do not want to again start the DC motor from 0 speed bring it up to 1500 rpm and so on so forth. Very often what we do is to provide a 3-phase switch here and then we will try to short circuit this switch. We will close the switch once; open circuit test is done. After open circuit test is done, we will keep the switch open, do the open circuit test. After open circuit test is done what we will do actually is to minimize the field current of the synchronous machine. So after minimizing the field current of the synchronous machine then short circuit the switch or close the switch to short circuit the armature terminals.

So I have the 3 terminals of the armature, which will be short circuited automatically by using this 3-phase switch. So let me say this is may be T_{sw1} 3-phase switch 1 so this is T_{sw1} will be closed. Of course I should have had ammeter here, at least in one of the terminal I should have put an ammeter. Because I would like to measure the current, short circuit current of this machine.

So when I actually measure the short circuit current of the machine I do not want that current to go beyond the rated current. I have short circuited the terminals of the alternator and I am still allowing the alternator to generate. Because I have provided some minimum excitation may be hardly any. I will slowly increase it as I increase the excitation, this current will go up. If I may call this as I_a, this as I_f, I_a will go up as we increase I_f of the alternator or synchronous machine.

I am running this still at 1500 rpm. If I increase I_f, I am going to increase the generated voltage. If I increase the generated voltage clearly this current will go up. So I do not want that current to go up beyond whatever is the rated value. So if I know the rated value, I have to make sure that the current is limited to the rated value nothing more than that. So maybe I am going to get may be I am just showing the rated voltage somewhere here. It may be higher I am just showing for the heck of it.

So this is my rated voltage maybe this is $E_{f\ rated}$, line to line voltage let us say it says 400 or 415, 460 whatever that is going to be the rated voltage. So this corresponds to I_{frated} normally. As far as the short circuit test is concern, I will again plot with respect to field current what is the variation of the short circuited armature current, so I will have a current scale also very clearly, I should have two scale, one is E, the other one is I_a. Both scales have to be there, so let us say with respect to I_f.

I am going to get probably short circuit current at rated value is somewhere here below that are here. So I am going to have something like this as the variation, this is the short circuit characteristic. So this is I_f versus I_a this is I_{a1} for I_{f1} and this is I_{a2} for I_{f2} and so on. So this what is going to be the variation. So this is SCC, this is OCC, open circuit characteristics and short circuit characteristics. So I have got both the characteristics. Now at rated value of field current which is corresponding to rated generated EMF at open circuit condition.

I would like to measure, what is the current and what is the total voltage? So, this is voltage whereas this is current, so get current at I_{frated} from SCC voltage at I_{frated} from OCC. So I have got both. So let me say this is I_{asc} let me call this as E_{foc}, so I can call $Z_s = \frac{E_{foc}}{I_{asc}}$. When I am having rated excitation, if I am getting a particular value of voltage under open circuit condition had I short circuited the machine at that point itself.

Only impudence, which is actually limiting the current is its internal impedance, nothing else. Let say my rated field current is 1 ampere. At 1 ampere my machine is producing 400 volts line to line voltage which is the rated voltage. If by chance I apply the same 1 ampere of field current to my alternator when it is running at 1500 rpm and I have short circuited the terminals. The current that is flowing will correspond to whatever would have been the short circuit current under rated voltage condition, this is under rated voltage condition.

So current is limited only because of the internal impedance of the armature. So at rated condition if I am able to measure short circuit current and at rated condition if I am able to measure the open circuit voltage. The ratio of these two indirectly gives me the synchronous impedance. So, synchronous impedance is going to be the ratio of the current obtained under short circuit condition at rated I_f.

And I am going to look at what is the voltage generated under open circuit condition with rated I_f. The ratio of these two will give me basically whatever is the value of synchronous impedance.

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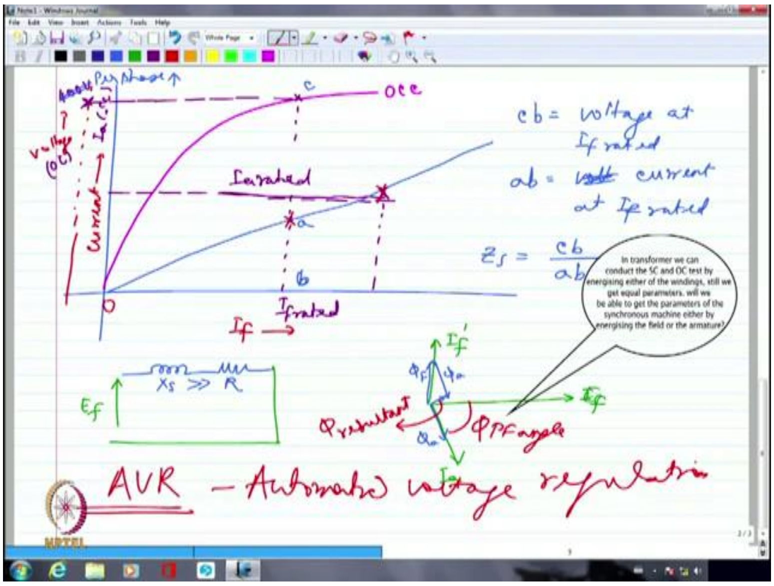

This is my characteristic let me show two axes that is better, right here. So this is my origin, so this is going to be may be voltage axis and this is going to be current axis. So I have two axes and I am going to I_f, I am first drawing the voltage characteristic, so it will go like this probably, this is what is actually OCC. Let us say this is the rated value of voltage probably, so I am going to say that this corresponds to I_{frated}. Now I am trying to now look at the short circuit characteristics.

So I have to first of all look for the point at which I am going to get rated armature current slowly I am going to increase I_f, I am going to plot 2 things, one is voltage under open circuit condition, the second one is armature current I_a at short circuit condition. This is voltage under open circuit condition so that is the reason. So this is corresponding to the red color axis. So this is actually the rated voltage that I am talking about. So this is the rated voltage may be 400 volts or whatever.

Some book shows it on either side of the graph, anyway it is the same. We are plotting two graphs in one particular plane. The other one what we are looking at is the short circuit characteristics. For short circuit characteristic I have to see where may be I_{arated} is been reached at what I_f. So maybe this is I_{arated}, if try to extend it here, this is what is I_{arated}. So this is getting joined here. So I can draw this as the short circuit characteristics, this is passing through this point.

Please, note short characteristic is linear, open circuit characteristics is involved with saturation. So I am going to have now because, I have drawn it like this I can always get what is the I_a value at I_{frated}. Let me call this as some ab. Let me call this voltage as cb. So cb is the voltage at IF rated, ab is the voltage, a current at I_{frated}. So I am going to say that $Z_s = \frac{cb}{ab}$.

Student:(())(34:00)

Professor: I am looking at what is the rated value of field current at which voltage is produced under open circuit condition. Under that condition itself had a short circuited my machine. What would happen? A current would definitely flow because I have short circuited. Until now it was open, so there was no current flow. The moment I short circuited there will be a current flow. That current flow would have reached infinity if the internal impedance of the machine had been 0.

It is limited to a finite value only because of the internal impedance of the armature. So, this is giving me a way to measure the internal impedance. So if I know what is the current that is flowing under rated condition that will actually rated field condition that will give me a way to determine, what is internal impedance of the machine, that is what I am precisely doing. So the open circuit characteristics and short circuit characteristics basically are done mainly to get the synchronous impedance value of the generator.

Student: In OCC do we plot a line voltage or per phase voltage?

Professor: Armature line to line.

I can always say let me draw this is per phase rather than this. If it is again star and delta, If I measure the current also phase current and voltage also per phase voltage I can measure both per phase.

Student: Why SSC is a straight line and OCC is non-linear?

Professor: Very good question, I was expecting this question. Why is the current not following the voltage? That we will have to definitely answer, what he is saying is, if the current is essentially voltage divided by Z_s the current and voltage should have followed the same path. Does not make sense to have two different paths. Please remember what we talked about the magnitude of the impedance.

We said this is X_s, this is R and X_s is much-much higher than R. So this is highly inductive in nature. The current is going to be highly inductive, it is going to be almost lagging behind by 90 degrees, am I right? So let us say I have my I_f here, I am answering the question of I am rate rating voltage divided by the impedance is current and the voltage and current should follow almost the same trajectory.

You cannot have the two characteristics which are entirely different, why are they different? We are just answering that question, so if this is I_f I said that E_f is somewhere here, this is I_f^l and this is E_f. If I am going to have a current in the armature which is highly inductive I am not having any external impedance, only thing I am having is X_s and R. And R is negligible small, X_s is way too large. So I have short circuited this and I have connected E_f here.

This is what I have done during short circuit condition. Now, I am going to have I_a probably as lagging as this may be quite large. Now I_f produces ϕ_f which is the main field flux. I_a produces a flux which is corresponding to armature. So I am going to have one of them as ϕ_f which is probably in phase and the other one as ϕ_a which is in phase with I_a. What will be the summation of these two? It will be mini squeal; it will be really mini squeal try to add these two. So I have to essentially draw a parallel vector to this.

So I am going to have something like this as the resultant. So, this is ϕ_a and this will be the resultant. Whatever I have shown as the small vector will be the resultant ϕ. So under short circuit condition the flux that is remaining in the air gap becomes really-really small because of which I am going to see that the machine never tends to saturation, never-ever under short circuit condition of an alternator it will go to saturation. It will not go to saturation because the armature flux and the field flux are literally in opposition to each other.

Under short condition I am not having any load here. Otherwise I will have a load here which will determine the power factor. Here is the power factor of the machine roughly this is the power factor. So this power factor angle happens to be almost close to 90 degrees because of this reason. If I connect the highly inductive load at this terminal it will almost behave the same way. So R_a and X_s essentially behave like pure inductance.

That pure inductance is going to make the current lag behind almost by 90 degrees, so these two oppose each other completely. And because they oppose each other completely literally the armature flux tends to kill the main flux. So you are going to have very-very minimum amount of flux under short circuit condition and that is the reason so I have short circuited but, I am getting the rated current only beyond I_{frated}. Normally, in the transformer if apply the rated voltage the transformer will burned.

But here I am applying $I_{f\ rated}$, it is generating rated voltage and I am going beyond that, I have come from 0 to I_{frated}, I have minimized the field when I started the short circuit test I have increased it slowly. It has come to $I_{f\ rated}$, after $I_{f\ rated}$ also I have to go little more, only then I am getting the armature current

See this is I_{frated}, I have started from 0 then I came to $I_{f\ rated}$ I was getting E_{rated} under open circuit condition.

This I_a is under short circuit condition. Because, the flux gets minimized tremendously under short circuit condition, essentially even the voltage generated somewhat is compromised. Because of which to actually pass rated armature current I have to increase excitation further. It was under this excitation when I was at rated value of EMF under open circuit condition. But what I am getting as an armature current is not even I_{arated}, I_{arated} is somewhere here.

Whereas this is the current I was getting under rated excitation under short circuit condition. I am not getting even that much, so I have to increase the excitation little further. Because the flux has been mini squeal very-very small value. Because the armature flux of opposes the field flux completely because of the 90-degree power factor angle. Lagging power factor angle, on the other hand had X_s been capacitive? Which is imaginary it is not going to happen I am just saying hypothetically.

If the X_s had been capacitive these two would have aided each other, absolutely you would have gone way beyond saturation, very-very huge amount of flux. If the saturation had not been there you would have seen a huge amount of flux that is one reason why whenever, you connect a capacitive load in a synchronous generator. Again we talked about this in transformer when we connect a capacitive load we had negative voltage regulation.

At no load if you had 230 volts, at full load capacitive you would have 240, 250, 260 volts whatever. Depending upon how much current you have drawn, the same thing holds good in synchronous generator as well. If I am going to have a leading load, I can have the voltage regulation to be negative, if I have a lagging load the voltage will plumbed it. It will really go to lower values. If I am connecting it to infinite bus, how can the voltage go to lower values? It cannot, because the infinite bus would say you better maintain this voltage.

So what has to happen is the generated voltage has to be increased. There is no other way, I repeat it, infinite bus voltage is let us say 400 volts. If I am having huge amount of synchronous reactance in the machine and the current drawn by the loads in the grid are all lagging, the voltage might try to go from 400 to 300 or 360 it will plumb it will go down. But, infinite buses going to say you cannot have lower voltage, it is not possible. If you cannot have lower voltage only way is to increase E_f.

So, increasing E_f will be done by adjusting the field current, this is done all the time in the power stations. It is generally known as AVR circuit automatic voltage regulation circuit. This is done very often in most of the power stations depending upon what kind of load the grid is phasing. If it is capacitive load, I have to reduce the excitation, if it is inductive load I have to increase the excitation, this is done very repeatedly.

Student: In transformer we can conduct the SC and OC test by energizing either of the windings, still we get equal parameters, will we be able to get the parameters of the synchronous machine either by energizing the field or the armature?

Professor: See one thing is you have to understand first of all that in the transformer, there was something called a primary which was drawing the current and that current was reflecting on to the secondary side, most of the time except for open circuit condition. So you had at least some current to measure and the voltage what you measured on the secondary side is the reflection of the primary voltage.

So, what you are measuring or congruent they are related to each other, it is not that they are completely unrelated. Whereas here if I try to measure to measure the field current that is not going to really give me an index of what is the impedance or the current that would have been drawn by my armature, they are disconnected circuit completely. And you cannot even say, the current carried by the armature is going to get reflected on to the field not at all. It absolutely depends upon what is the amount of load that you have connected.

The current will only depend upon that and to supply that load I should have given sufficient amount of mechanical power from the prime mover that is all it is related to. The field is only working as a wire media; it is a facilitator. It is definitely not giving any resources; it is only a facilitator. So you cannot really take the field current as the current which would reflect on the impedance of the armature that is not possible.

The same way in the short condition obviously the voltage that I would measure across the terminals of the armature will be 0 because I have short circuited, so I do not have the way to measure the armature voltage. So, that is the reason it is a very-very beautiful method, whoever have devised it. To get what is the voltage that would have been generated in the armature under open circuit condition vice versa.

What is the current that is been drawn by the armature? Had it been short circuited with that time of generated voltage, so very clearly there is a huge amount of difference between transformers circuits and synchronous generator circuits. The equivalent circuit as well as the way it is been analyzed. So, that is the reason why they are quite different.