Electrical Machines

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Lecture 36

Synchronization of Alternators

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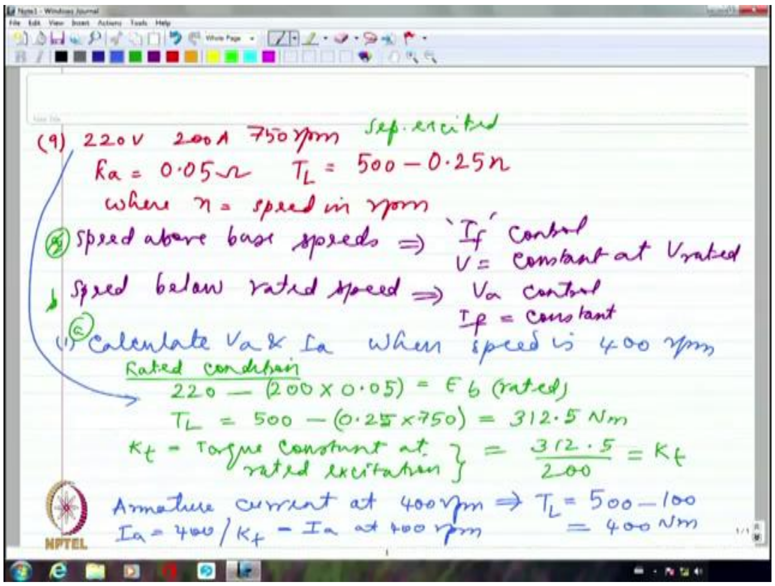

So the problem statement goes as follows, so it is 220 volts, 200 ampere 750rpm that is what is given as the DC motors rating R_a is 0.05 ohm and T_L that is the load torque which is given as $T_L = 500 - 0.25n$ where n equal to speed in rpm and it is given speed above base speed or obtained by I_f control. That means V is held at constant rated value and speed below base speed or rated speed this is obtained by V_a control and I am assuming I_f is held as a constant, normally that is how it is done.

And what is being asked is calculate V_a and I_a when speed is 400 rpm. So the first thing is calculating V_a and I_a when speed is 400 rpm. So first of all let us try to calculate it under rated condition. So let me first solve for it for rated condition. So for rated condition $220 - (200 * 0.05) = E_{b(rated)}$.

I can also calculate $T_L = 500 - (0.25 * 750) = 312.5 Nm$. So I can also say if my I_a it's a separately excited motor, so I do not have to worry about bifurcating I_a into I_f and so on and so forth, so I can simply say so this is separately excited because of which I can say torque constant at rated excitation.

This is only at rated excitation. So under the condition I should be able to say $k_t = \frac{312.5}{200}$. Now I have to calculate at 400 rpm what is V_a and what is the value of I_a. So let me say this is A. So let me try to calculate what is the value of armature current at 400 rpm.

So I should first of all calculate what is the load torque, load torque at 400 will be $T_L = 500 - (0.25*400) = 400Nm$. I should be able to calculate the armature current by using the torque constant, in the torque constant I should be able to calculate the current. So I should say $I_a = \frac{400}{k_t}$, that should give me the current. So this is I_a at 400 rpm for this particular load torque.

The moment you solve for I_a and I have the speed as 400 rpm I should be able to calculate what is the value of V_t, $V_t = E_b + I_a R_a$. So E_b I can calculate.

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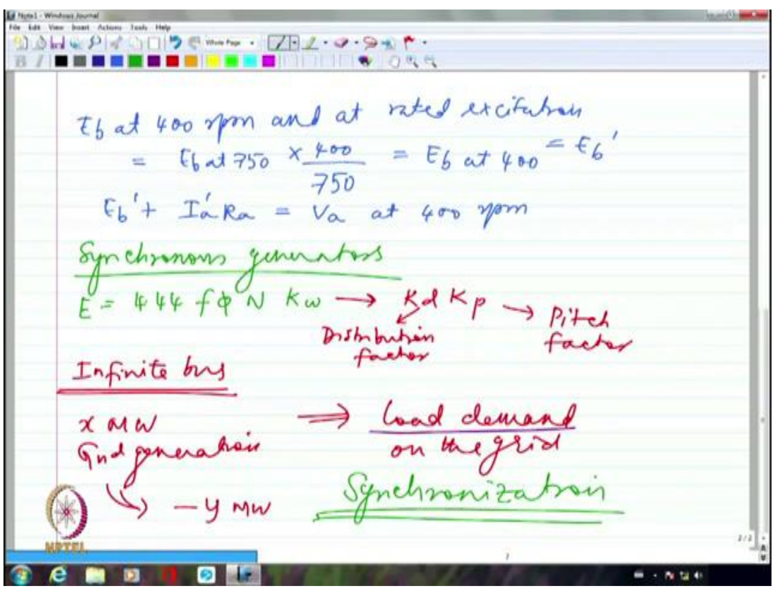

So E_b at 400 rpm and at rated excitation = E_b at 750rpm $* \frac{400}{750} = E_b$ at 400rpm $= E_b^l$.

If I have E_b at 400, if I call this as E_b^l then I can say $E_b^{\,l} + I_a^{\,l} R_a = V_a \; at \; 400\text{rpm}$. So I must have followed a similar thing for the other one all where the field control is being implemented where I am going to assume that the voltage is maintained constant at rated value.

Student: Can we find out K_e and then back EMF at 400 rpm?

Professor: You can do that too, so that Is I am telling you as long as follow one of these methodology I cannot question it, because we normally assume that K_t and K_e are the same as long as you use the speed in radius per second.

So if this is the confusion than I think both methodologies are valid because sometimes some of the problems have some amount of discrepancy unless it is deeply looked into, that is the problem. So the problem formulation itself was a difficulty there that is the reason. So in the case of synchronous generator we said basically that we are going to have either a permanent magnet or electro magnet in the rotor which will be rotated at synchronous speed and when it is being rotated at so called synchronous speed, if it is a 2 pole machine it will be 3000 rpm, if it is a 4 pole machine it will be 1500 rpm.

Armature will have 3-phase conductors located in the inner periphery of the stator and you are going to get induced EMF in all the 3-phases corresponding to 120-degree phase shift from each other because they are placed at 120 degrees away from each other. So let us say I have basically a machine which is going to have the voltage induced to be $\text{E}=4.44\text{f}\phi\text{N}\text{k}_w$.

The winding factor comes up because the windings are distributed and it may have short pitching. So this $k_w = k_p k_d$, k_d distribution factor and k_p being pitch factor.

These are going to be the two factors that will be involved this is definitely true even in induction machine if I am using it as a generator. If at all I am using an induction machine generator this has to be true definitely and we are not really talking much about this when we were discussing induction machine because we never talked about it as a generator much, that is the only reason we did not talk about it. But otherwise this is the induced EMF equation for a synchronous machine.

Now if I have multiple number of synchronous machines that are all connected finally to the grid, the grid is generally like an ocean. When I compare to the grid, the capacity of any individual synchronous machine, the individual synchronous machine is going to be a drop in an ocean basically. So we call the grid as an infinite bus. We call it as infinite bus because the voltage and the frequency of this grid are kind of set and stoned.

They are not going to change, if I say that it is a 400 volts what I am getting in my laboratory from the grid it will be remain enlarge at 400 volts. It can deviate very-very little. Similarly, the frequency if I say it is 50 hertz, it should remain at 50 hertz. The maximum deviation I may have is from 49.5 to 50.5, generally. I will try to maintained the frequency and voltage normally because so many of them are actually poring their power into the infinite bus and all of them are working at a particular value of voltage and frequency.

So you would hardly see any variation that is coming up just because may be one load is added or one load is subtracted that is not going to make a big difference in terms of the voltage and frequency. It will make a difference if I try to probably remove N number of generators completely from the grid. If I am going to have the grid supplying let us say X megawatts and if I am going to remove so many generators which are corresponding to probably some Y megawatt where Y is almost comparable with X, even 50 percent or something.

Then there will be a power imbalance. What I am trying to say is let us say X megawatt is my grid generation and I am going to have this is exactly make by the load demand. I am having load demand on the grid, I am going to have also as X megawatt. Suddenly out of X megawatt if I just minus from Y megawatt that is I remove so many generators from the grid may be there is a fault, may the generator stop functioning all of them not functioning is very rare.

But let us say something happened and I had to remove. When we remove this what will happen is there is a power imbalance because of which this load unless I shed, I have to shed the load what I mean by shedding the load is removing the switch which is connecting the load to the grid. Let us say I have connected my entire supply, my house hold supply to the grid that is through of fuse.

If I remove the fuse it is opened up that is all I am talking about. So if I shed many loads then if it becomes the load also becomes Y megawatt, it is perfect X minus Y megawatt it is perfectly fine. Rather than that I have not removed my load, I have just left my load I have not realize that so many generators have comed out. In that case what is going to happen is whatever are the generators that are working already their kinetic energy will be kind of depleted.

The kinetic energy that are stored in the form of kinetic energy in the rotating parts of the machine slowly that will get depleted. So what is going to happen is the steam turbines or hydro turbines which were rotating this particular machine hey have only a finite capability, they will not be able to provide more and more power than what they were providing. So what is going to happen is slowly the kinetic energy that were stored in the rotating parts will be converted into the electricity and then it will try to feed the load more than what it is capable off.

But in the process, the speed will come down definitely. When the speed comes down the frequency will come down. If the frequency come down ultimately the grid will collapse that is what happens sometimes if suddenly one of the complete lines conked out. That is let us say I have Dadri power station which is generating a huge amount of electricity which is catering the needs of Delhi. So in case there is a problem in the switch yard of Dadri power station.

The switch yard is the one which will connect all the generators ultimately through a transformer which will step up the voltage and back to the grid. That is what it is going to do. Let us say there is some problem in the switch yard, so maybe many circuit breakers how opened. So none of the generator from Dadri is being connected to the Delhi gird. So what is going to happen is, if people have not noticed and they have not switched off many of the loads in Delhi which is a power guzzler normally.

If that is not done then you are going to see that eventually it turns out to be unstable condition because the frequency will fall because the speed will fall and eventually it will become extremely unstable the entire thing comes out a few years ago I do not remember may be 2010 or 2011 there was a major power outage because of the entire Northern grid collapse because of the HVDC link, high voltage DC link which is actually coming from Rihand which is near Varnasi which is feeding power to the Dadri from Dadri we guzzle up the power that DC link conked out.

Because it conked out completely the entire Northern grid was in darkness. So what I am trying to tell you basically is the infinite bus is infinite as long as I think things are all fine. If many of them conked out, many generators conked out or many loads for some reason conked out which can also happen if one particular feeder is tripped completely, feeder is a transmission line which feeds power to some industrial area probably.

So something conks out I am going to have a power imbalance. If there is a power imbalance between generation and load, I am going to have either the speed increasing enormously or speed decreasing enormously. If the generating station realizes many loads having shed off, then they have to reduce the amount of steam that they are pumping into the steam turbine. If they see that more and more loads are coming up they have to notch up the steam that is going into the steam turbine.

So that the power its speed is a constant, the torque is the one which they are changing by inputting different amounts of steam that is all they are doing, the speed is a constant, the speed will not change what so ever unless there is a power imbalance. So on the whole whenever I connect a generator to the grid it is a very TDS and long process that process of connecting a generator to the grid is known as synchronization.

So synchronization of a generator means that I am connecting a generator to the grid and the grid voltage and frequency or set and stoned. So I have to modify basically the voltage if it is not matching, if the frequency if it is not matching, I have to modify only my generator I cannot expect to be modifying the infinite bus that is not possible. So let us take a look at what is the process of synchronization.

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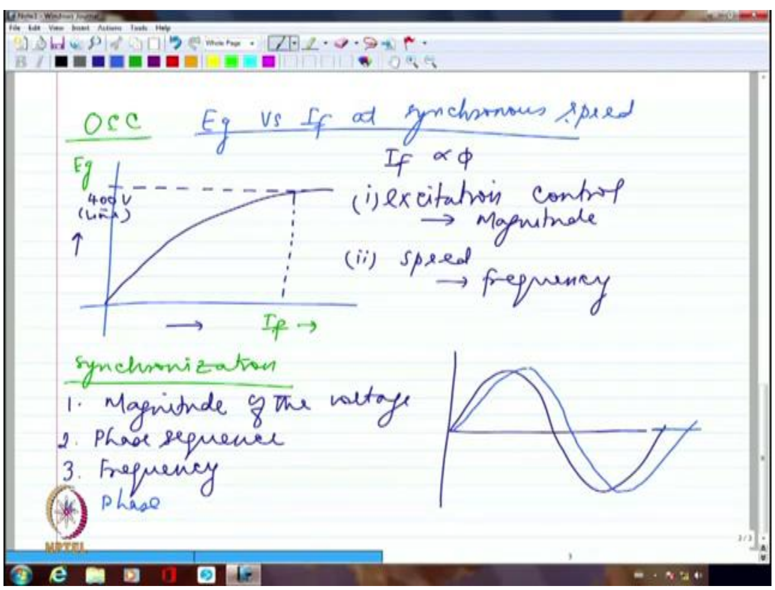

So first of all we talk very briefly about OCC or open circuit characteristics. Which we actually said in, talked in greater detail in a DC machine even in synchronous machine it is almost similar. So OCC is the voltage generated per phase or line to line voltage either way is fine versus I_f at synchronous speed. So if I say that at synchronous speed if I am running my prime mover and I am trying to look at what is the generated voltage versus field current that gives me the OCC.

So let us say I have the OCC somewhat like this, so this is going to be my E_g and this is going to be I_f and I am talking about the OCC which is probably going like this. So may be at a particular value of I_f I am getting actually this E_g to be approximately rated voltage. Let say my machine is rated for 400 volts line to line or 230 volts per phase whatever. So I am measuring may be line to line voltage and this is 400 volts, line voltage RMS value.

So this field current is generally termed as the rated field current or rated excitation, this is going to be my rated excitation or rated field current and I am generally assuming that I_f and flux are not really linearly related. But they definitely are fairly linearly related until my operating point is arrived that. I will not operate it much beyond the saturation generally I will try to operate it just before the saturation.

So this is my field current, so what I am trying to get at is the voltage magnitude can be adjusted by adjusting the field current, that is all I am trying to get it. The voltage magnitude definitely can be adjusted by adjusting the field current and frequency can be adjusted by adjusting the speed. So I have two specific controls in the generator, one will be excitation control which will play around with the magnitude.

So this is related to the magnitude of voltage and the second one is speed. The speed will be control by adjusting the prime mover speed itself and speed control will adjust actually the frequency. So whenever I want to synchronise the generator with the grid I had to definitely look at this thing first whether they are matching or not. So for synchronization actually I will look at majorly 4 performance parameters. One is the magnitude of the voltage which I can definitely adjust with the help of the excitation. The second one I will check is phase sequence.

I hope you understand what I mean by phase sequence? I may be generating ABC in my generator may be the grid is in ACB or I am thinking that what is my B may be actually C and what I am thinking as C may be actually B. So I do not know, so if I just close the switch and connect it to the grid, I am gone. The generator will be completely burned out I cannot afford to do that.

Because when I am talking about the grid voltage may be it is V_b is actually $V_m \sin(\omega t - 120)$, may be my B phase what I am thinking as B phase in my generator will be $V_m \sin(\omega t + 120)$. I cannot connect definitely the two then it is like line to line short circuit, I am trying to short circuit two different voltages, which is deadly. So I cannot really do it if the phase sequences are different.

Student: Will the voltage magnitude not change with the variation in frequency?

Professor: The generated voltage depends upon the speed as well but if I have already brought the frequency up to 50 hertz. I would not like to play around with the speed, obviously you are going to have the voltage magnitude depended upon frequency as well as flux. If I have already brought up my frequency to 50 hertz, I would not like to play around with it.

Then what should I do? I will adjust I_f, both of them play a vital role no doubt but mainly I am going to look at the excitation because it will not affect the other parameter that is the reason. So I have to match the phase sequence as well if the phase sequences are not matched I am going to have a big problem. The third thing I have to match is the frequency. The frequencies of both the voltages should match.

If they are not matching may be I will see that at some instant both the voltages are matching, after sometime there will be a phase difference. Let me draw two waveforms, one is probably at 50 hertz, this is let us say the grid voltage waveform. If I have another one at 49 hertz I will have basically the phase shift between these two slowly and steadily increasing. One is $\omega_1 t$ one waveform corresponds to $\sin(\omega_1 t)$, the other waveform corresponds to $\sin(\omega_2 t)$.

So if I try to look at what is the difference between ω and ω_2, that $(\omega_1 - \omega_2)t$ is going to keep on adding further and further as the time progresses. So I have 50 as the frequency in one waveform, 49 as the frequency in another waveform. So I am going to get 1hertz as the difference in the frequency. So I am going to have $2\pi * 1 * t$ as the accrued phase difference between the first waveform and the second waveform.

So I have to match the frequency as well as phase simultaneously. All 4 have to match, the voltage magnitudes have to match, the phase sequences have to match, the frequencies have to match, the phases also should match but phase and frequency are highly dependent on each other. So this process generally is automated in most of the power stations, where I have to synchronise actually the generator to the grid that is automated because you are talking about 100s of megawatt.

So you do not want to do it manually and commit a blunder and have the whole thing blown over on the top of you. So that is the reason why it is generally automated but what we do in the laboratory generally is done manually.

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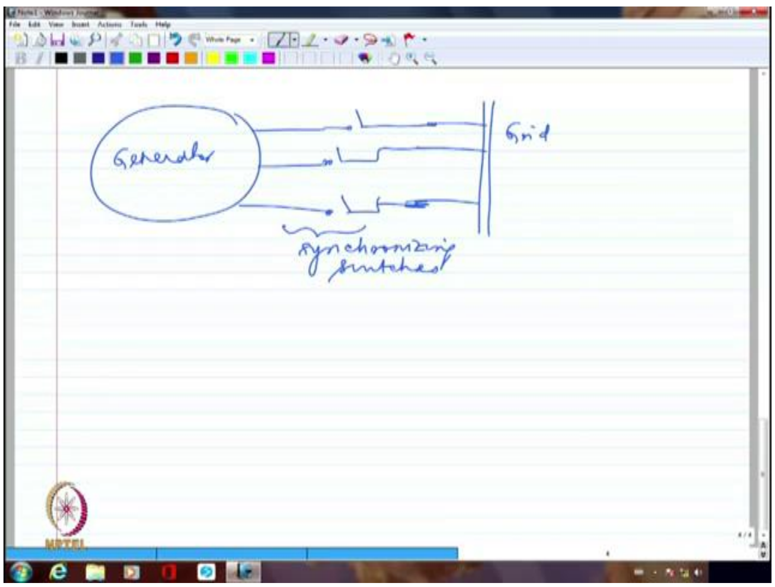

So let us probably slightly take a look at the synchronization process how it is done for smaller generators. From the generator I have 3 terminals, which are the armature terminal. Here is my grid, I am going to show this as the grid from which I am also getting 3 terminals. What I am looking at is to close these switches, this switch is closed, this is the second switch which I want to close, this is the third switch which I want to close. So these switches are synchronizing switches.

What I am trying to do is to connect the generator to the grid directly, if the 2 or not matching in every way it is like short circuiting 2 different voltage sources. Whether the frequency is different, phase is different, phase sequence is different whatever I do I have actually if you look at it here.

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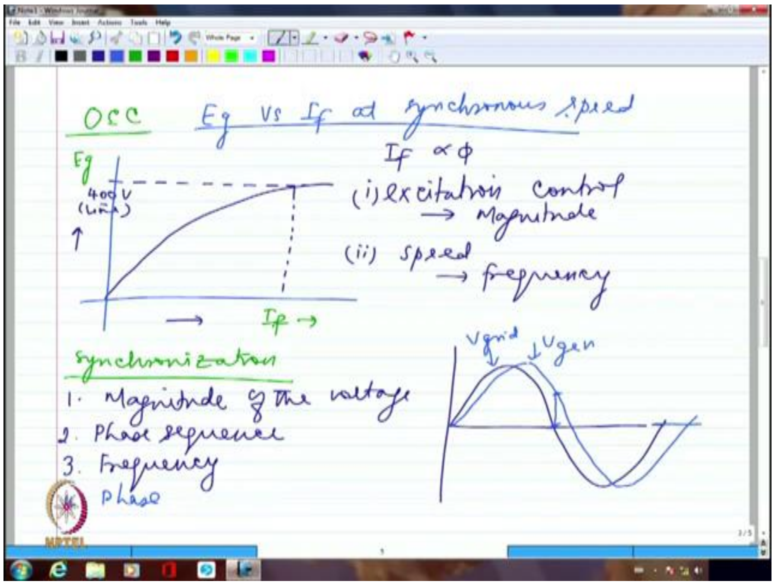

This is one of the voltages, so this is probably V of the generator and this is the V of the grid. You see that at this point there is no difference at all between the two voltages. So you can close the switch that is fine at that point. But if I try to close the switch here you can see that between these two there is a huge amount of voltage difference, if I try to short circuit a huge amount of voltage difference I will very clearly see a huge current flowing what is the resistance between those 2 points where I am trying to close the switch? It is literally 0.

So the current will be infinitely large, so when I am trying to close the generator to the grid I have to make sure that the voltage is at the terminals of the generator will be exactly similar to what are the voltages at the grid point. Otherwise I will have a huge amount of short circuit current that will be flowing through the generator into the grid and the generator will conk out first, that is what is going to happen. So I cannot effort to do that. So when I am synchronizing generally in the laboratory what we try to do is.

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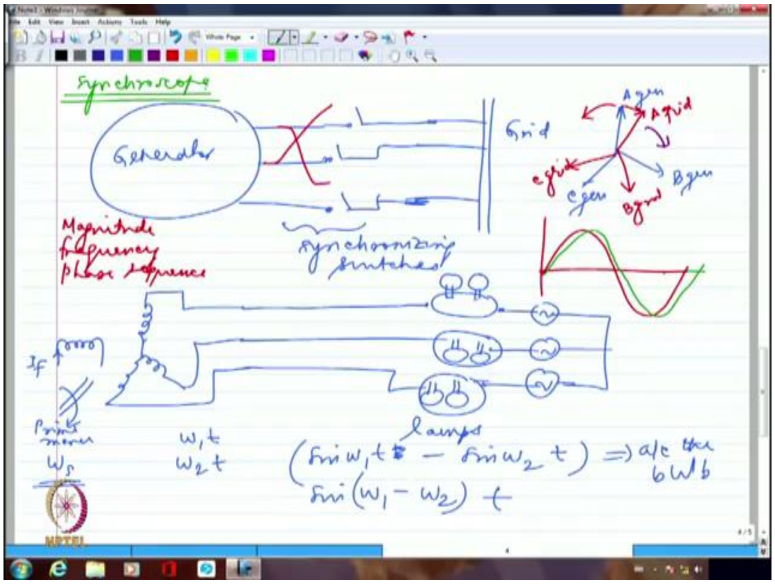

I have the generator here and let me show the generator basically with the 3-phase winding and I am going to have the field binding here. What we do in the laboratory is with an electromagnetic is not done with the permanent magnet because I want to be able to adjust the excitation. So this is going to be my I_f. Now I have these are the 3 terminals of the generator and here are my mains which is actually in the laboratory again, this is equivalent to infinite grid and I am going to normally measure the voltage here and measure the voltage across the generator terminals.

If the two are not matching each other I am going to adjust the excitation until I am able to see that both the voltages are the same. So voltage magnitude matching is very-very simple, not a big deal at all. But definitely before that I would have run this rotor which is couple to your prime mover in a speed which is corresponding to synchronous speed. So I know also that the frequency is going to be really close to 50 hertz because I am going to have the grid frequency close to 50 hertz, I want this frequency also close to 50 hertz.

So first thing I do is to start the prime mover, start the generation process in my machine and once it is generating I can measure what is the value of voltage, the voltage should be matched by adjusting the excitation. So I have roughly matched the frequency and roughly matched the magnitude as well that is what I have done. Now I have to match the frequency exactly. I have to match the phase sequence as well.

There is something called a phase sequence indicator, you can use a phase sequence indicator if not we can even look at it manually and we would be able to say whether the phase sequences are matching. How do we do it? Normally what we try to do is there are ofcourse the switches here but even before the switches we will normally connect 2 lamps here. I am showing the lamp pretty badly, this is 2 lamps we connect in between the generator terminal and the actual, the grid terminal.

Why do we connect to lamps? Because normally our machine is going to be rated for 230 volts per phase or 400 volts line to line. So if I put only 1 bulb this is all single phase bulbs whatever bulbs we are using normally or working on single phase that is only 230 volts. If I apply 400 volts it will not be able to withstand. So it is better to put two of them in series. If you put two of them in series, you are sure that it will withstand that much of voltage if there is a huge voltage difference between these two terminals.

So I will put normally 2 bulbs each across each of these terminal I am going to have 2 more bulbs here and I am going to have 2 more bulbs here. So these are the lamps. Now if the frequencies are exactly matching and if I am going to have the phase sequence also matching and if the magnitudes are also matching and if there are no phase difference between the two voltages, I will have the bulbs not glowing at all.

If the two voltages match exactly there is no way, the bulbs can glow but it is very difficult rather impossible for me to get the exact matching like that because I may think that it is 50 hertz actually grid frequency may be 49.98 hertz. Still there is a small difference, cannot help it and what you measure as the speed may be 1500 rpm actually the indicator shows it is 1500 it can be 1498 for what measuring error there can be.

So what we will look at is actually if I am having two of these supplies one is $\omega_1 t$, the other one is $\omega_2 t$, two supplies I have one is from the generator, the other one is from the grid, one is $\sin(\omega_1 t)$, the other one is $\sin(\omega_2 t)$. When I am actually looking at difference between these two that is what is coming across the bulb. So I am going to have $\sin(\omega_1 t) - \sin(\omega_2 t)$ this is what is coming across the bulb.

So if I say this is, this will be essentially $\omega_1 + \omega_2$ will be 1 component, $\omega_1 - \omega_2$ will be another component. So $\omega_1 + \omega_2$ will be a very-very high frequency so I will not be able to see actually the intensity increasing and decreasing at all but $\omega_1 - \omega_2$ I would be able to observe with my naked eye. Because it is really going at a very-very slow frequency.

If I say 49 hertz and 50 hertz it is 1 hertz difference. So the rate at which the sinusoidal wave is increasing and decreasing will correspond to $\sin(\omega_1 - \omega_2)t$. So the bulb intensity, the light intensity will increase and decrease in a sinusoidal fashion it will look as though it is in a sinusoidal fashion but it is proportional to I^2. So even in the negative half cycle it going to give there is nothing like a negative intensity, it will give only positive intensity.

So you will be able to see the light is glowing and coming down in its intensity and so on. If the rate at which the intensity is increasing and decreasing is fast that means $\omega_1 - \omega_2$ is large. If he rates at which the intensity is decreasing and increasing is slow that means I have almost matched ω_1 and ω_2 very-very well. So I have to continuously observe the lamp and adjust the speed slightly.

If I adjust the speed may be I am thinking that it is running at 1500 I have increased it to 1510 1515 rpm, I am seeing that may be the intensity is very fast it is actually increasing and decreasing very-very fast that mean I have gone in the wrong direction, so I have to come back. What we do in the last laboratory is to use a DC motor as a prime mover. So DC motor speed control becomes very important from that point of view.

So we try to adjust the speed of the prime mover which is actually my DC motor by adjusting its field armature I will try to adjust the speed. I will go either in other than higher than 1500 direction or lower than 1500 direction depending upon whether the intensity with the variation of intensity becomes faster or slower that is going to actually decide whether you are going in the correct direction.

So it may become in such a way that it is actually going painfully slowly, you would see it going through the change in variation of the intensity, the variation in the intensity will be going through painfully slowly at some point which is very good for us, because that is where our frequencies are matching. So magnitude is matched, frequency is matched, if the phase sequences are the same the intensity variation of all the 3 phase bulbs will go hand in hand.

If I am going to have A like this, B like this and C like this, if I am going to have this is the A of the generator, this is the B of the generator, this is the C of the generator. If I am going to have let us say A of the grid, B of the grid and C of the grid like this I will have all of them glowing if the frequencies are matching there is a phase difference, there is a small phase difference that is what I have shown.

The frequencies are matching, the phase sequence is also matching I will have between them there is a constant value of voltage maintained, the difference between these two that is what I have to calculate. So the difference between these two will be something like this, this is what is going to be the difference. So all the 3 phases will have the difference which are equal almost equal.

So we will have all of them glowing almost similarly with similar intensities. If the phase sequence had been different very clearly I am going to have this rotating in this direction whereas this rotating in the opposite direction, that is what it means by phase sequence are different as simple as that. Instead of having ABC if I am having ACB that means if it is rotating in the opposite direction. Definitely I will not have, now I have to look at the difference between A and A, B and B and C and C very clearly they will be not together, they will not be changing together.

They will be actually changing in terms of the difference between A and A, B and B, and C and C they will not be equal, they will not be actually varying with equal intensity and so on. It is going to be kind of stepped variation may be one will go to a high after that another one will go to high and the other third will go to a high after sometime. They will not go to together; they will not go hand in hand. So phase sequence we will be able to see that they are not matching if I am not going to have all the 3 bulbs varying in their intensity simultaneously rather than that they are having phased out variation in their intensities. You can try to derive the mathematical expression also you guys would be able to definitely figure it out.

One will be $\omega_1 t - \omega_2 t$, the other one will be $\omega_1 t - 120 - \omega_2 t + 120$. The third one will be $\omega_1 t + 120 - \omega_2 t - 120$ try to look at all the 3 how the waveforms come up. You would know that very clearly the difference is not going to be co-phase they are not going to go in hand in hand. So phase sequences if they are different only way I can do it is to interchange these two connections. So I have to put this here, put this here that is the only way out.

I have to just interchange two of the terminals. If the phase sequences are wrong, then I cannot change the infinite bus that is not in my hand. So I have to change only this particular the two terminals of my generator, interchange them as far as the connection is concerned, then phase sequence will match. So now we know how to match the magnitude, how to match the frequency and how to match the phase sequence.

But you cannot do this interchanging when the generator is live. So you have to switch off everything again start a fresh, you cannot do this when the generator is live never do it when it is live. So what you will do is switch off the whole thing, start from scratch, start the DC motor again bring it 2500 rpm, bring the excitation to whatever is the rated value then look at the magnitude, match the magnitude.

Now phase sequence is matching at least, so that you do not have to worry then match the frequency by looking at, at what rate this is changing all those things. Now at some point even if there is a small difference in frequency as I told you this is my generator sinusoid and maybe the other one is almost close in frequency but still there is a small variation may be. Because I am doing it manually, so I do not know if it is like 49.95 and 50 still there will be a small phase error accumulated.

But at some point the phases will match eventually because I am looking at $\omega_1 + \omega_1 - \omega_2$. So that is essentially going to match at some point maybe down the line then $(\omega_1 - \omega_2)t$ becomes 360 degrees it will match. When it matches your bulbs will be all dark at that point you have to close the switch. So what you have to do is to first voltage magnitude have to be matched then the frequency will be matched make sure the phase sequence is matched.

Phase will not still match in all probability but because there is a small amount of frequency difference, the phase keeps on changing at some point the phases will match there is no other way, $(\omega_1 - \omega_2)t$ will become 360 degrees or 2Π radian at some point. Wait for that point where all the three pairs of bulbs go to zero intensity just close the switch that is what we do in synchronization.

So synchronization of the alternator is a big process and all 4 have to be matched, if all the 4 are not matched, we will have definitely a huge amount of problem in terms of two different voltages getting connected that to imagine generator is going to generate about 20 kilo volts. Generally generating voltage is not more than 20 to 30 kilo volts we use a transformer to step up. So we transmit it at either 465 kV or 450 kV, 765 kV transmission lines are there. So we are going to step it up. After stepping up it is actually connected to the grid.

So you cannot effort to make a mistake there, you are talking about 700 hour kV. So it is deadly if we try to connect it without proper synchronization. So for this generally we use something called synchro scope in the power station which actually would check automatically everything and then connect it.