Power Electronics
Professor G. Bhuvaneswari
Department of Electrical Engineering,
Indian Institute of Technology, Delhi
Lecture 13
Single-Phase and Three-Phase AC Voltage Controllers

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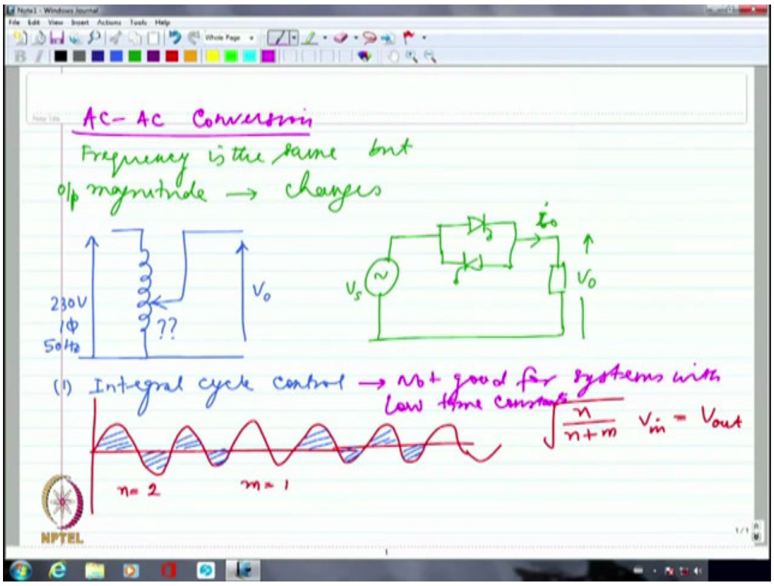

There are two kinds of AC to AC converter. Normally, one is AC voltage controller, which we started on the other day, the other one is cyclo-converter. So, we will start of first with AC to AC conversion, where frequency is the same but magnitude that is output magnitude changes.

So, this is very similar to using a variac, if I use a variac (autotransformer), we essentially had a variac somewhat like this, we would apply 230 volts, single phase, 50 hertz here and if we actually move this jockey point, correspondingly we are going to get different values of magnitude at the output. So, this magnitude depends upon how many turns are here, how many turns are here that is going to decide how much is the magnitude, but the frequency is the same. Input was also 50 hertz and output was also 50 hertz, there is no difference as well as the frequency is concerned.

Almost similar is the case with an AC voltage controller, if I am going to have a back to back connected thyristor configuration or SCR configuration somewhat like this and I am going to connect the load here and this is my input voltage. So, this is V_S and this is going to be v_0 and this is going to be i_0, I should rather say small i_0 because instantaneous current.

If we want to plot the wave form of the current, then I should show this as instantaneous current. So, we fed there are two types of control, one is integral cycle control, where I am going to have for n number of cycles, the two thyristors are going to be turned on at 0 degree and 180 degree respectively and for the next m cycles they are not going to be turned on at all.

So, if I just look at the RMS value over n+m cycle, I will have $\sqrt{\frac{n}{n+m}}$, as the RMS value. So, integral cycle control essentially will look at something like this, so I may have multiple number of cycles like this and I am going to probably keep this on for let us say two cycles and I do not turn it on for one cycle. Again, for the next two cycles, I am going to keep it on and for the next one cycle, I am not going to keep it on at all.

So, I would say in this case n equal to 2, m equal to 1, so I am going to have $\sqrt{\frac{n}{n+m}}v_{in} = v_0$

Because I am looking at the RMS magnitude basically. So, if you actually look at it, individually they are still like 50 hertz although it is looking as though I am trying to apply it for two cycles together and one cycle I am not applying it, but that does not change the frequency of the output voltage, it is still like 50 hertz.

So, if I apply it to probably an induction motor it will still visualize the voltage as 50 hertz. It is not going to visualize it at as any other frequency, but as I told you, this is not good for those systems which are going to have lower time constants. So, the inertia is very small for a drive, then you would see very clearly during this time, it will rotate and then suddenly it will come down to zero speed and again it has to start a fresh and so on. So, this particular system is not good for systems with low rather a low time constant.

Only if my time constant is high, like a thermal system where it is going to take a while for the temperature to rise. Similarly, it will take some time for the temperature to come down. So, in those cases integral cycle control can work, otherwise it cannot.

If I am looking at the alternating current, it is still having 20 milliseconds as the cycle time. If I just look at any one of the cycles as said, I am going to have between the positive and negative half cycle, if I look at the entire period, it is still 20 milliseconds. If input is 50 hertz, I will still have output to be 50 hertz, exactly. It may not come at some point, it may be completely absent at some point but wherever it is present, it is still following the same frequency, I am not changing the frequency.

So, that is why we call this as a constant frequency system, whether we look at the input or output. We are not changing the frequency. We will look at the cyclo-converter, where you would very clearly see the input frequency and the output frequency would be different.

So, right now, all I can say is, because the positive half cycle and negative half cycle, if you look at it and for the entire cycle, the cycle time is still the same as the input, I would say that the frequency has not changed really.

So, this particular system is good only for those kinds of configurations, where I am going to have a huge time response; response time has to be large. So, it is definitely not good for small single phase induction motors and such things.

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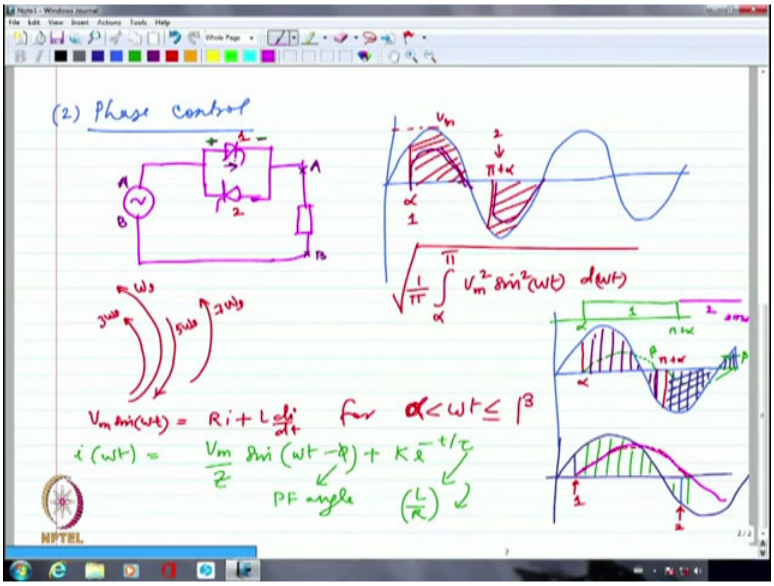

The next type of control what we were talking about the other day was 'Phase Control' or 'Phase Angle Control'. So, in phase control, we are still going to have a back to back connected thyristor pair or a triac.

So, here is going to be my source and this is the load. Now, I am going to actually control it in such a way that, this is my sinusoidal voltage and I am probably going to fire this at α here and I am going to fire. So, one is fired at this point and if I may call this is 2, this is fired at $\pi + \alpha$ symmetrically. So, positive half cycle and negative half cycle have to be, the firing has to be symmetric. So, if I do this, I may have if it is resistance load, what we talked about the other day, if it is a resistive load, I am going to have essentially the current following the same wave shape, right. It will follow the same wave shape, only thing is it will be V/R.

So, I will have this particular device to be forward biased only when I am going to have plus here and minus here and that will happen only during positive half cycle. So, I need to necessarily fire this device number 1, only during the positive half cycle. I cannot fire it during the negative half cycle. So, if I do that and if it is a resistive load, I am going to have a current somewhat like this, this is how the current is going to be. If I look at the voltage, the voltage is going to be actually only this portion.

So, I will have the portion, whatever I have shown a shaded portion that is going to be the output voltage. So, this is going to repeat itself in the next cycle as well. So, here also the frequency does not change. I hope you understand, because if I look at the positive half cycle, negative half cycle although I have zero voltage interval or zero current interval, if I try to start from the beginning of one half cycle to the end of the other half cycle, it is still 20 milliseconds.

So, the frequency has not changed, only thing is the wave shape is not sinusoidal any more. So, that can have definitely repercussion on the functioning of many of the equipment, which you are supplying with this kind of voltage. You might have noticed that when you have a fan rotating with full speed, you may not really hear some kind of noise, , whereas when you reduced the speed because you are applying a non-sinusoidal voltage, that actually creates a large number of harmonic currents to be injected into the motor and I hope all of you remember the basic functioning of an induction motor. If you have actually 50 hertz supply apply to an induction motor, you are going to have a revolving magnetic field setup, which is corresponding to $120f/P$. P is the number of poles.

So, if it is a 2 pole machine, the revolving magnetic field will be at 3000 RPM and so on and so forth. So, if I have multiple harmonics, that is I am going to have say third harmonic, fifth harmonic, seventh harmonic and so on even harmonics will be absent because there will be half phase symmetry. if you try to actually get the average value, average value will be zero. So, also will be all the even harmonic. So, all the even harmonics will be absent as long as I have symmetrical firing. The positive half cycle and negative half cycle are exactly the replica of each other.

So, in that case I am going to have third harmonic, fifth harmonic, seventh harmonic and so on and so forth being injected into the motor. So, which means I will have one revolving magnetic field at ω_s, another revolving magnetic field probably at $3\omega_s$, other one at $5\omega_s$. We will see that this will be generally in the opposite direction. I do not want to really extend upon this much but again I am going to have one more revolving magnetic field at $7\omega_s$ and so on and so forth.

So, I will have several revolving magnetic fields super posed on each other. So, the rotor is heavily confused. It can be accelerated because of the fundamental revolving magnetic field or it can be accelerated because of third, fifth, seventh and so on and so forth. So, whatever is the dominating one, that is going to contribute to the real speed of the induction motor. The dominating one normally happens to be the fundamental.

However, rest of the torques are also interfering with the operation of the motor, which will work more like a breaking torque rather than a motoring torque, because they are trying to rotate this at the different speed, so they are not going to aid the rotation at ω_s or slightly less than ω_s, they are going to rather create some kind of havoc in the complete dynamics of the system and that is the reason why you hear that noise. There will be lot of vibrations because there will be motoring action because of the fundamental torque or fundamental revolving magnetic field along with that there will be breaking action simultaneously because of the higher harmonic revolving magnetic fields.

So, this is essentially going to create the noise that you hear in the motor drive normally. You might have seen also if you have a home invertor, which is not giving you sinusoidal output, which is going to be some kind of square wave or quasi square wave output, when you switch over from the regular sinusoidal grid supply to the invertor supply, you will hear again the same noise. The invertor essentially is not supplying sinusoidal voltage it is supplying some kind of square wave voltage or some chopped square wave voltage because of which you would normally hear, a lot of noise in the motor.

So, you will know, when it is switching over from the grid supply to the invertor supply immediately you will know, because of the noise that you hear in the motor drive, specially fan if it is running, so you would hear that. So, this is one of the easier ways of controlling the voltage magnitude no doubt, but this is definitely not the best way of controlling the voltage magnitude because you are trying to chop out some of the portion of the sinusoid, you are applying only some portion of the sinusoid which means you are not really pumping the motor with sinusoidal currents, you are actually pumping it with harmonic currents, that is the reason.

So, in this case if I have to get what is the voltage, I had to say, $\sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2(\omega t)\, d\omega t}$, this will be the RMS value of the voltage that I will be getting, when I am having resistive load. We are talking about this in the case of resistive load.

I replace this by an RL load, Now, what is going to happen is, I will have to again write the equation $V_m \sin\omega t$, V_m is per phase. We are talking about single phase. So, I am talking about per phase peak. So, $V_m \sin\omega t = Ri + L\frac{di}{dt}$ for $\alpha < \omega t \le \beta$. If I am talking about the RL load the current might continue beyond π, because there will be inductance stored energy and that inductance stored energy is going to definitely make the current continue even beyond the positive half cycle, like what we saw in the case of a rectifier. There also we said that, the two devices which were actually being forward bias because of the supply voltage during positive half cycle, they will continue to conduct even after the end of the positive half cycle because of the inductance stored energy.

So, if I look at the voltage and current waveform corresponding to this, let us say this is my voltage waveform, and I am firing device number 1 at α and I am firing device number 2 at $\pi + \alpha$. So, I am going to have the current rise slowly and at what point it reaches peak, it depends upon again $L\frac{di}{dt} = V_m \sin\omega t - Ri$, if that becomes 0 then I am going to have di/dt reaching its maximum, I mean di/dt becoming 0, which means current is reaching maximum.

So, may be current reaches maximum here and it is probably going to continue until here, right. I have to definitely solve for the transient equation, and I will have one complementary function and particular integral, transient solution and steady state solution. The steady state solution will be $\frac{V_m}{Z}\sin(\omega t - \phi)$, that is the way normally you are going to have the function right, ϕ is the power factor angle for the RL load and Z is $\sqrt{(\omega L)^2 + R^2}$.

So, that as far as the transient solution is concerned, we will have an exponential decay in term, where we might write that as some $Ke^{-\frac{t}{\tau}}$. τ is the time constant of the RL circuit. So, if I write a solution for this, I have to write this as

$$i(\omega t) = \frac{V_m}{Z}\sin(\omega t - \phi) + Ke^{-\frac{t}{\tau}}$$

where ϕ is the power factor angle of the load, $\tau = \frac{L}{R}$.

Now, K can be solved for by substituting the initial condition. So, initial condition in this case is I F alpha equal to G, that is the initial condition. So you should be able to definitely solve for the entire equation that is not a problem.

But now, because the current continues until here, I will have this particular device 1, which is carrying current in the forward direction. Please note 2 cannot carry the current in the forward direction, 1 has to carry the current in the forward direction and if 1 is carrying the current in the forward direction, if I call this point as A and this point as B, A is always connected here, and B is here connected here. That is how it is going to be. So, whatever is my voltage across AB, which is the supply voltage that is going to come up across the load as long as one is conducting.

So, I should have this entire voltage coming up until here. This is the way this voltage is going to come out, until β. Wherever the current stops, rather it reaches 0 value. So, it will reach 0 value, when the inductance stored energy ceases to exist, until now the inductance stored energy was making sure that the current continues, so it was taking care of whatever is the resistance loss and also the opposition provided by the power supply, it has essentially taken care of both of them. But after some time because the energy is loss di/dt has been now negative, so automatically it is going to come to 0.

Now, the same thing happens on the other side as well, I am going to have again the current rising and probably it is going to go until here which is π+β.

So, I am going to have the voltage here again coming up until this point. So, I will have this entire voltage coming up here like this, from here it will start, and it will go until here. This entire portion is going to come up as the load voltage.

So, in this particular case, it is not very easy for me to calculate the RMS value until I solve for β. So, for solving a β, you need to first of all get K value by substituting the initial condition and after getting the initial condition you will get a close form expression for the current.

Now, you have to say this current will become 0 again at β, so if β=0. Once you have got the *i* expression, you can say if beta equals to 0 then solve the beta and it is not going to be easy to solve for that in all probability, because you might have to use. So, there will be some trigonometric expression and there will be, exponential expression together, so you might have to use some kind of transcendental equation solution method, iterative solution method. So, it is not going to be easy to solve for that normally.

Now, if I say that this is my α value and the current has continued until here, I reduced my α. Let us say, my α is currently at 45 degrees. I just bring it down slightly, now what is going to happen is, if I try to bring it down this is my sinusoid, so I am going to fire it right here, even earlier. So, which means the current would definitely start increasing from earlier agreed.

So, the energy stored in the inductance can also become more, I hope you understand, so what will happen is I am trying to fire this other device at this point, I am trying to fire the other device at this point. So, I may have the current actually just going and reaching beyond this particular $\pi+\alpha$, if I have large amount of energy stored in the inductance, it can go beyond $\pi+\alpha$. In which case, I am not going to have any control over the voltage, I hope you understand because I am firing 1 here and I am firing 2 here.

But as long as 1 is conducting, I am going to get this entire voltage coming up weather I like it or not this entire voltage will come up. So, I will have the voltage coming up until this β, if I may call that as β and β is beyond $\pi+\alpha$. So, I am going to have continuously the voltage is coming up and after this particular, $\pi+\alpha$, if I am not able to fire 2, then completely I will not have any voltage at all.

But as a rule, I told you that any of the thyristor converter circuits, be it rectifier, be it AC voltage controller, we will not give 1 pulse, we will give a train of pulses and the number of pulses we give will be large number and generally it will be for 180 degrees, if it is a single phase case and if it is three phase case, I will give it for 120 degrees.

I will never give 1 single pulse for a microsecond or something, no we never do that because this is the case, where I still have the current going in the forward direction. When the current is going in the forward direction even if I try to fire device number 2, that will not be possible for me to fire it, because I am going to have when this device is conducting, I will have a voltage drop like this and that is small voltage drop is good enough to reverse bias the other thyristor.

So, when one thyristor is conducting whatever I do, the antiparallel thyristor cannot be fired and because of that I cannot just give one pulse and stop, I need to give a train of pulses, it is very important for me to give a train of pulses otherwise I am not going to able to fire the other thyristor. So, I would actually give the pulse in such a way that, if I am talking about α to $\pi+\alpha$, I will give for 1 and from $\pi+\alpha$ to $2\pi+\alpha$, I will give for 2.

This is how normally I will give pulses but it will not be a single square pulse, because it will go through always the pulse transformer, so I will have high frequency adding and so on and so forth whatever we talked about earlier, pulsed transformer will give you the isolation between the gate and the power circuit and the control circuit.

So, please note that now, if I am applying completely a sinusoidal voltage, because there is no control at all. My current will also be definitely sinusoidal, if I am applying a sinusoidal voltage why would the current not be sinusoidal it have to be sinusoidal. So, now I am not getting any control absolutely and if I try to look at what is the phase shift between the voltage and current, wave form, it will be exactly same as the power factor angle of the load. It cannot be any different from the power factor angle of the load.

You try to fire it at α, I started as though the current is starting at α, but it is not true because here it is going beyond α, which means the same thing should have been true as far as the positive half cycle is also concerned. Transient initially yes it might have started from α, but eventually it will settle down in such a way that the phase shift between the current and voltage becomes ϕ, which is the power factor angle.

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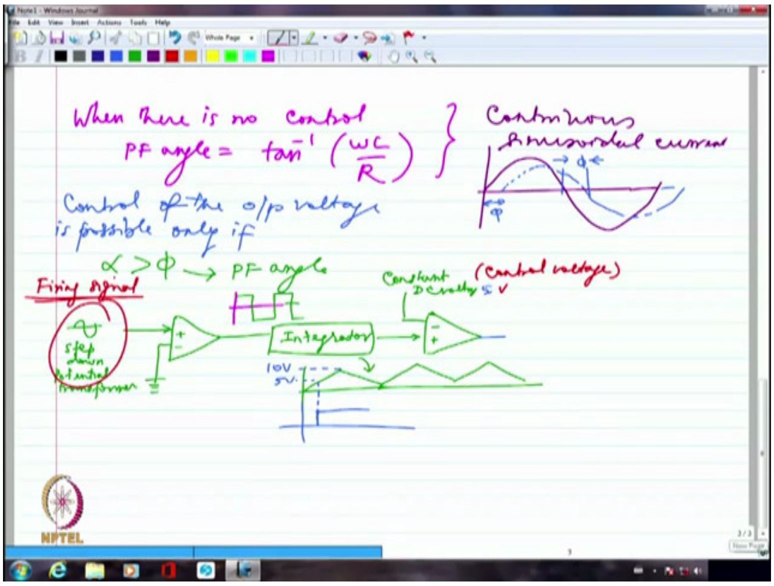

So, when there is no control, when there is no control then, I am going to have the power factor angle, $\text{PF angle} = \tan^{-1}\left(\frac{\omega L}{R}\right)$. It is not going to be any different. When there is control, the current is discontinuous. When there is no control, I am going to have essentially continuous current although it is alternating current. Alternating current, it will pass through 0 just for moment, momentarily it will pass through 0 but I will have essentially a continuous current.

So, in this case, I should say it is continuous sinusoidal current. So, I will essentially have if this is my voltage, I am going to have the current exactly again sinusoidal with the power factor angle being phi or whatever, so this is going to be my power factor angle ϕ.

So, the bottom line is, if I try to fire my AC voltage controller below ϕ, an angle below ϕ, I lose control. I do not have control, because the inductance will anyway push the current until ϕ, the current is going to push until ϕ weather I like it or not. So, the current is containing until ϕ or $\pi+\phi$ whatever I am really not going to be able to say that 1 device will go off before I fire the other device, that is not going to happen.

So, we will get control. So, control of the output voltage is possible only if α is greater than ϕ, where ϕ is the power factor angle. So, this is one of the criteria that is very very important for the control of any of the single phase equipment, if I want to have a control over the voltage. Fortunately, probably for three phase, a single phase induction motor although the inductance is somewhat larger, we will generally not control it below 45 degrees or 50 degrees of firing angle.

So, we will always have the range because the power factor angle will roughly be about 50, 60 degrees. So, we will only have the control range from 50 digress until 180 degrees in the single phase induction motor case and we will not go until 180, because if we go until 180, the motor will not get any voltage. So, we will not generally go until 180 but we try to limit the range of the firing control only from power factor angle ϕ until whatever is the maximum firing angle that could be fire. That is way normally it is done and invariably the firing of rectifiers or AC voltage controllers will be synchronized with whatever is my incoming supply.

So, normally the firing circuit will work in such way that, I first take the sinusoid from the supply itself by using the potential transformer which will be like a step down transformer. So, from 230 volts, it will step it down to 3 volts or 2 volts. So, that kind of a stepping down action we have to do.

So, this will be done with the step down potential transformer. So, it is essentially as good as having an open circuit on the secondary side. It is like no load test on the transformer. Similar condition will exist here. I will not connect any big load, and it will be rated for 1 volt ampere or even less, very very small volt ampere rate.

So, this sinusoid will be actually given to a comparator, operational amplifier. The same kind of operational amplifier in open loop condition when we use it as a comparator to plus we may give this and minus may be grounded. If we do that, what we get here will be a square wave, because whenever the plus terminal is at a higher potential than ground, I am going to get a positive saturation voltage and whenever I am going to have the positive terminal that is the sinusoidal voltage is less than ground, I will get a negative saturation voltage.

So, I can get a voltage here such that it will be somewhat like this. I am going to have a square wave coming out. Now, this I can use probably with the help of the level shifter or I can even have the +VCC as 15 volts -VCC at 0 because there are operational amplifiers which work like that. So, I do not even have to go until negative but if I have negative also, I can use after this an integrator, again an operational amplifier circuit.

So, if I use an integrator, I will get the output to be something like this. If I do not have any offset error, then this is how the integrator will work. Whenever I am going to get a positive voltage constant as I integrate, it will ramp up and whenever I have a negative voltage it will ramp down. This is how it is going to be. Now, this can be compared again, so integrator output is this. This can be again given to Op-amp comparator, maybe I can make this as plus and in the minus, I can give some constant DC voltage.

So, if I know that the peak of this is going to be let us say 10 volts, for example. So, if I give this constant DC voltage to be 5 volts, then I am going to have the comparator output actually giving me whenever my integrator output is greater than 5 volts, I am going to have a positive signal, otherwise I will have a negative signal. So, I would have the intersection of these two voltages, if this is 5 volts for example, this is going to give me a signal somewhat like this.

So, this voltage, the constant DC voltage is generally specified as control voltage, because this is the one which is going to decide the firing angle. If I have 5 volts, I will have exactly somewhere in the middle. So, that is going to be about 90 degrees. This whole thing is 180 degrees and this is another 180 degrees. So, if I choose 5 volts, I will basically get a firing angle of 90 degrees, if I choose less than that 2.5 volts, I will get 45 degrees and so on and so forth.

So, this particular voltage, what I am using as the control voltage, decides the firing angle. So, in good old days, when we were using only analog electronics circuits to generates the firing signals for all these things, we used to do this basically. All of us have done this to fire the thyristor circuits.

Please note, the entire thing is now synchronized with the sinusoid. The complete thing is synchronized with sinusoid. So, please note that the line commutated converter, be it rectifier, be it AC voltage controller anything that works from an AC supply has to be synchronized with the AC supplies, so that the firing signals go at the appropriate instance, otherwise you will not be able to designate this is what is positive half cycle and this is what the negative half cycle.

So, all these have to be synchronized with the input sinusoidal wave. So, this is basically the firing signal generation that is done for AC voltage controller. So what I am trying to get that is if I know the power factor angle then I have to adjust the control voltage as per the power factor angles, so that I get control over the voltage, otherwise I will not get control over the output voltage. That is what I am trying to get it.

Therefore, the control voltage plays a very vital role in deciding the firing angle and the firing angle will be decided based on whether I require control, if I require control, it has to be greater than the power factor angle ϕ.

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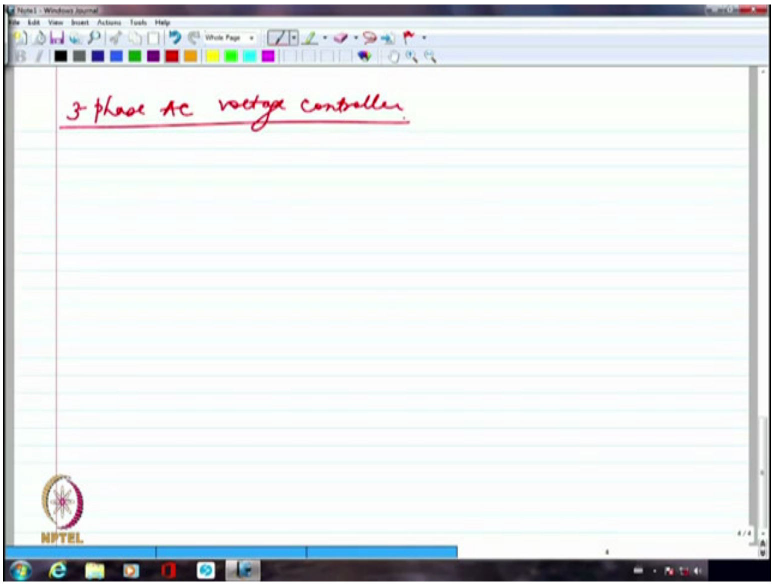

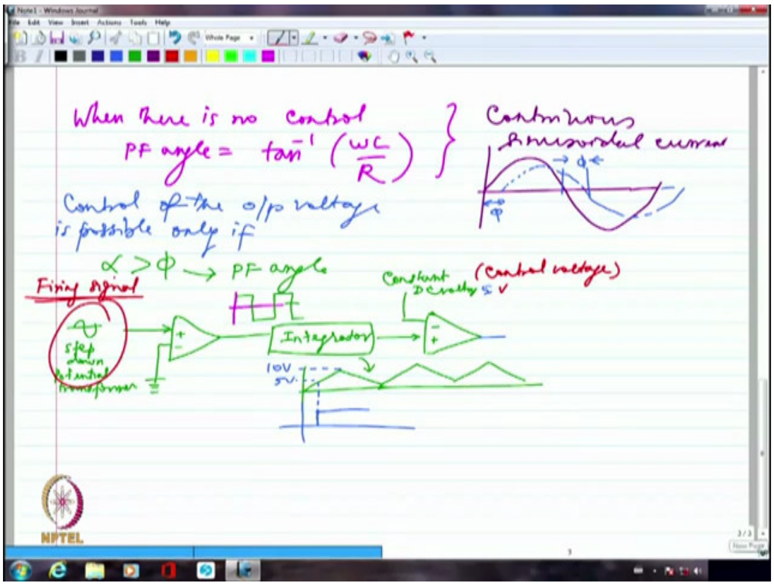

Let me try to now go for the three phase AC voltage controller. The question was, this will generate firing signal only at α then 2π+α and so on and so forth 4 π+α, because of which it is generating the firing signal only for t_1 not for t_2. So, if I want for t_2, I might have to just invert this, this has to be completely 180 degree opposite and then again I can use integrator and so on and so forth, so which will give me exactly the opposite of whatever I am getting or 180 degree shifted wave form for the other one. So, all I can do is, I can use one more comparator with plus here and minus here that will do the job.

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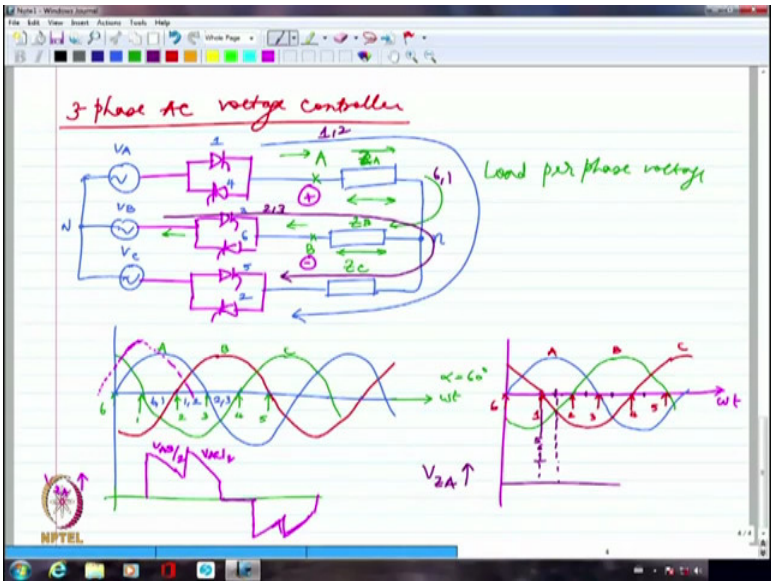

Now, let us now go over to the three phase AC voltage controller. There are several configurations and one of the toughest circuits analyze I have seen is the three phase AC voltage controller. So, let me take only one single configuration which is the star connected configuration, let me go into delta. I am going to take only a star connected configuration, what I means is, I am going to have the three phase supply voltage is connected in star and the AC voltage control devices also connected in series directly with this and the load also I am going to take in star.

Now, I am going to take the load also exactly connected in star. Let me again start with resistance load, otherwise it could be more confusing. Let me start first with resistive load and let us say, the numbering is essentially the same as what we did 1 4 3 6 and 5 2. This is how they are numbered.

So, let me call this as V_A, V_B and V_C with respect to neutral. This is the neutral of the source, whereas this is the neutral of the load. The load also I am showing as star connected, so that is neutral of the load.

Now, let me take a firing angle of 60 degrees. Let see how the wave forms go, because I am just drawing right in front of you, let see how it goes. So, I am going to take 60 degree firing angle. This is A phase and I told you that the firing angle in this case is always calculated with respect to phase voltages. So, I am going to have this is the B phase and this is going to be the C phase. These are the three phase voltages. And if I am firing device number 1 at 60 degrees that means I should have fired device number 1 here, because this is A phase this is B phase and this is C phase.

So, I am firing device number 1 exactly at this point for α equals to 60 degrees. So obviously, I will have to fire device number 2 here, device number 3, device number 4, 5 and 6 should have been fired here, and fix when it is fired, I should have B to B negative, yes B is negative, no problem. Similarly, when I am firing 1, A should be positive, A is positive that is not the problem.

So, before 1 is being fired, 5 and 6 should have conducted together. But now, when I am firing 1, let me start looking from this point, when I am firing 1, I am going to have actually 1 and 6 conducting together, so I am going to have the current flowing like this and it is going to return like this. Will 5 conduct at this point? I have to check. Because 5 can very well conduct, if it is conducer, the situation is conducer and 5 will conduct only if C phase voltage is positive. But C phase voltage is not positive, then I am firing 1 fortunately, if it is resistive load that is why I did not want to go into inductive load first.

If it is resistive load at this point, when I am looking at this point, I am not going to have clearly C is becoming negative from this point. So, 5 cannot be conducting, I will have only 1 and 6 conducting and when 1 and 6 are conducting what I am getting as the load voltage is A here and B here, assuming that my devices are not having any voltage drop. I am getting essentially V_{AB} across the two portions of the load, the third portion is inactive, the third portion is not even conducting, only two portions are conducting.

So, if I may call this as load A, so let us say this is Z_A, Z_B and Z_C. Only Z_A and Z_B are active Z_C is not active. So, if I try to look at what is the load per phase voltage. If I look at what is the voltage across this alone or the voltage across this alone that is the load per phase voltage. If I assume that it is balanced load, VAB is coming across Z_A and Z_B and Z_A and Z_B are of equal magnitude. So, I should have $V_{AB}/2$ across Z_A, $V_{AB}/2$ again across Z_B. Both of them have to be half of the total line to line voltage that is coming across each of the load.

Now, I have to look for V_{AB}. So, if I have to draw the V_{AB}, this is V_A, V_{AB} should have been 30 degrees leading, so it must become peak somewhere here and then it should come down something like this at 30 degree it should have come down to 0, that is V_{AB} what I have drawn in pink color that is V_{AB}. Now, I have to say from this point onwards, I am going to have V_{AB}. So, I will have V_{AB} coming up may be like this, that is the peak I suppose or close to peak whatever and I am going to have this coming down like this. This is how it is going to be.

That is $V_{AB}/2$, what I will get will be $V_{AB}/2$. So voltage across $V_{ZA,}$ only voltage across Z_A or impedance of A phase, that impedance across that what is the voltage if I try to draw, this is the load per phase voltage. Per phase voltage of the load, so this will be $V_{AB}/2$, is this clear.

When I am having 6 and 1 are conducting, I have only AB voltage coming across Z_A and Z_B. So, voltage across individually Z_A and Z_B individually will be $V_{AB}/2$. Only thing is you have to understand that this point is positive with respect to neutral, whereas this point is negative with respect to neutral, because the three is the current is flowing towards that. So, that is at the lower potential clearly, with respecting neutral I will have one of them as positive one have them as negative because of the current direction, as simple as that.

Now, when 2 takes over, will 6 go away that I have to check again. When 2 takes over right, whether 6 will go away, because 6 corresponds to B phase. Fortunately, B is becoming positive. So, B will go away, that is 6 will go away when I am firing 2 automatically. So, I will not have 6 conducting, from this point onwards it will be 1, 2 and 1, 2 is V_{AC}.

So, in all probability I will have a similar wave form, because I will have again this is $V_{AC}/2$. Because A phase and C phase will conduct now together. So, if I try to draw the current for the next one, I should draw it as though the current is flowing like this through this. Now, B phase is inactive, for the next 60 degrees.

So, I am going to have $V_{AB}/2$, then $V_{AC}/2$. After $V_{AC}/2$, I am firing 3. When I fire 3, weather 1 will go away? Yes, 1 have to go away, because A phase is positive and it is beginning to become negative here. So, obviously when I fire 3, 1 is going away. So, if 1 is going away, I will have only 2 and 3 conducting together from this point onwards.

So, I am actually going to have 60-60 degree interval. Here, 6 and 1 will conduct, here 1 and 2 will conduct, here 2 and 3 will conduct. Provided it is resistive load. I have not touched upon inductance. Now, if 2 and 3 are conducting here, please note I would rather have the current this way, the current will go like this and return like this. So, this is for 2 and 3 and this is for 1 and 2 and this green is for 6 and 1.

So, I am going to have now 2 and 3 conducting, Z_A is going to be inactive. So, I would probably have this abruptly coming down and just keeping mum for some time. When 2 and 3 are conducting, Z_A is inactive, completely inactive. So, I will have literally 0 voltage, no voltage at all across Z_A. Now, I will have a similar one on the other side, when 4 is conducting, 3 and 4 conducting will be V_{BA}. So, opposite of V_{AB}, I will have $V_{BA}/2$. Similarly, when 4 and 5 are conducting it will be $V_{CA}/2$.

So, in all probability it will be a replica of this but in the opposite direction, something like this. Please note, we have taken a specific case of firing angle and resistive load. We have taken 60 degrees, if we have taken slightly earlier, for example 45 degrees, I would have fired 1 slightly earlier, when I fire 1 slightly earlier, C phase is still positive, 5 will not give up. 5 will say, I will also conduct because I am forward biased, why not I conduct, as simple as that.

So, whenever I am going to have the firing angle less than 60 for or load I will have sometimes three devices conducting, sometimes two devices conducting. So, if I try to look for a firing angle less than 60 degrees, for example, if I fire 1 here, 2 here and so on and so forth. If I fire 1 here, please understand, 5 will continue to conduct because 5 will continue to conduct, I will have 5, 6, 1 all three of them conducting simultaneously.

When I have 5, 6, 1 all three of them being connected to the load, it as good as having a normal three phase supply, I hope you understand. It is not any different from having a three phase supply, when I have 5, 6, 1; 5 belongs to C phase, 6 belongs to B phase, 1 belongs to A phase. So, when I have 5, 6, 1 conducting, it is as good as having a normal three phase supply connected to the three phase load.

So, only for that duration where 5, 6, 1 will conduct, if I try to look at what is A phase voltage, what is B phase voltage and what is C phase voltage, it will be corresponding phase voltages itself. V_{AN} for the first one, V_{BN} for the other one, V_{CN} for the third one. Had it been an inductive load? What was going to happen for the same case? That is what I want to check.

So, if this is ωt for the same 60 degree firing angle, so this is going to be my one of the phase sinusoid, this is going to be the next phase and this is the third phase. Let me take the same 60 degree firing angle, so I am going to fire 1 here, 2, 3, 4, 5 and 6. We said earlier that, when I was firing 1, automatically 5 will go away because it was having resistive load and C was becoming negative. So, obviously that has to go away, but now I am having inductive load. If I have inductive load, the inductance stored energy is going to pitch in definitely, that is not going to allow 5 to go out, because the current is still flowing through the inductance, abruptly the current can not come down to 0.

So, even at this point where I am firing 1, I will have 5 containing to conduct despite the fact that I am going to have C phase voltage coming into negative half cycle. So, at this point itself, I will have actually 5, 6 and 1 all three of them containing to conduct. All of them will continue to conduct together and how long 5 will continue that depends upon essentially, what is the kind of inductance value I am having in comparison to the resistance.

If the inductance value is really dominating, I will have a good amount of energy because of which I would have had probably 5 continuing even until here or here or whatever, but if the inductance stored energy is not too much, it will go closer and closer to the resistive load. If I assume that may be until this point, 5 is containing to conduct, then I should definitely assume the same way, until this point 6 will continue to conduct, until this point 1 will continue to conduct, until this point 2 will continue to conduct and so on and so forth. So, I have shown different points, where I may have continuation of conduction of the previous device it should have gone off, but it has not gone off because of inductance.