**Power Electronics Improvements**

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**Lecture - 7**

# Power Electronics Improvements

Last class we started about the power factor problems associate with phase controlled converters. Then, we studied what is the problem with the single phase fully control converter and we found that for a single phase fully control converter that is a single phase fully control converter; this is the four thyristors, four thyristors will be controlled, commutations is natural commutation that is when the incoming phase that is now the phase which is turned on or the thyristors which is turned on will switch off the previously conducting thyristor the bottom or also at the same at the when the bottom thyristors turned on the previously conducting thyristor at the bottom will be turned on.

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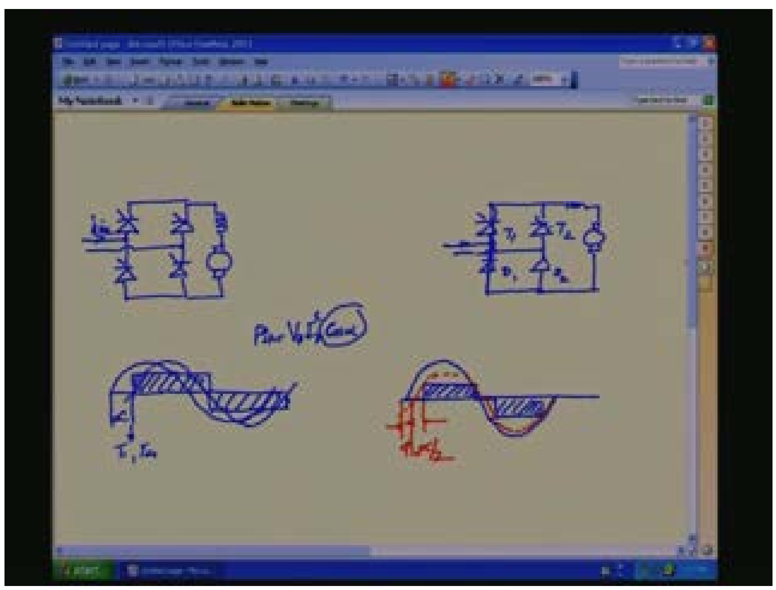

Now, with respect to the firing angle; suppose this is our mains voltage, for continue taking we will be talking about the this one and assuming current is highly, output current is highly DC, we are assuming the ripple is negligible, when the top when the top device T 1, T 4, T 1 and T 4 are turned on, current will be going like this; when the T 2 and T 3 are turned on, input current will be like this but output currently will be the rectified version of these current at the load side. So, this is the current waveform at the input side that is this side, input side, input side.

The fundamental component of this current will be approximately something like this; the phase relation with the respect to the total current on the fundamental current is something like this. So, if and also we also know that the input power that is a fundamental RMS power that is the one which will be of any useful, it will be of any useful work transferring from the source side to the load side.

So, the fundamental power P input power is equal to $V_{RMS}$ that is the input RMS side, voltage RMS, then the current RMS, current RMS of the fundamental $I_1$ R into the phase different, displacement angle between the voltage and the current waveform. Here, because of the firing angle; firing angle is initiated at alpha, so current will start moving start flowing through T 1 and T 2 at this point. At this point, T 1 and T 4 will be connecting.

So, the fundamental current is displaced by alpha; so, power will be cos alpha. So, as the firing angle increases, the cos alpha will decrease and there is a there is a decrease in the power factor and also we told what is the power factor; we told the power factor for the same power as the firing angle increases, input will draw large current; large current so that the power is constant. So, it can decrease the efficiency of the system; on this higher current, it can create losses in the system.

So, we want ideal case to draw the maximum power for a particular condition, for particular output voltage from the input, the current should be phase angle or the displacement angle between the voltage and the fundamental current should be 0 so that the power factor cos alpha should be unity. But in the phase control converter, what we found it is cos alpha. Now, when we went for the semi controlled converter; the semi controlled converters are used when we want only the or when we do not want the, when we do not want the negative voltage, negative DC voltage, controlled voltages at the output. We only want the output voltage vary from 0 to positive. Then we will be using only the semi controlled converter that means two thyristors are controlled.

What is the advantage of that one? We can then, the gate rise, we can have a save saving on the gate drive circuit and cos can be reduced. So, for the semi controlled converter if you go if you see here, it will be like this; this we have taken in the last class, the semi controlled single phase full wave semi controlled converter will be like this, this the diode. We have two diodes; bottom portion, we are using only diode - $D_2$, this is $D_1$ and top, we will have the thyristors to control the output voltage.

So, this is our load. Now, we can represent as the DC motor. So here, these the input $I_1$ current; so here how the voltage, the fundamental current with respect to the input voltage will be? So here, it will be if you draw the waveform, this is our mains, when the current waveform, see because of the diode as I told before, whenever the diode forward biased, it will not wait for any A drive circuit; whenever it is forward biased, immediately it will conduct. But thyristors will switch off when the next thyristors turned on. So, when T 1 is turn on, at the positive site T 1 is turned on; when these point that is this point, when these point becomes when these point becomes negative, this diode will immediately conduct and unless these thyristors turned on that is these T 2 is turned on, T 1 will not switch off.

So, during the portion when this point goes negative, there is a short circuit to this one and output voltage will be 0. So, the current waveform if you see here, input current; during the freewheeling period, input is not giving any current to the output. So, that point it will be 0, then here, this way it will happen. The input current is like this, input current waveform is like this, this we have talked about in the last class.

Here, the fundamental, if you see the fundamental, let us draw with the current fundamental current waveform will be approximately like this. So, even though firing angle is alpha, this is the alpha, the displacement angle is that is from 0 side, 2 zeros, voltage zero crossing, current zeroes, it is this is 5 is equal to alpha by 2. So here, the power factor there is an improvement in the power factor. Now, I really speaking, what we want is unity power factor. So, is it possible for as to get a unity power factor? Then what is required here? So, let us take a semi controlled converter, the same semi control converter.

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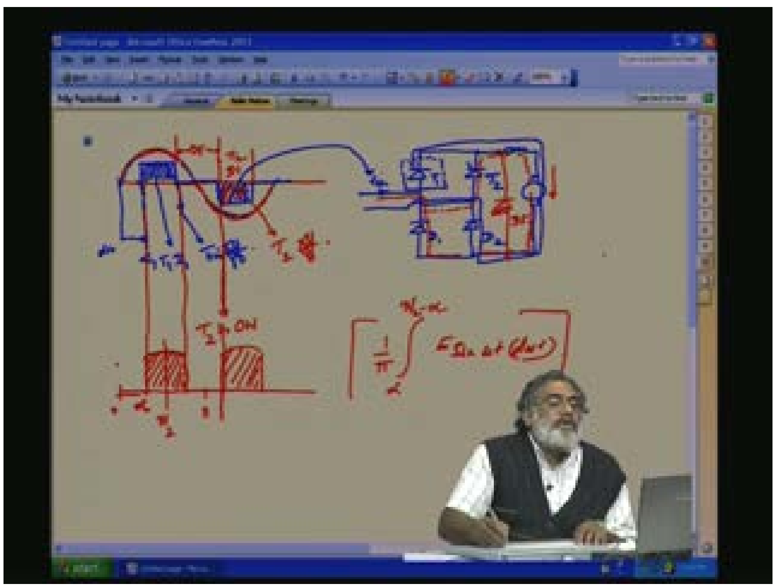

Let us take a condition like this; these are our mains waveform, voltage waveform. Now, if we can have a current waveform like this that is the conducting period through the input side is centred at the mains phase voltage is the current waveform. Then what is the advantage here? Here the fundamental, even though we are getting pulse to current through the mains, fundamental current will be always, the displacement between the fundamental current and the voltage will be always 0 and the power factor will be maximum that is cos 0 is equal to 1; a condition like this, we will get it. So, this is the best way of drawing power. How is it possible with a semi control convertor? Let us see.

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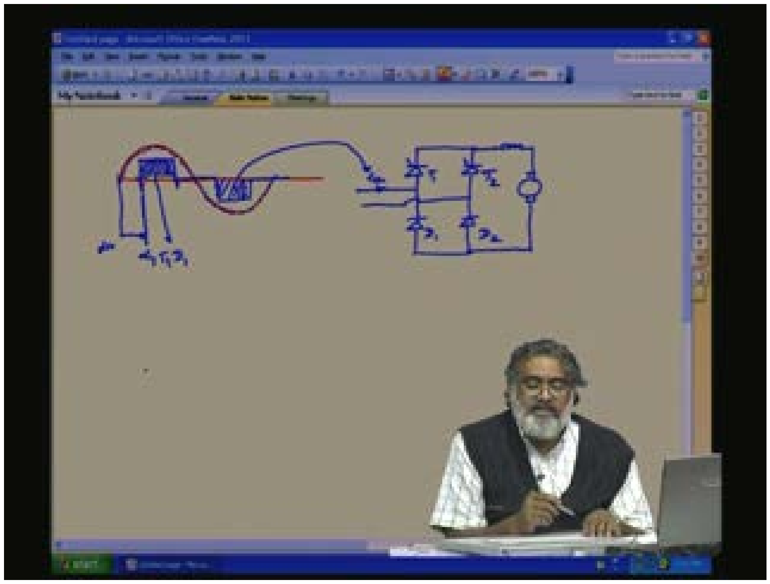

Again, we will draw the power circuit; this is semi converters, so bottom portions are the diodes, our input, this is the current, we are talking about. How to get a current waveform? Like this; this is our T 1, T 2, $D_1$, $D_2$. How to get a condition like this? So, if you see this figure, the firing angle starts here. Alpha is equal to 0 here; this is the firing angle alpha, some firing angle alpha starting from here. At this point, the current T 1 on $D_1$ will be conducting, this point T 1 on $D_1$ will be conducting, T 1 and D1 will be conducting.

Now, suddenly the input current stops here, at this point. The current has stopped means the power circuit that is the thyristors and diodes are not allowing any current flow from the input side to the output side. So, what we should do? In this case, at this point, at this point, we should switch off T 1 by somehow. T 1 is off; we have to switch off T 1.

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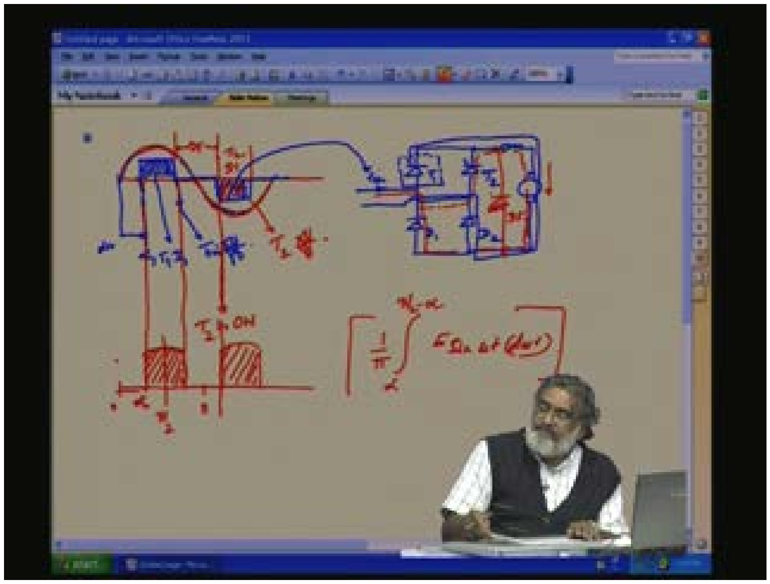

That means we require a force commute, some external circuit; using some external circuit you should force commute at this time. But there is another problem; previously this current was input current was flowing through the through this way, it was flowing and it was returning back to the mains like this. Now, thyristor T 1 is turned off; this current is there, suddenly you cannot change the load current. So, we should provide some other path for this load current to flow and T 2 is not turned on.

Now, if you see here, the T 1 turning off is not through T 2 turn on, T 2 is not yet turned on and we have turn off T 1 through some external circuit. We will study one circuit, one interesting circuit later. But thyristor will switch off but current cannot dyed out immediately, load current. What will happen? If you switch off like that there is no alternate path for the device flow. The di by dt suddenly will increase and it will force the current flow through T 1. T 1 will not be turned off, so for to make sure that T 1 is turned off, what we have to do? We have to put another part that is the freewheeling path here, you have to give diode DF.

So, during this input 0 current periods that is these periods, DF will be connecting. Then again, at this point, we will be turning on, T 2 is turned on, T 2 is on. The moment T 2 is turned on and the mains is negative; so $D_1$ will be immediately turned. So, this point is negative now. So, D 1 is forward biased and $D_1$ will be immediately turned on. Now, the current will flow through this way. The moment T 1 is turned on; this point will come across this one, D 1 is turned on, this point will come here, this diode will be reverse biased and other immediately switch off and current will flow through the load and return through D 1, it will return to D 1. That is this portion, during this period T 2 and $e_1$ are connecting. Now, again at this point, at this point, T 2 is off, T 2 off.

So, T 2 off; what will happen? Immediately the current, current is unidirectional, unidirectional in the load, DC value, it will free freewheel through the diode. So, this way, we can away unity power factor. So, always here the quality of the power supply is very good as for the power factor is concerned. We have taken fundamental at zero displacement with respect to the phase angle between the voltage on the fundamental currently 0.

So, what will be the type of voltage waveform appearing across the load? If you see, during the conduction period that part of the waveform will come across come across the load. If you see here, this is the conduction period here. During this portion, the voltage waveform, that part of the voltage waveform will appear across that is this much portion will appear across the load part. Part of sin wave centred at the weak point of the sin wave, sin wave; we are assuming the input main sin wave, it will appear across the load.

Then during the negative portion, it will be this portion but it is rectified waveform, so it will come this way, this will come across this. This is due to this, this is this happens due to the force commutation using the thyristor. Here, what will be the output DC voltage with respective firing angle? We know this is 0, the central will be phi. So, the output ripple frequency is two times the fundamental.

So, what will the output voltage waveform here? The period, period is equal to phi 1 by average value. So, 1 by phi average value, integral, let us say, Em; we can taking Em sign omega T cos Em sign omega T D omega T, Em sign omega T means the lower limit will be alpha that is a firing angle. What is the upper limit? This is pi by 2; upper limit will be, see this is symmetrical, so this is if this is alpha, this distance is phi by 2 minus alpha. So here, it will be pi by 2 minus alpha. This we can integrate and we can find out the output DC, ripple for this one.

Now, we have 2 degrees of freedom; one, previously the old of phase and phase angle control we had only one degree of freedom; one degree of freedom, we can only have the start of the firing angle that is alpha, start of the turning on the devices. Now here, but switch off happens whenever the other thyristors symmetrically fired or during the negative portion of the voltage waveform, again same alpha starting from the zero crossing, we have to fire the next thyristor.

Now here, we are not; that type of commutation is called natural commutation. But here we are doing forced commutation but we require one extra diode here but power factor improvement is here. In this case, during this two degrees of freedom; what extra… okay, power factor improvement is there; what is what are the additional advantage its possible? Let us say one in one case, let us take in one case. I will again draw the waveform.

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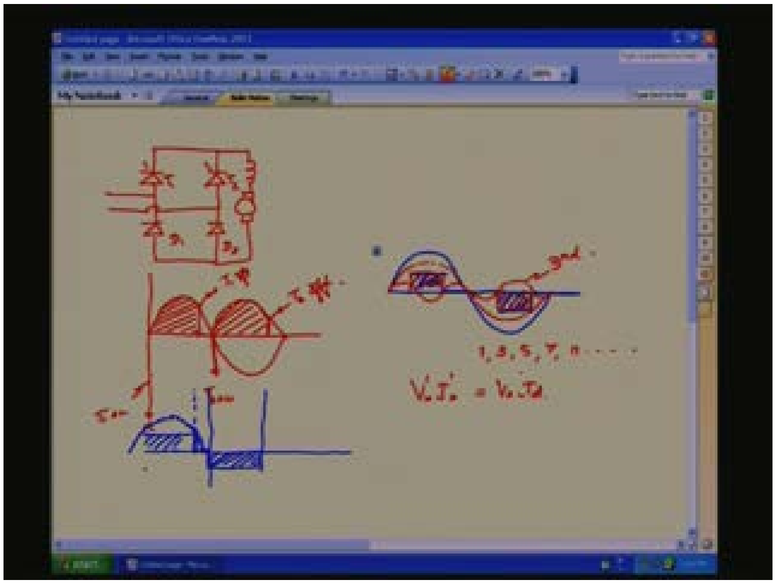

Thyristor, diode, thyristor sorry I will remove this one, diode, power load, again T 1, T 2, $D_1$, $D_2$. Let us draw the input mains here. See, we are sequentially, we are coming to one point here. Previously, with the firing angle, the displacement keeps on increases with respect to the firing angle. Now, with semi convertor, we made that displacement, we have reduced to alpha by 2 that phi. Now, with the force commutation, we made that phi is equal to 0.

Now, is it possible for us to make phi negative or though currently is leading with respect to the input current is leading with respect to the mains? Let us see; waveforms like this. We are always firing at alpha is equal to 0, let us say. The firing is with respect to this one and we are turning of here, this is the turning of portion, the forced commutation, T 1 off. So, what will happen? This is the portion of the voltage input voltage waveform coming across the load during the positive half cycle. The negative half cycle, again we are turning on at this point.

So, at this point, T 1 is on, we are giving the gate pulse. Here we are turning on; at this point we are training on T 2 on. Again, at the same distance same as here, we are turning off T 2. T 2 is off. So, what will be the type of current waveform you will observe here? Let us, so if you take here, the current waveform at this point, freewheeling starts where beta is there, this point. So, current waveform will be here, comes here, this side, it will be 0, then again it goes negative here. See, this way it goes. So, if you see here, the fundamental the fundamental if this is the fundamental voltage, the fundamental current is leading the mains voltage.

So, these type of application where leading current; we can use it in compensation for line voltage drops. Supposing line voltage drop, large inductance is there, L omega drop is there; so by giving a leading current, that drop can be that line drop can be we can compensate here. So, these type of things are this is one way of this is another advantage of this two degrees of freedom. Here, the fundamental supply current leads the voltage. So, the displacement factor is leading and as I told this feature may be desirable to compensate for line voltage drops, for system line drops, we can use it; line drops, we can use this one.

So, what I want to bring here is so here, we have two degrees of freedom that is we can whenever we want, we can turn on the device; whenever we can turn off the device. So, what is what we achieved from here? By doing this way, what we what it is we want unity power factor, the fundamental voltage and the fundamental current should be in phase, the displacement should be 0. So, we are always talking about the fundamental current.

So, fundamental current if you see here, if this is our mains waveform and we told this current is symmetrically priced here, the input mains current, the input current on from the mains; so fundamental is in phase with the input voltage. There is there is a one advantage; this is the fundamental, this is the fundamental current. But if you see here, this waveform if you do the Fourier series, it has other harmonics, fundamental will be there that is the desirable one.

Then we have the third harmonics; if you do the Fourier series, fifth will be there, seventh will be there, eleventh will be, all these harmonics will be currents …. This harmonics, this harmonic currents, the third harmonics will be something like this; this is the third harmonic component. Similarly, fifth harmonics will be there, this is the third harmonic. So, this current anyway will be there. So, fundamental third, if we take large number of harmonics and when they submit, you will get the fundamental, the total input line current that is this one, you will get it.

So, the fundamental only will be giving the power that is if you say assuming the efficiency is 100%, the input power here $V_{RMS}$ that is in this case, it is V fundamental RMS, then I fundamental RMS will be equal to our $V_0$ into Id, Id is the total DC current. But still, there is the harmonics are there. These harmonics; what it can create? It can also create heating loss of high score or losses. This is the power circuit, also the device drops. So, it will also, it will also consume some power but is not is not useful power that will not available at the output; this gets wasted there in the device, one is I square r losses, I square r heating loss.

So, efficiency of the system will come down. Now, one way the efficiency or the quality of the power supply system, we improved by a forced commutation making the power factor unity. Now, there are harmonics. So, how to suppress this harmonics? One way to suppress these harmonics currents; can we use some filter, some sort of filter so that the fundamental will pass through and the harmonics will get harmonic current will be suppressed? Okay, this we can, this may be possible theoretically but whenever we give any proposition that is variable control voltage for practical application, we should give a cost effective solution.

So here, without harmonic filters, is there any way, we can suppress the harmonics? See, let us come to this one. Let us study about how we can do it? Here, we have to use pulse width modulation, here we have to use pulse width modulation. This idea taken from the communication people; pulse width. Their advantage of the pulse with these, we will shift the high amplitude harmonics. Here the high amplitude harmonics, after the fundamental high amplitude harmonics is the third one. So, we want to shift the high amplitude harmonic to the high frequency side. Suppose, the high amplitude harmonics, we can shift it to 11 times the fundamental or 13 times or 20 times of fundamental or 21 times of fundamental.

What will happen? If you do that way, whether is there any advantage is here? Let us study about that one; what how we can use it. See here, how to control the harmonics at the high site not the current harmonics, the voltage harmonics. See, whenever the current harmonics is there, should be voltage also there. So, voltage harmonics, we should shift to the high frequency side. See, here if you see, the voltages, this the voltage we got. Now, this voltage also will have the fundamental output side, fundamental as well as the harmonic. So, these harmonics; so for we are talking about only the DC value but if you see the voltage across the load, you have these type of ripple waveform coming.

So, what we want; the ripple voltage will have the ripple harmonics also. That is ripple harmonic, what are the things? Fundamental, apart from the DC value other harmonics; here it will be 2 times the fundamental, then its other multiple will be there. So, these harmonic voltages will generate, it is all harmonic currents. So, these harmonic currents at the load side, it can create losses. So, what I was, want to tell you now; how to suppress the harmonic currents and harmonic voltages at the load side so that the harmonic current drawn by the, harmonic current drawn by the harmonic ripple; we can be reduced because as the high frequency increases, increases; so the current due to the harmonic current will be decreased. So here, I told we have to use the pulse width modulation. So, let us see how we can do it?

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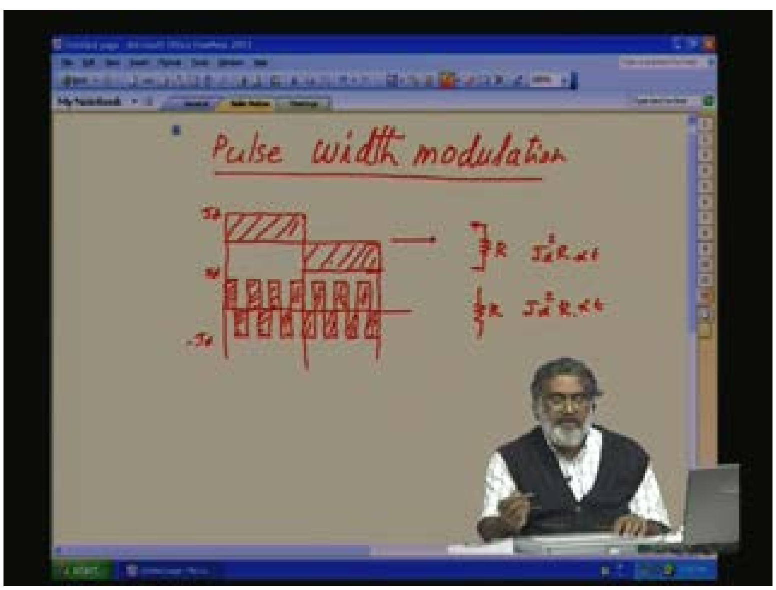


So, let us talk about pulse width modulation. What is the basic idea behind the pulse width modulation? Let us take a square wave. This is square wave sorry this equal width, that is take a square wave current. Let us take this current is flowing through a resistor. So, Id is the peak value, this is the R. What is the heat generated, the power, energy dissipated in the resistance? The power is equal to Id square, this is the Id square R, this much Watt will be dissipater multiplied by the time total energy.

Now, this current pulse, square wave pulse again value of Id, I will I will be chopping like this. So here, this is also Id minus Id. Here also, the same pulsed current if you pass through the resistance; here also power dissipated will be equal to Id square R, Id square R or multiplied by T that is energy. So, equal timing, equal energy will be dissipated in the resistance whether this shape is square pulse or the narrow pulse of high frequency.

So, what is the difference between these two? As far the power is concerned these to current waveform or if this is the voltage waveform if the voltage appearing of the resistance, then the power dissipated will be D square by R. So, in both cases, the power dissipated whether if you take the current point or voltage point; this current the power dissipated will be the same or the energy for a particular this energy dissipated in the resistance will be the same.

But if you see here, if assuming if this is a voltage waveform, if this is a voltage waveform; as far as the energy is concerned, this voltage waveform, this filter have the same energy content from the resistance point of view but how about the harmonics if you do the Fourier series?

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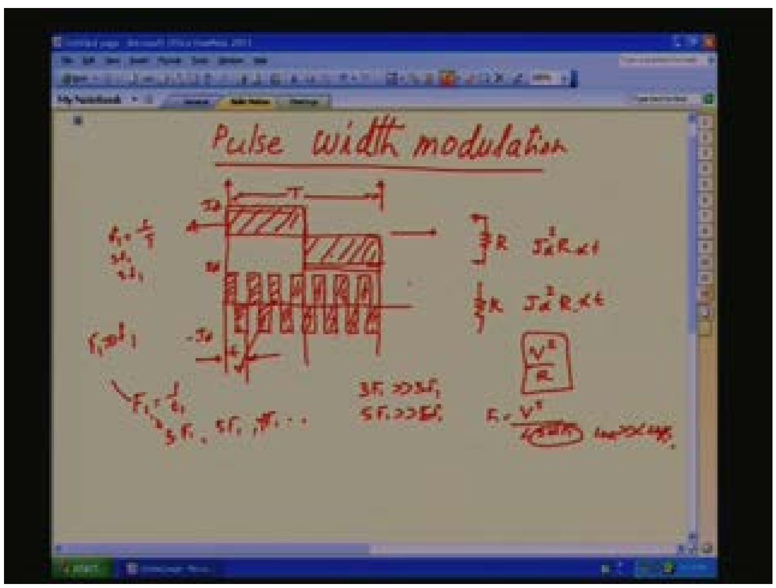


This will have a have a frequency. If this is the period t, if this period is the T, it will have the fundamental frequency $F_1$ is equal to 1 by T and next harmonics will happens $3F_1$ $5F_1$ that way it goes for this one. Now, how about for this one? This one, the fundamental frequency will be let us see this is small small t; so the period is much less, so the frequency, $F_1$ for this one is equal to 1 by $t_1$ is much higher than this one. This $F_1$ is much higher than $F_1$.

So, the harmonics, the multiple of this one, $3F_1$, $5F_1$, $7F_1$all these harmonics will be much greater than this one that is $3F_1$ will be much greater than $3F_1$; $5F_1$ will be much greater than $5F_1$. So, what will happen if such a voltage waveform? So, as for as energy is concerned, so what happened? The energy of the system at various harmonics here is shifted to a higher frequency here, the second wave form. But the total energy is dissipated when it pass through a when it apply across a resistance, the total energy is the same. If the voltage is it is V square by R but in the second waveform, the energy is shifted to the high frequency.

So, suppose let us take a waveform where this type of frequencies, the chopping is done in such a wave that not the if we can done the fundamental mains waveform, if you can chop it into high frequency side, then what will happen? The current, this the ripple voltage will be coming across the load at high frequency side at high frequency and the current drawn by, the current will be that if the if the amplitude of frequency $F_1$ if it is $V_5$, the impedance, the load impedance equal to $L_5$ into 2 phi $F_1$ that is L omega, this is L omega for the second case.

So, this impedance will be much higher than, L omega $F_1$ will be much higher than L omega $F_1$ due to $F_1$. $F_1$ the $F_1$ is subscript omega $F_1$. So, the current if for the voltage same frequency component the current drawn by the load will be much much, amplitude will be much lower than the case where the square waveform is applied across the load. So, what is the advantage? The harmonic currents can be suppressed but the total voltage depends on the total area divide by the period. So, instead of concentrating all the area in one side, we can distribute, we can chop it. If you do that way, the output voltage the harmonics spectrum the harmonic losses of the system can be reduced. Here, we use PWM operation.

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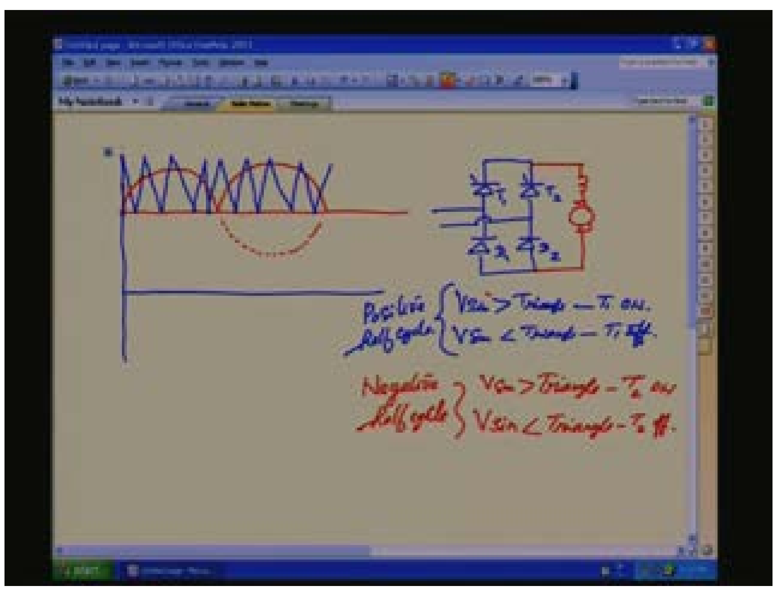

Let us say how we can do it. Let us take our mains wave form. This is the negative side; negative side, we will put it here, rectified mains waveform. This waveform, we will be comparing with a triangle wave, a high frequency triangle wave, high frequency triangle wave, we are doing like this. This frequency of the triangle waveform is high compared to our mains wave. Then, see if you see here, let us take our single phase converter, here T 1, T

2, $D_1$, $D_2$; previously we start we can turn on T 1 at any time and we can turn off T 1 thyristor one due to forced computation any time.

So, let us take the case when this, our mains is greater than the triangle waveform. We are turning on T 1 that means our sin wave V sin greater than triangle; we are turning on T 1, T 1 on. When V sin less than triangle, we will be, T 1 will be off. This is during the positive half cycle, positive cycle. Now, our turn on turn off of T 1 is independent of turn on turn off of T 2. Now, during the negative half cycle, again, when V sin greater than triangle, T 2 on; V sin less than triangle, T 2 off. Then let us see, what is the type of voltage ripple coming across the load?

So here, first condition, sin greater than the triangle that is this point, upto this point, sin is greater than. So, during this portion, this much part is coming across the load. So again, for clarity, I will draw the repeat the sign waveform here.

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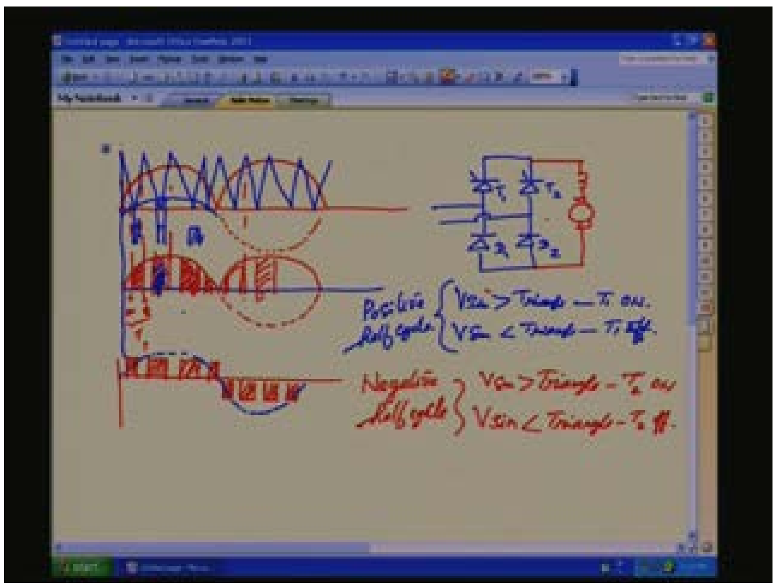

Negative, we have rectified here. So, rectification happens on the converter side. So, during this portion, whenever sin is greater than which is on, this much portion will be appearing across the load. Then again here, at this point, we are turning of T 1, T 1 on, on, this is off that is T 1. Again, during this portion, it appears across the load that is here, again here, till this point, again here. So, here the waveform triangle is not on properly, otherwise you will get symmetrically placed pulses here. The same thing happens here also, in the other side also; same greater than the. So, here will be turning on T 2, T 2 will be turning on and T 2 will be turned off at this point.

So, these type of pulsed waveform coming across the output load. Previously, part of the full part, O of the mains waveform was coming here. It is a pulsed to part. Now, the average value depends on the area, total area divided by the period; here period is 1 by phi. So, as I told before, this pulse waveform we can have the same output DC voltage but what is the advantage here? Because of the pulse frequency, the input current waveform; how it will look? Input current whenever T 1 is on, we have the input current like this; T 2 is on, we have the current like this sorry T 1 is on, it will be like this that is rectangular pulses. The negative side, you have like this. Fundamental will be, here also we have unity power factor. But what is the advantage because of the pulsed waveform?

These pulsed waveforms have high frequency component. So, the harmonic currents drawn by the load will be much less compared to the previous schemes. So, this way, the efficiency of the system can be improved. At the same time, output voltage can also be controlled. Here how do you control the output voltage? So, we found the pulse width duration, this duration depends on the period during which the sin is greater than the triangle. After the sin ample decreases; so let us take a case like this, the pulse duration, the T 1 will be on for very small durations in the on period here. So, similarly output voltage will, output DC will also vary.

So, triangle frequency is fixed, sin amplitude we will increase and decrease such that the output voltage is controlled; at the same time, the ripple frequency, output ripple frequency are shifted to the high frequency PWM side. This how, the PWM sin triangle PWM, how the frequency components are shifted, we will come to that one later stage but here we can we have to know that the next higher order harmonic, not the third, fifth; third times, it will go to not with respect to the fundamental, it will go to the with respect to the triangle frequency.

So, if we use higher triangular frequency, the current the harmonic currents drawn by the load can be reduced. But the problem is with thyristors. Thyristor require a fine, we have required external turn off circuits. So, high frequency PWM may not be possible with thyristors. But presently available IGBT’s, we can have high frequency PWM.

So, how we can have an output voltage control with a unity power factor for positive, for the positive direct say for the output voltage directions using PWM; we will be studying in the next class. This is presently available IGBT makes it convenient to have variable voltage control with unity power factor, high frequency PWM using that is front end AC to DC converter with PWM convertor with unity power factor.

So, a lot of convertors are available, one converter; we will study. Initially, originally I think, this converter was used for traction drive applications for front end converter AC to DC converter; the input was single phase. Then how the harmonics suppression, we can do with the same triangle comparison. We will study in the next class.