Pulsewidth Modulation for Power Electronic Converters

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Lecture - 08
Applications of voltage source converter - III

Greetings and good day: welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. So, in the first 5 lectures we have been looking at various power electronic converters.

We looked at we looked at DC to DC converters voltage source converter and current source inverter and multi level converters and for the last couple of lectures we have been looking at various applications of voltage source converters, this is just an overview of various applications of voltage source converters before we get on to this issue of pulsewidth modulation.

So, as part of this overview of on these applications of voltage source converters, you know today is going to be the third lecture in this and third and the final lecture on this topic and we initially focused on the motor drives, essentially in the first part first lecture and in the second lecture we focused on power factor correction. We looked at unity power factor rectifiers, how can you rectify? How can you have AC to DC conversion? Drawing near sinusoidal currents from the mains at a high power factor, that was the question we looked at and what we are supposed to look at is today is how do you compensate for harmonic currents, that are drawn this harmonic current compensation is what we applying look at.

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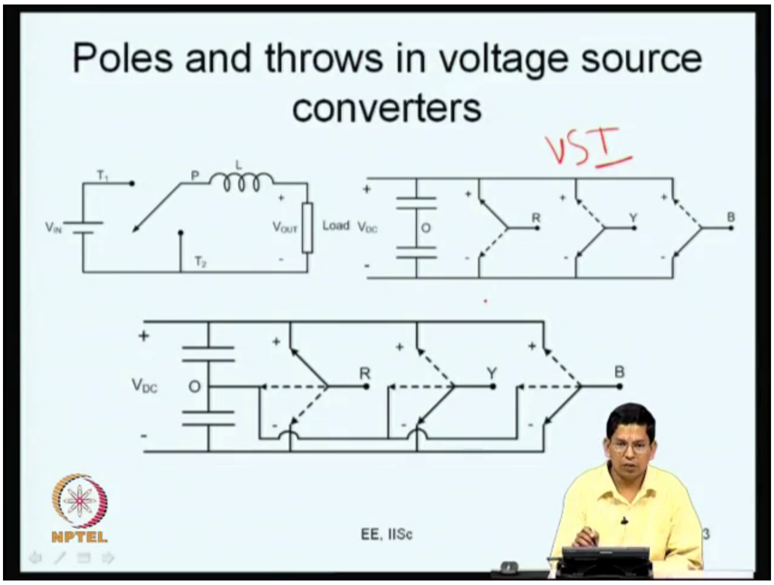

So, we will be anyway quickly reviewing what done in the last couple of lectures, now as we saw you know these all these shows different voltage source converters, I mean Firstly, we are starting with the DC to DC buck converter and next what we have is the DC to three-phase AC voltage source inverter. And then what you have is once again DC to three-phase AC a multi level inverter or the 3-level voltage source inverter and all these have been depicted in terms of generic switches. Here you have a single pole double throw switch in a buck converter and here also you have single pole double throw switches in a voltage source invertors VSI. So, here you have 3 single pole double throw switches for each for every face now.

In a multi level convertor you have 3 single pole triple throw switches. So, 1 single pole triple throw switch for each face now. So, this is what you know this is what we know already. So, what we do is we realize certain average voltage.

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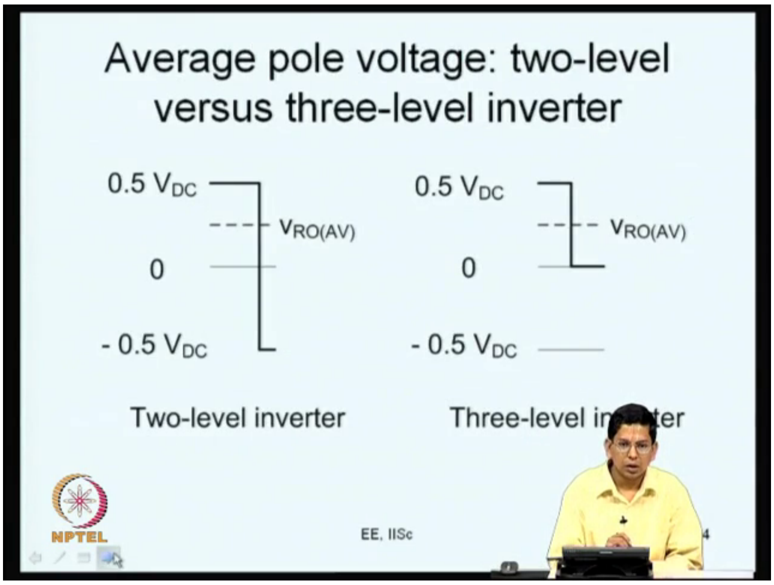

If you need certain average voltage with the 2 pole, I mean if the with the 2 level inverter, we apply 0.5 V DC for certain amount of time and minus 0.5 V DC for the remaining amount of time within a switching interval. So, that the average voltage over the switching interval is equal to what is the desired value.

Similarly, if you are using a 3-level invertors, you can you have different levels available. So, for a positive average voltage you can use you know you can apply 0.5 V DC for certain amount of time and 0 for the remaining amount of time, as appropriate so that you get your average voltage equal to what you want. Similarly if your average voltage is negative then you can apply you can realize it you by time averaging of 0 and minus 0.5 V DC.

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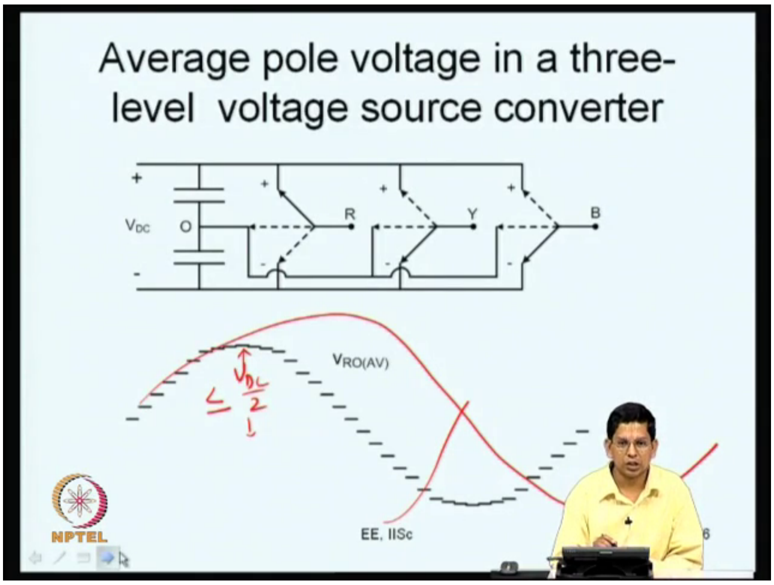

So, you can realize any average voltage I mean any value of average voltage that is anywhere between plus 0.5 V DC and minus 0.5 V DC. So, what we do is over a line cycle over a fundamental cycle, the average pole voltage is modulated in certain fashion which is usually the sinusoidal fashion.

So, in a this is a 2 level voltage source inverter and in every switching interval you produce certain V RO average, that is average pole voltage R is the midpoint of this leg called the pole and O is the midpoint of the DC bus center V RO is the potential at r measured with respect O and V RO average is the average value V RO over a switching interval.

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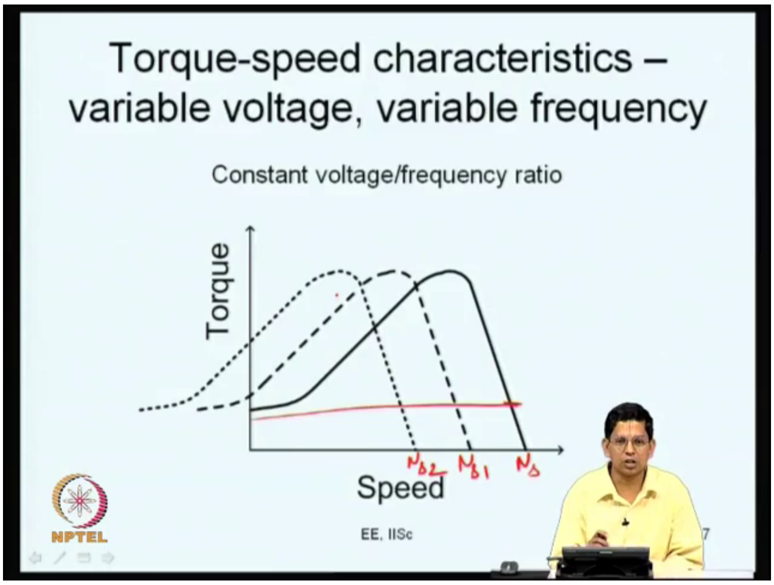

Now let us say this is you know r; let us say this is V RO average, now V RO average what we do is we modulated in a sinusoidal fashion. Similarly, even if you have a 3-level converter on the AC side if you what you need is sinusoidal voltages essentially. So, you know one way to do this, I mean the average pole voltage can be modulated in a sinusoidal fashion as shown here now.

So, what we can do is all these sinusoids are variable, that is the amplitude of the sinusoid as we observe the other day can be anywhere, it can be less than or equal to V DC by 2, because the highest average voltage can be either plus V DC by 2 or minus V DC by 2. So, you can have an amplitude anywhere up to V DC by 2 with such kind of sinusoidal modulation, that is when the average voltage is being varied average pole voltage is being varied in a sinusoidal fashion right. So, the amplitude can be controlled and this frequency can also be controlled you can make a sinusoid, you know if you can realize the sinusoid which is of a shorter time period like here or you can realize that sinusoid of a longer time period, shown here both these kinds of all these are possible now.

So, you can vary the frequency and you can vary the amplitude and because now so what you have is your inverter essentially it becomes source an AC source of variable voltage and variable frequency and this is what you need in a motor drive, in the motor drive you can just vary the voltage even at a fixed frequency and certain degree of speed control could be achieved as we saw in the previous lectures, but the range of the speed control is very limited and also this is useful only in certain applications such as pump drives compressor drives etc.

In a large fraction of motor drives what you would need is you need a control of voltage over a larger area, I mean over a wider range of speed and you know practically over the entire torque speed range, if this is your full rated torque you basically want your control over the entire range, that is any value of torque all the way from 0 to rated torque and any value of speed all the way from 0 to full speed that is what you want now.

So, you should be able to control this at any operating .now. So, you know if you apply a variable voltage variable frequency AC you can AC totally shift the torque speed characteristic of the induction motor, as we observe the other day change in frequency changes the synchronous speed. So, the synchronous speed is N s. Now let us say N s1 N s2 these are all proportional to the stator frequency and if you maintain the stator voltage to be a proportional to the stator frequency the flux is more or less of is maintained constant. So, you have the same magnetic field intensity and you can produce the same amount torque. So, that the peak torque does not reduce considerably when you do that now, this is the idea of constant V by f the induction motor drive now.

So, you can you know you operate this drive over an entire range of speed, starting from 0 to full speed and torque 0 to full torque now. So, this is one of the important applications and this is an application which will be often using in our own course, while we are dealing with pulsewidth modulation now. And this is essentially open loop control you can have closed loop control, as I already mentioned before and they are dealt with in other courses under this NPTEL on motor drives.

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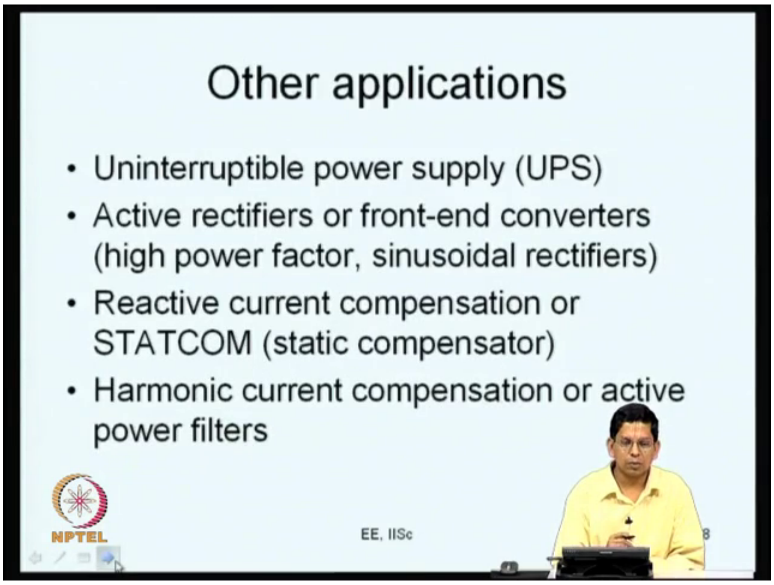

So, now you have these various other applications that the ubiquitous uninterruptible power supply we you find them almost everywhere. So, you know as we have already said it is a battery bank and it inverts and things like that and we also had a look at our detailed look at active rectifiers or front end converters in the last lecture.

Basically these are sinusoidal rectifiers which draw sinusoidal currents from the AC mains. And at high power factor and we also saw how to inject reactive power into the mains using a voltage source convertor and today the emphasis is going we will quickly review those things before we go on to harmonic current compensation.

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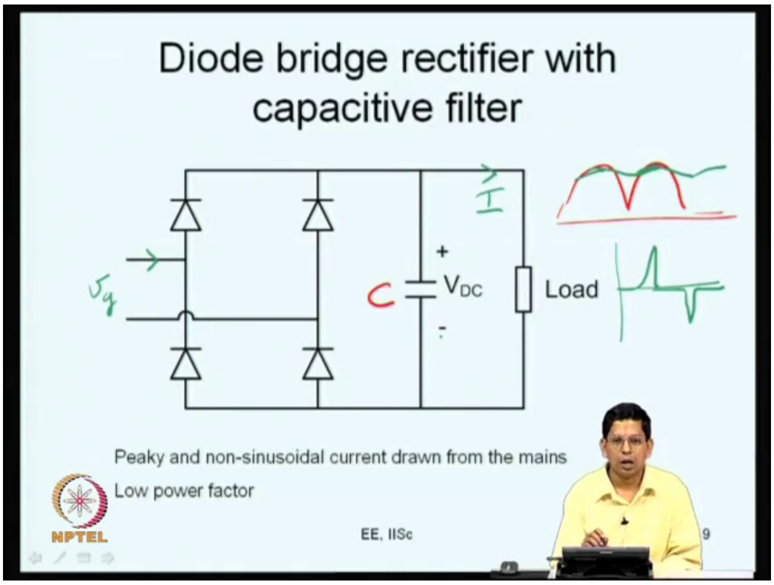

So, what we saw why we needed an Active rectifier, this is the conventional diode bridge rectifier and as we observed before the conventional diode bridge rectifier, if you consider a resistive load the output of it will be a rectified sinusoidal waveform as shown here, now this waveform has some average value, but it has a high ripple on that if you are talking about a power supply an ideal power supply should have 0 voltage ripple.

So, the voltage ripple must be negligible, but this is not the case here the voltage ripple is considerable. So, what you tried doing is a simplest thing that you can do is to put a capacitance here at the output as we have done here, this capacitance c at the output as we have done here. This helps maintain the voltage fairly close you know due to whatever it is average value. Now, once you connect a capacitance like this what happens is the waveform I mean the voltage across would becomes something like this, that is the capacitance holds the charge the mains voltage can reduce, but the capacitance still holds the charge and the voltage remains considerably high.

And again the next half cycle the capacitance gets charged again. So, you have something like you know the there are charge discharge cycles once in every half cycle, now if your line cycle you take it as 20 millisecond, that is what it is said 50 hertz every ten millisecond it has 1 charge and discharge cycle. So, as we saw in the last class if you look at this current the current here is going to be 0 for most part of the cycle, why because the capacitance voltage is greater than the mains voltage for most part of the cycle and only for a short portion of the cycle in only a small portion of the cycle, closer to the peak voltage of this mains voltage closer to the peak.

Here if I call this as V G closer to the peak of this V G you have a situation where the capacitor voltages less than or you know is not more than the mains voltage and therefore current flows only during that region and that was the reason we for we saw yesterday that you just have such kind of pulses observed here. This duration is a very short duration during which the diodes conduct only during these intervals you know the diodes are forward biased. And during these intervals the capacitances is charged the rest of the interval the capacitance is supplying the power, whatever power is required by the load is being actually supplied by the capacitor, it comes out of the stored energy and the capacitor gets recharged during this small interval like this.

Now, this is all right if you look at the DC side of this it might you know if you have designed their capacitance properly sized it properly, even if a ripple is within acceptable limits this is act as a DC power supply for many applications, but it has a problem when you view it from the AC side, in the AC side it draws non sinusoidal currents now that is you know something that we do not want, because we were talking of harmonic pollution yesterday and it draws at a very poor power factor, that is again something that the utilities do not want now.

So, we want this to be sinusoidal and we want this to be also be the sinusoidal current, also to be drawn at a fairly high power factor these are the two things that we want now.

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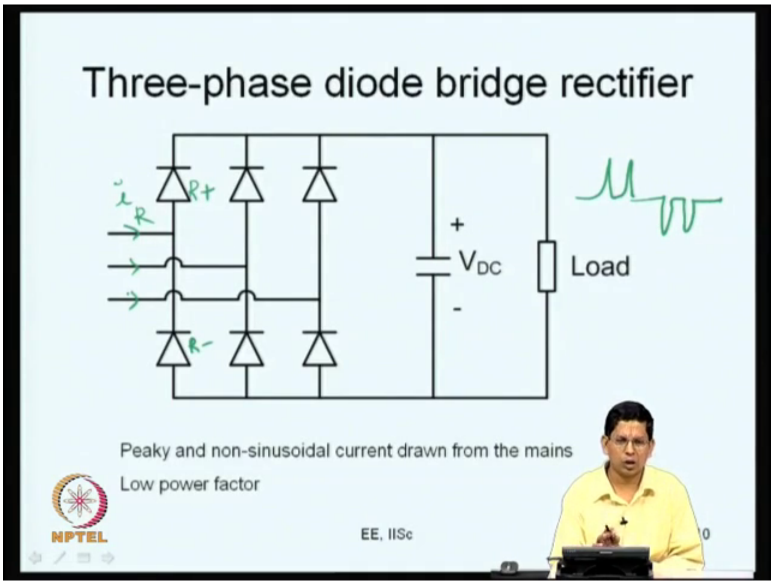

You can see the same story is valid for a three-phase AC to DC also except that you know here a particular diode let us say this R plus let me call it and r minus let me call it. So, the current you know there will be some current flowing here, when R plus R minus is conducting. So, these will conduct whenever let us say Vry or Vbr are close to their positive peaks or negative peaks, when we are why glows goes close to it is positive peak there will be some conduction. Similarly, when Vry the line voltage Vry is close to it is negative peak, you will again have some conduction the same thing about Vbr being positive or negative.

So, you will find instead of you know one current pulse, you will find actually kind of 2 current pulses in every half cycle, in this kind of diode bridge rectifier still the waveform is highly non sinusoidal very far away from what a sinusoid is and the power factor is very poor and these are things that we really do not want and that was the reason.

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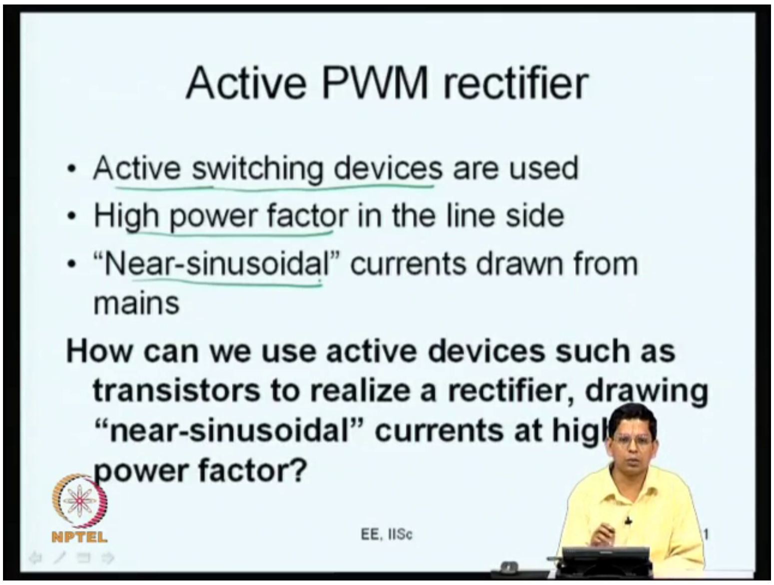

Why we thought we would go in for an Active PWM rectifier and this Active PWM rectifier as we know that involves Active switching devices and it tries to draw power from the mains at high power factor and it tries to drawn near sinusoidal current, sinusoid with very little amount of ripple on top of it such kind of a current from the mains now.

Now, we have looked at the question as how can we realize such an Active PWM rectifier using transistors and you know to function as such a rectifier, I mean which draws near sinusoidal currents from the mains at high power factor.

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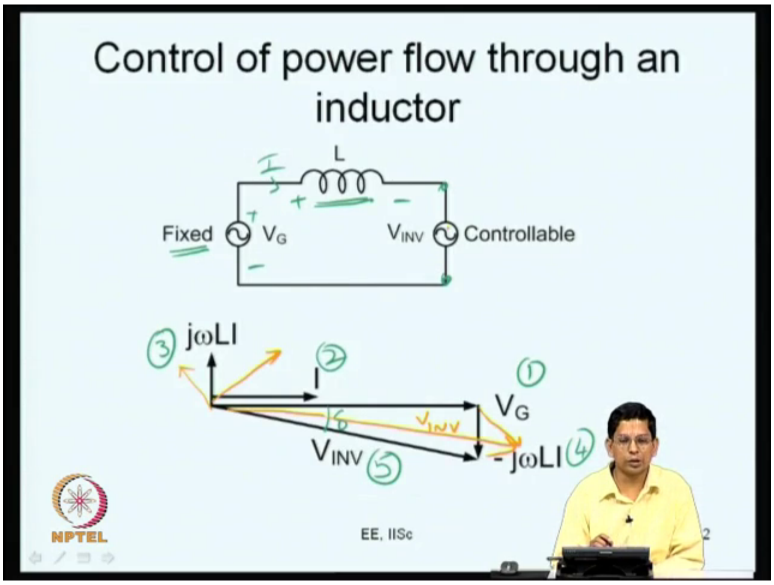

So, we first looked at the question of power factor. So, if you want to control this power factor what do we do you have a fixed mains on this side and let say you have a series inductance you connect a series inductance. Now why an inductor is not a bad idea in any way there because you want to smoothen the current drawn from the mains and the inductor has this property of smoothening the current and therefore, you connect let us same inductor in series of the mains.

Now what do you do you apply certain voltage here, what is you know some controllable voltage you apply here this voltage will control the power flow through the inductor or it will control both the amplitude and the power factor of the current that you are talking about of the current that you draw from the mains now. So, let us say you want unity power factor that is what we are being you mean we want. So, this is the grid voltage let say we want to draw a current I if which is in phase with the grid voltage. So, it is like this. So, this is 1 this is 2.

Now, because of the inductance there is going to be a drop across it, because the current flowing through the inductor there is going to be the reactive drop of the inductor and that is this item 3 that you have. So, this is the drop across the inductor and this drop needs to be subtracted from the mains voltage this needs to be subtracted from the mains voltage and that is the fourth item here. So, when you have done all this you get what you need this is V inverter. So, this is the controllable voltage you need to apply if you apply an voltage of. So, much amplitude and at such a phase angle let me call this is delta behind V G and of the same frequency as V G then you can control I as decide the amplitude and phase of I can be controlled now.

Well you can say that if I wants to be higher then, you we found that you know j omega li will be longer and your V inverter will be different, I can be of any other power factor to for example, let me just illustrate a situation that I has some such slightly leading power factor. We want to dry at some slightly leading power factor in such a scenario, what simply happen is this J omega Li is ahead and minus j omega LI is something like this and your V inverter is going to be a line like this is going to be a V inverter.

So, all that you need to do is you need to apply the appropriate value of V inverter, to draw a current of desired amplitude and phase angle of course, the amplitude has to be within limits. So, you can certainly do this now by applying such a voltage source. So, the question is how I can realize such a controllable voltage source or controlled voltage sources, the question. Now the answer is obvious we have a voltage source convertor precisely to do that.

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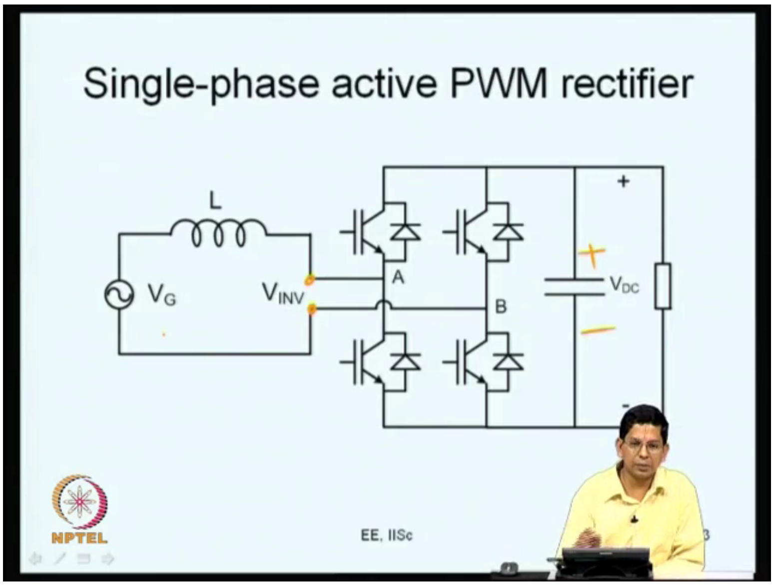

So, you have a voltage source convertor and it has a DC bus voltage, let us presume that the DC bus voltages fixed and that is why I said closed loop control is required here. What you essentially have you have an outer voltage control loop and an inner current control loop as you are aware that the outer loops are always slower. And the inner loops are faster the outer voltage loop is you know it takes it makes the voltage DC bus voltage steady and the inner current loop is much faster. So, you can presume that the voltage is steady and what the inner loop does is controls the current and what it basically does is it specifies the amount of V inverter that require really requires to be applied now.

So, let us if you say that you know DC is fixed then you can modulate the inverter appropriately, that is you can switch the devices appropriately. So, that you get the V inverter that is decide you can get any value of voltage as we saw the other day I mean just even a while back, but the average pole voltage can be anywhere up to V DC by 2 and Vab is basically Vao minus Vbo. So, the potential here you know the average voltage here I mean it can be anywhere up to V DC. So, you can get some sinusoidal voltage of amplitude up to V DC in this scenario here.

So, you can basically control the voltage source and that is what you are you applying to do that is how you realize a single phase Active rectifier. Now I also mentioned that this is a boost converter yesterday right and the DC bus voltage has to be much higher than, I mean it has to be substantially higher than the peak line to line voltage.

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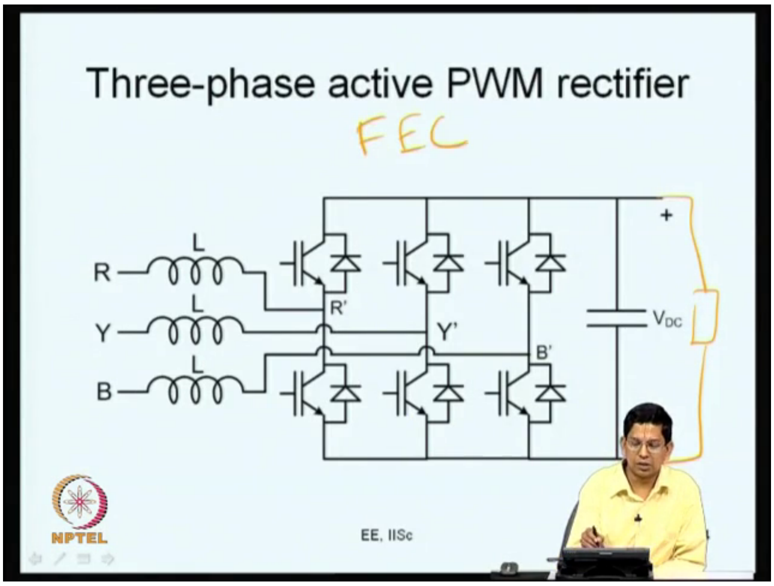

So, if you say that this is the three-phase counterpart of that, if you say I want the three-phase AC to DC rectifier all that you need to do is this.

Where you have a single inductor here you have 3 inductors here and connected to the mains RYB and you can actually have a load connected here, if you wish you can have a load I mean this is in the rectification, I mean the load is connected on that side or the load can also be another it can be an inverter for example So, that is the case when you would typically tend to call this as a front end converter because you may have an inverter feeding a motor as the load and in this case this is the line side converter or the front end converter right. Hence the terminology front end converter that is sometimes used for this if is we abbreviated as FEC now.

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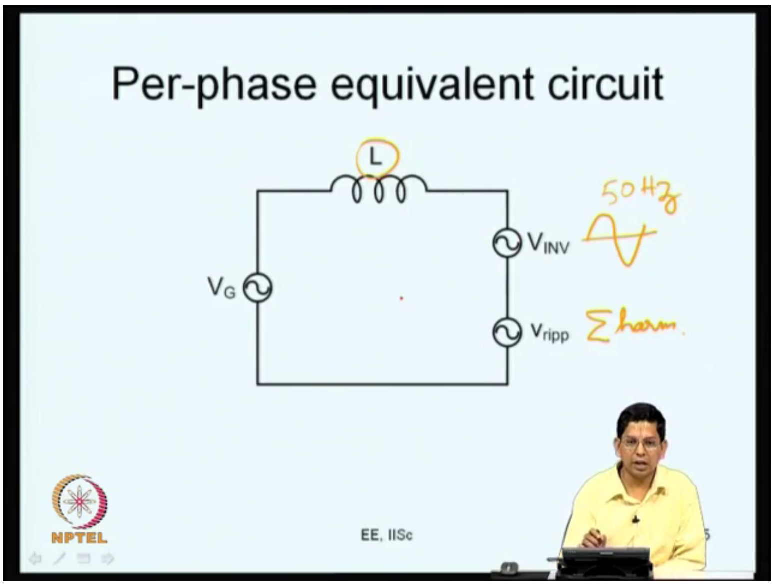

So, let say what is the purpose equipment whether, it is single phase or three-phase you know three-phase can be seen by this per phase equivalent circuit, what they essentially have is you have the grid voltage V G. Let us assume it to be sinusoidal at it is appropriate frequency let us say 50 hertz and you have this per phase inductance L.

Now what you are applying is V inverter, now this actually what we have in this earlier case we ignored. Basically when we said this we considered only the fundamental component. Whereas, your inverter voltage has both the fundamental component this is the sinusoidal component this could be the 50 hertz component and this could be the ripple is the sum of all the harmonics.

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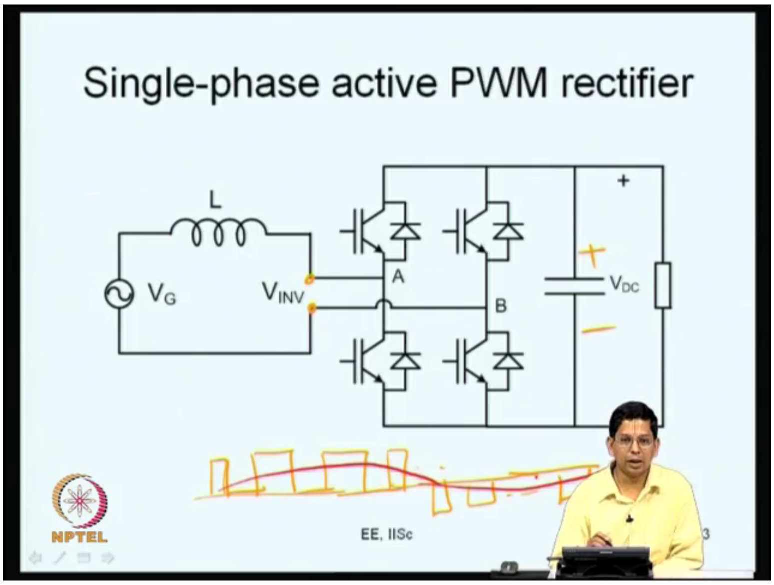

So, the waveform that you really have there or here for example, this waveform is either plus V DC by 2 or minus V DC by 2, if you if you should look at this waveform here for example, in a in a single phase case you will have typical waveforms like this, you will have something like this, is what you will have in the positive of cycle and in the negative of cycle you will have wave forms like this, you will have the pulses being applied here. This is not sinusoid it over it has a sinusoidal component like this, but this waveform is not a sinusoid. So, what we are trying to do is we are trying to split this waveform into it is fundamental and a ripple.

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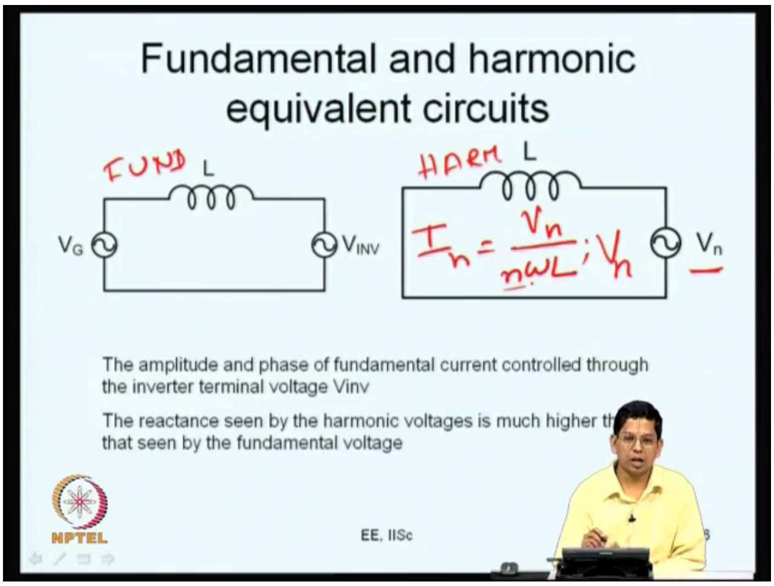

So, the same thing that you can see here also the; per phase voltages are really like that, so this is the fundamental component. So, this is the remaining part which we call as ripple right. So, this is the equivalent circuit now. So, this equivalent circuit if based on this equivalent circuit you might want to calculate the fundamental current or you might want to calculate the harmonic currents or the ripple current. If you want to calculate the fundamental current this is the equivalent circuit, this is the fundamental equivalent circuit. This is valid for fundamental because this V G is at the fundamental frequency and this V inverter is at the fundamental frequency.

The ripple voltage contains harmonics and these are all at various frequencies other than the fundamental frequency and therefore, you know it is essentially a short as far as fundamental is concerned and therefore this is the fundamental equivalent circuit and if you are looking at the harmonic equivalent circuit both, these are not there that is V G as well as V inverter these are 50 hertz components. So, in the harmonic equivalent circuit they do not appear. So, what all that you have is a specific harmonic component. Let us say Vn which is the nth order harmonic by nth order, we mean it is frequencies n times the fundamental frequency and that is flowing through this inductor current L.

So, the nth harmonic voltage is going to cause nth order harmonic current and this current is limited only by the inductance L, now what is the reactance offered as we mentioned the other day in will be Vn times Vn upon n omega 1. So, n omega L is the where omega is the fundamental angular frequency n is the harmonic order n omega L is the reactance seen by the harmonic voltage Vn right. So, the higher order harmonics have a greater value of n or the harmonics in general have a greater value of n is equal to 1 for the fundamental component. So, the harmonic voltages in generally in general see a higher value of reactance and therefore harmonic currents are quite low and you know if when you ensure that your harmonics are at very high frequencies say of the order of kilo hertz, if you switch the inverter at frequencies of kilohertz your harmonics are going to be of the order of kilohertz.

So, you know the ratio of the harmonic, I mean the harmonic order is likely to be basically several tens or sometimes even hundred, so the harmonic currents are very small; why because the reactants seen by the harmonic voltages are very high and that is how you achieve near sinusoidal currents this is what we looked at.

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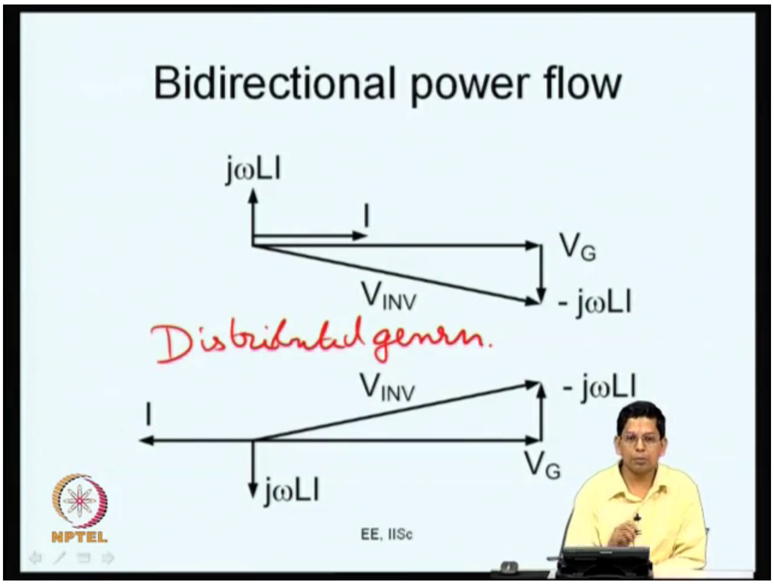

So, you can draw at unity power factor and you can also draw near sinusoidal currents, if you want the power to flow in the opposite direction it is possible. Now this is what you do in a distributed generation, let say power is available from a photovoltaic cell and so you want to pump that power into the mains this is something that you do typically.

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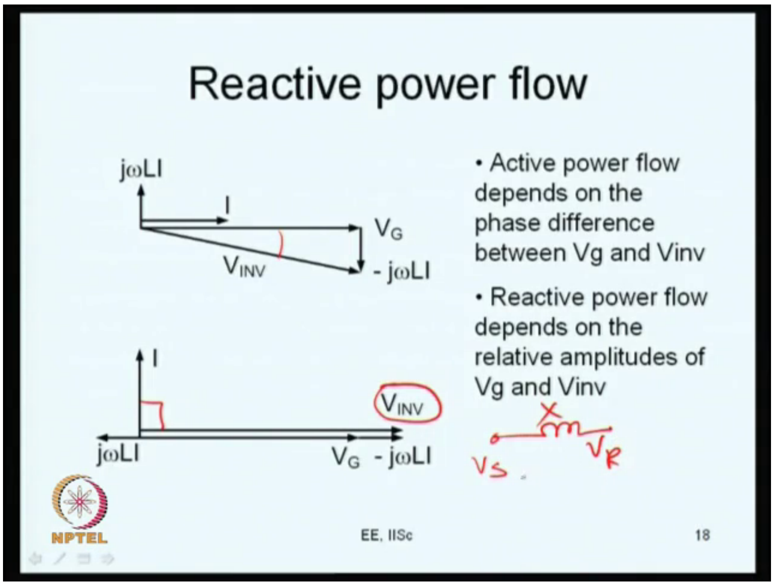

So, then you can also control the reactive power flow excuse me. So, the reactive power flow you can you want to inject reactive power flow many times, you may have other loads which are drawing reactive power and you want the supply reactive power through a voltage switch converter. So, what you do. So, you have supply you know you control the current such that the current leads the voltage by 90 degrees. So, if you do that this is the V inverter voltage, the inverter terminal voltage that is required if you apply a inverter terminal voltage as indicated here, you will be able to control the amplitude of the current and the make sure that the phase of the current is ninety degrees ahead of the grid voltage.

So, from these 2 observations you can see that you know one is for Active power flow because, there is some phase difference between V G and V inverter and now it flows from whichever one is leading, to the whichever one which is lagging, that is here in this case from grid to the inverter now alright. So, here previously it was the other way also in one case it is from the grid to the inverter here it is from the inverter to the grid. So, in the next case where this reactive power flow, the reactive power flow flows from something that has a higher amplitude to the other one which has a lower amplitude. So, it is very the idea is very similar to the transmission line problem we looked at right, there is some sending end voltage and there are some receiving end voltages and this is the reactance X. So, we know how power here is controlled through the sending end voltage and receiving end voltage.

So, the power flow is proportional to VS VR and sin of delta, which is the angle between the 2 voltages divided by x and that is how you basically essentially control this power here. So, the situation here is very similar to that and whatever you have studied in transmission it can be extended this, I mean the power flow through transmission lines can easily be extended here now.

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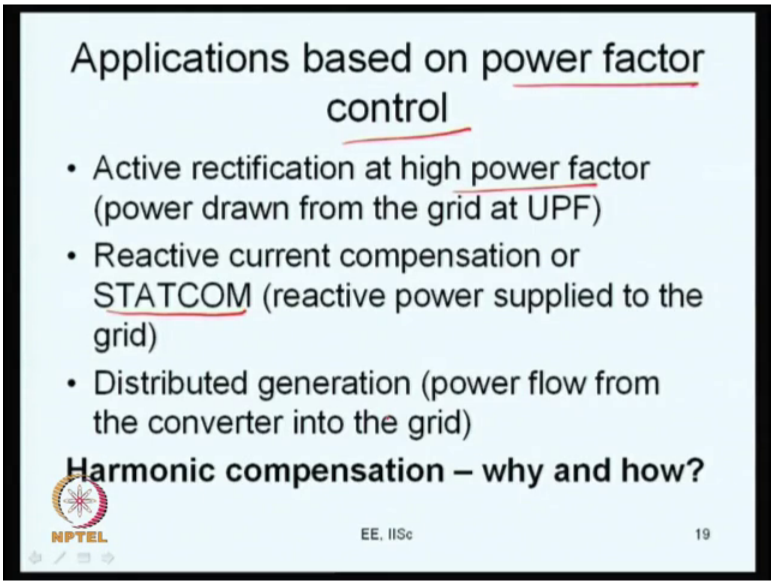

So, these are the various applications based on power factor control, the first application kind of we saw is motor drive and the second application we can what we can say is can something quite related to that is also is ups and the major set of application is these applications based on power factor control.

So, you are able to have Active rectifier, you are able to rectify convert AC into DC drawing sinusoidal currents from the mains at high power factor and you are able to inject reactive power into the main source, what is called a static compensator or STATCOM using a voltage source converter. So, you are able to supply reactive power to the mains and there is also this distributed generation. Now if we have something like a photovoltaic cell you can pump that power back to the mains, I mean you can pump it into the mains through power converter. And we have to look at now this question of harmonic compensation why and how any load, you know what we had a quick look at what was the non-linear load and what is the linear load.

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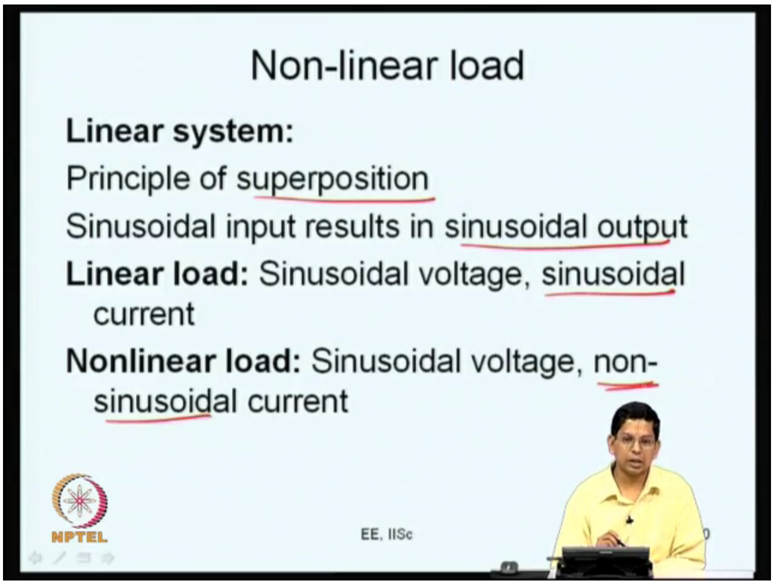

So, linear system to you knows the restate, what we did was you know if they obey superposition that is in the time domain.

So, if you apply any signal U of T, it provides an output Y of T if U have T skilled Y of T will also be skilled and similarly that is about in if for an input U 1 plus U 2 the corresponding output will be Y 1 and Y 2 if you U 1 results in an output Y 1, U 2 results in an output Y 2, U 1 plus U 2 results in an output Y 1 plus I 2 those are the properties of linear systems. If you view that in these frequency domain using sinusoidal excitations, for a sinusoidal excitation a linear system will result in a sinusoidal will produce a sinusoidal output of the same frequency, so that is the characteristic of that. So, line if you do the linear load you apply sinusoidal voltage on to that it draws sinusoidal current, if it is a non-linear load it will apply non sinusoidal current here.

If you just simply take a filament lamp for example it is a linear load why you apply a linear voltage it draws, I mean sinusoidal voltage it draws sinusoid current from that the same is not true about diode bridge rectifier, the same is not true about let us say a computer.

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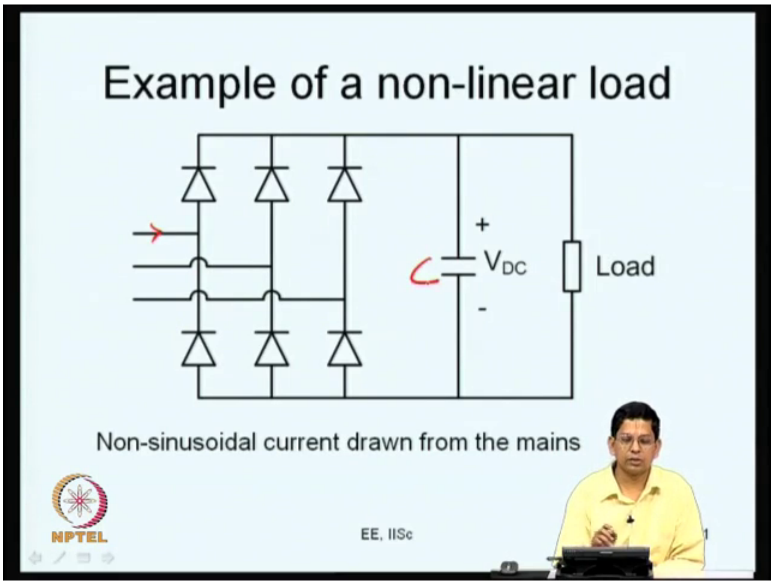

So, this is what we saw as an example of a non-linear load, which we discussed you know ahead ah rectifier the current that it draws here is not sinusoidal current. So, simply a diode bridge rectifier with capacitor filter is a very good example of non-linear load, non sinusoidal currents are drawn from the mains, so what if non sinusoidal currents are being drawn here.

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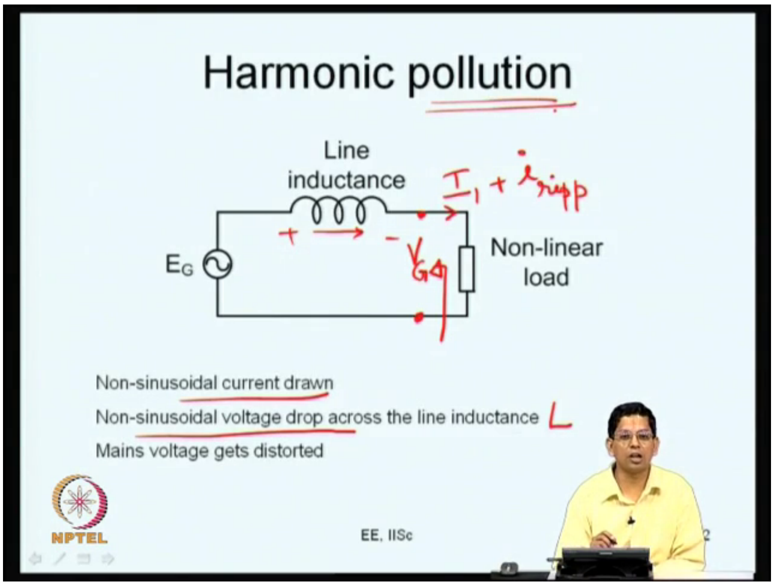

So, now, let us say this is the voltage mains that we see you can look at this, mains voltage you know the model that you can use is an ideal voltage source in series with certain amount of line inductance now, what you do is when you use a non-linear load the non-linear load draws not only some fundamental current, but it also draws certain ripple current. I am indicating the fundamental current by I1 and I am indicating the ripple current by i ripple. So, what happens is this i ripple flows through this. So, that is it consists of several harmonics. So, when harmonic currents flow through the inductor the voltage across the induct that will be corresponding harmonic voltage across the inductor now. So, across this inductor you have some ripple voltage, the harmonic voltages across this. So, it is not just a sinusoidal voltage it is there are some harmonic also there.

So, if you look at the mains voltage between these 2 terminals this voltage is no longer sinusoidal. So, there is nonsinusoidal current drawn results in non sinusoidal voltage drop across the inductance line, this is the line inductance and because of this the mains voltage gets restarted it is because we have connected a non-linear load, other loads connected in parallel we will also see and it started wave form. So, that is why we use a term harmonic pollution what we basically mean is the distortion of the mains voltage due to connection of non-linear loads, if you connect non-linear loads the main they tend to draw non non-linear sinusoidal currents, these non sinusoidal currents have drop across the line inductor which is non sinusoidal in nature now.

Therefore, the mains voltage itself becomes non sinusoidal, so this distortion of the mains voltage due to non-linear loads just what we call as harmonic pollution now.

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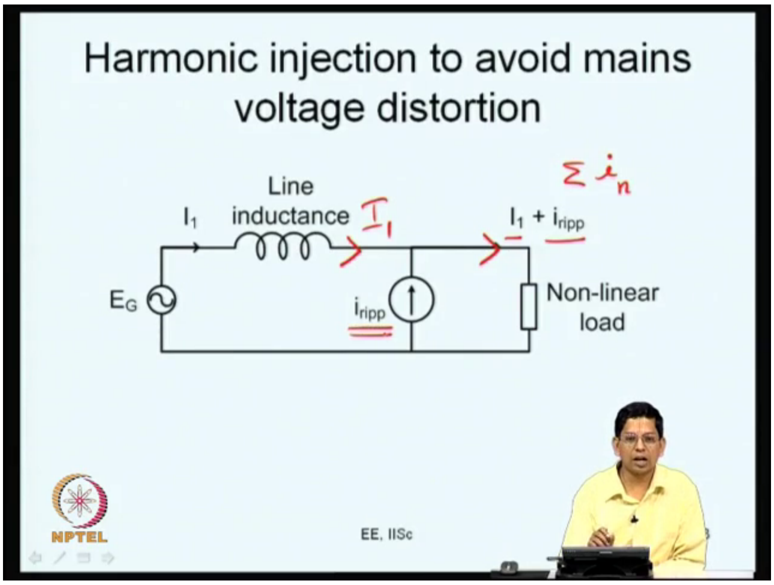

So, let us say we want to avoid this harmonic pollution, how do we avoid this harmonic pollution as we indicated here. We there is a current flowing here it consists of a fundamental component, it also draws a ripple component. Now this is because you know the ripple is the sum of all harmonics this is a ripple is sum all several harmonics.

Now, why is the current so because that is the nature of a non-linear load so it draws? So, if the non-linear load has to function it means to draw such kind of current now, but your problem is from the mains you do not want to supply a non-linear current, you do not want only the fundamental current to flow from the mains, as long as fundamental current flows from the mains there is no problem, only when harmonic currents flow from the mains there is some issue.

So, what do you do you try to see whether you can have any other current source which can supply this i ripple, if you can have current source like this now you can certainly handle this problem, you can make sure that the entire ripple current or all the harmonic currents flow from this and only the fundamental current flows from this. It possible well it may not before all the harmonics at least many of the significant harmonics and a lower order harmonics you can realize this. The question is how do you realize such a current source? The answer is well we can use a voltage source converter to behave as such a current source now.

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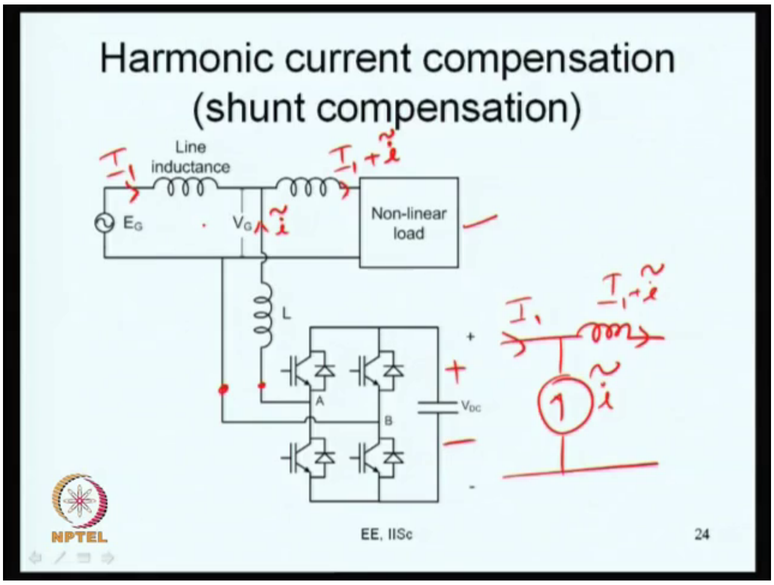

So, what you do is you have same situation, where you just want to draw this fundamental current from the mains and you have a non-linear load which has the fundamental plus some ripple, I am calling it as some I tilde let us say here or it I can also call it as I ripple as I did indicated before. So, now, what I want to do is I want to supply this entire I tilde from here, what I am trying to do is I have a voltage source converter, I presume that the DC bus is charged to an appropriate value of voltage right. This once again assumes closed loop control in the outer loop, you are controlling the voltage and the inner loop you are controlling the current all right ok.

So, you it is possible for you to apply certain voltage at the terminals, such that the effective current is what you want. The effective current is what if this requires a closed loop operation, again the entire control is not part of this course is we are only having an overview of the application, we are trying to see the basic principle of operation as to how you know of what type of filters, how a voltage source converter can be used for harmonic current compensation. The details of such control methods are available on available in other NPTEL courses do not want the harmonic currents to flow from the mains. So, you have provided like an alternative source that alternative sources this voltage source converter.

So, now this voltage source converter is AC ting like a current source which injects this, ripple into the I mean the ripple current that is needed by the non-linear load and the rest of the current the fundamental current comes from the mains and this is your I tilde and so I1 plus I tilde flows through that, you may not be able to compensate for the entire amount of harmonics, but as I mentioned a little earlier most of the significant harmonics can be probably cleaned upon, you can produce a substantial improvement doing this now.

So, what is the benefit of doing this now, as I said you are drawing only the mains current from the I mean the only sinusoidal current from the mains and therefore, you are not going to result in some same kind of a harmonic pollution which we talked about earlier. So, the line inductance will only see a drop due to fundamental current and therefore, this mains voltage V G here is going to be sinusoidal, it will not be non sinusoidal as seen by the other loads now. So, this way you are able to prevent harmonic pollution. So, this is shunt compensation you are injecting something in shunt. So, I have now shown only a single phase case here, it is also possible to do it for a three-phase case.

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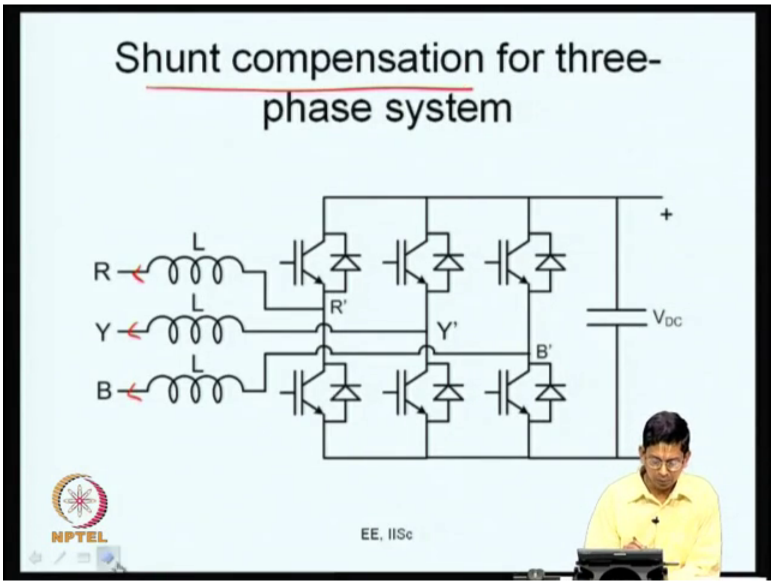

So, what you are going to have here is basically a three-phase converter with the DC bus and currents being injected here. So, this will be ripple currents, but they will be three-phase currents maybe fifth and seventh harmonics, may be fifth seventh eleventh thirteenth harmonics and whatever.

Now let us say you want to compensate up to thirteenth harmonic 5 7 11 and 13, in India the supply frequency is 50 hertz in the thirteenth harmonic 650 hertz, now you want to compensate up to 650 hertz, you need the converter to switch at a frequency much higher than 650 hertz. So, we can roughly say probably 10 times that of the highest frequency that we are interested in. So, 650 times 10 the 66500 or 60.5 kilo hertz is what you want. So, you need switching you know you need the converted the switch at a frequency in the you know near about of 60.5 kilo hertz, to be able to effectively clean up to 650 harmonic kind of things now.

So, the currents injected here for example, could be fifth seventh eleventh and thirteenth harmonics. So, these harmonic currents will no longer flow from the mains to the non-linear load, instead this will flow from this power electronic converter which is called as a shunt Active filter to the non-linear load now. So, you can have it either for a single phase or it can look at the same thing for in the three-phase situation now. So, this is shunt compensation now.

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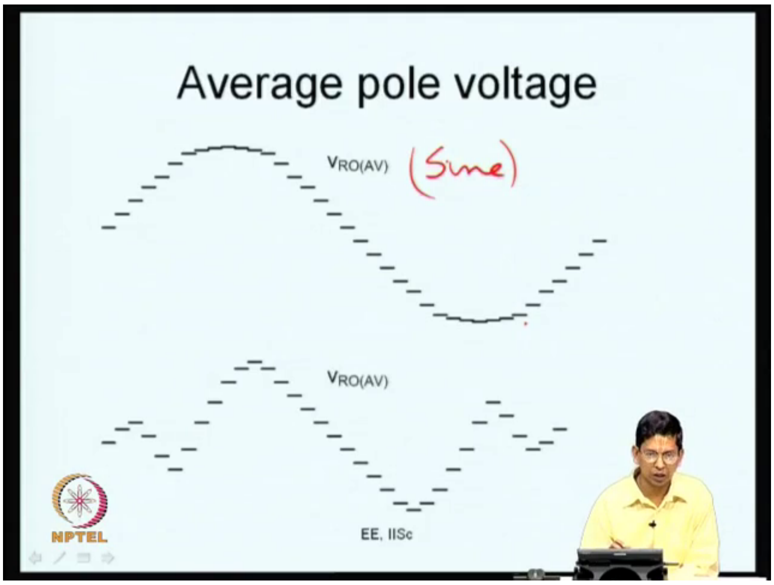

So, you can also look at series compensation like what we are saying, before that let us take a quick look at the kind of average pole voltages, that we will have see this was the average pole voltage you can see that this is a sine wave, you can see that this is a sine wave. This would be the nature of average pole voltage when you know in a drive application because a motor drive you know requires sinusoidal voltages to be applied and you can expect such sinusoidal waveforms, you know in the other applications such as Active PWM rectifier or such as STSTCOM because what is essentially getting injected into the mains or so are drawn from the mains or sinusoidal currents now.

In an Active filter what we are trying to inject is harmonic currents, some set of harmonic currents that you are trying to inject. So, the modulating signal are the way the average pole voltage waveform varies will not be sinusoidal now, it will be a combination of several harmonics, just some indication of how possibly it could be is given here right. So, just to you know make it clear that it need not sinusoidal here and it is sum of several harmonics here.

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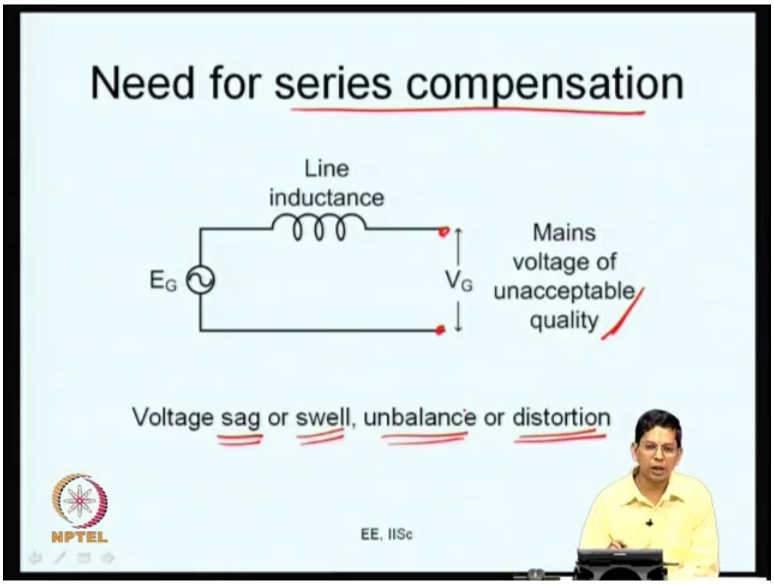

So, we go on to the series compensation now, so what do you mean by series compensation or before that why do you need series compensation, now let us say you have your mains and mains can be modeled as you said before by means of an voltage source and a series line inductance now and let we have this terminal voltage V G this is what is available, if you have a load this is where you want to connect the load now.

Now let us say this mains voltage is not of acceptable quality, the quality is unacceptable what do we mean by unacceptable quality? maybe there could be a voltage sag that is you may have a sinusoidal voltage there, but it may not be the voltage that is expected if you expect 230 volts, it could be just 190 volts or 200 volts or something like that you know the sag could stay on for a short way or a longer way or whatever. So, this is voltage sag now instead of being 200 and thirty volts it could be 200 and 70 volts and 200 and eighty volts either. So, this is again unacceptable this is not acceptable. So, you do not want it to be too lower than what is expected value, again you do not wanted to be much higher than what is the expected value now these are unexpected conditions now.

Another thing that can happen to you is the mains voltage can be distorted, why it is distorted maybe there are several non-linear loads connected in parallel you may not have a connected others might have connected. So, there are other loads already connected the like we said and they are maybe drawing harmonic currents from the mains and that has been resulting in harmonic pollution.

And therefore your V G could be distorted and the other thing is it is usually you know it is a three-phase supply and the three-phase supplies could be unbalanced, that is because of you know some differences in their lines are mostly due to loading, the load need not be balanced and therefore, you know that the three-phase voltages are available need not be balanced now. So, you can also now you will also the situation of the voltage being unbalanced.

So, these are all certain issues that make the voltage quality unacceptable now. So, you want to have an acceptable quality waveform here. So, what do you do? What you can simply do is this is your V G this is your mains voltage that is available and that is an art of acceptable quality.

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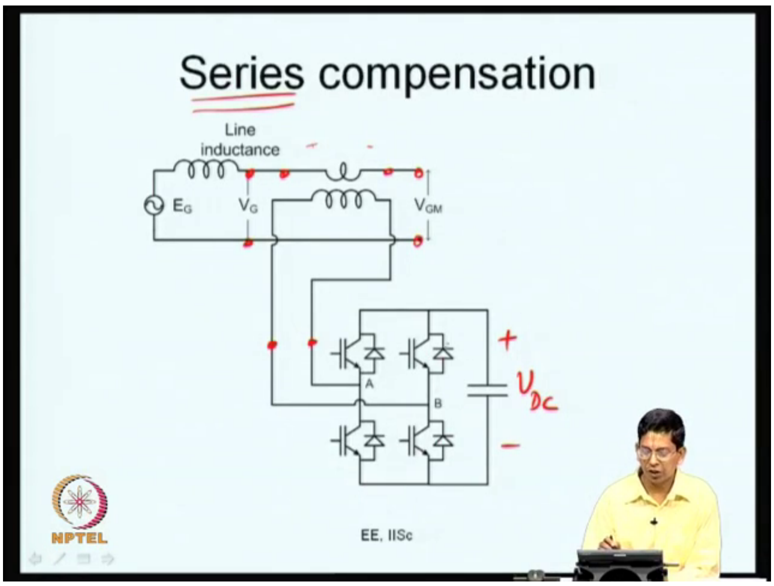

You try injecting in series with it some other waveform, which will bring your mains voltage to some acceptable quantity. Now let us say you are suffering from voltage sag the problem is a voltage sag. So, what do you do you try to inject certain voltage which is in phase with that. So, the 2 get added up and therefore, the voltage that you see at VGM is close to what you expect something like 230 volts.

Now let me say you have a voltage swell on the other hand. So, what do you do in series with it you inject a voltage which is kind of out of phase and therefore, you know your VGM will be less than V G the amplitude at VGM you know will be less than V G and you can get you know what you wanted and 230 volts or so voltage sag or voltage swell can really be handle like that, then what do you want to do with distortion let us say you have some sinusoid plus harmonics here what we try doing is you inject those harmonics and phase of possession you inject those harmonics here in phase of possession. So, you may not have that kind of distortion at this VGM what is indicated as VGM. So, VGM is of acceptable quality.

So, how do you do all this that is all done by applying certain voltage here? So, who produces that voltage it is a voltage source converter once again you have a voltage source converter which is charged to certain voltage VDC. So, we presume that you know it is charged and by switching, the converter appropriately the various switches modulating the switches appropriately, you can produce the required voltage and therefore, you can go in for what is called as a series compensation. Of course, as in previous case this requires that this VDC maintained. So, what you are once again have is you will have an outer loop, where you know VDC is being maintained and this is what is called as series compensation.

Now you can look at the series compensation also for three-phase kind of situations. So, you in three-phases, as I mentioned there could be voltage unbalance also. So, you can use a three-phase converter this is only a single phase converter having 2 legs, the three-phase converter will have 3 legs now and then output you have may have a three-phase transformer and you can inject a three-phase voltage in series with the available mains voltage.

So, the voltage that is being injected in series will add up to the mains voltage and the res to make the resultant voltage so in a way form of acceptable quality. So, you know the voltage amplitude will be when there, may if there is any unbalanced those unbalance would be set right and if there are any distortions and the distortion could also be reasonably set right. So, you can produce ah three-phase voltage waveforms of acceptable quality by following a similar approach now.

So, you can also have combinations of shunt and series and there are many things like that, as I mentioned a little earlier Active power filtering is a subject in itself and you can certainly find information about this in certain other courses related to power electronics on NPTEL right . So, now let us just complete and you know take a quick or look at whatever we have been doing or all these days now, the this I mean this is probably the third lecture when we are being covering the applications of voltage was converters.

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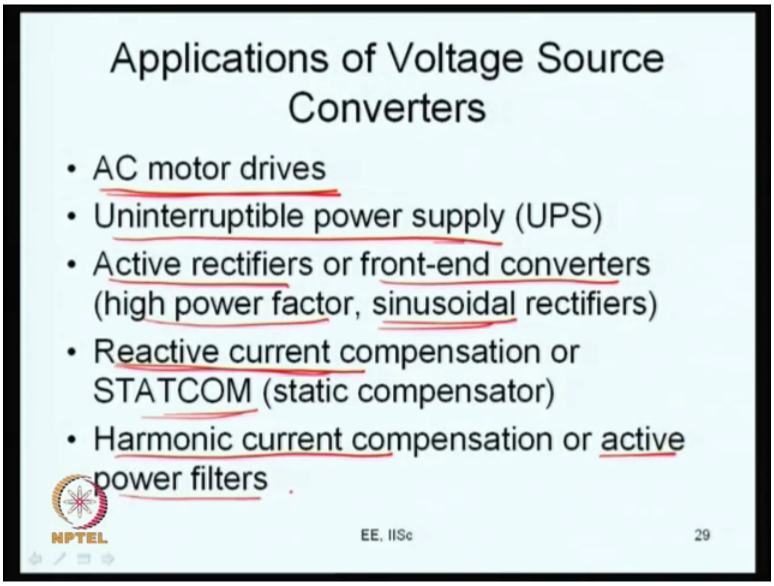

So, 1 of these points that we want to make is about AC motor drive, these we kind of we know we looked at it as a simplest 1 of the simplest problems in the earliest possible application. So, in an AC motor drive you have a voltage source inverter and the DC side power supply is taken as fairly fixed and on the AC side you want a variable amplitude and variable frequency AC. So, you are able to generate that variable amplitude and variable frequency AC and you are able to control the speed of operation of a motor now.

So, in case of an uninterruptible power supply also you have a voltage source inverter which is feeding some AC load well that AC load could be of you know any power factor or whatever that you might think of. So, it may have a range of power factor. So, in this situation in the case of an uninterruptible power supply, what you need is the DC voltage will be inverted in to 50 hertz or 60 hertz whatever the standard may be in that country. So, it will be a 50 hertz output voltage is all that you will produce there. So, the output frequency will not change, where is an AC motor drive the output frequency will vary over considerable range, maybe it can vary over from 1 hertz to 50 hertz or 2 hertz to 50 hertz or up to 60 hertz or whatever it can vary now.

So, here on the other hand in uninterruptible power supply the output frequency does not change, now also the output amplitude might not change the output amplitude has to be whatever the desired value. So, it is range of operation in terms of modulation index and frequency it is pretty much limited in the case of an inverter which is part of an uninterruptible power supply, now you also use voltage source converters in Active rectifiers or front end converters.

We just saw this because when you want rectification that is when AC is available and what you expect is DC, you need rectification as we saw a little earlier rectification. If you can just use diode bridge rectifiers to do this, but a diode bridge rectifier cannot give you whatever voltage that you desire, it can give you only a fixed voltage and this fixed voltage is I mean it is related to the peak line voltage in the mains and there will be also some amount of regulation, this voltage we may not be really fixed that where you cannot really control that voltage.

So, if you want to control the voltage you go into other kinds of rectifiers, which are not you know you going for Thyristor rectifiers that was the next stage with a Thyristors rectifier. You can control the DC output voltage, but still a Thyristors rectifier also draws non sinusoidal currents. So, you draw non sinusoidal currents and the waveforms are distorted and the power factor is very poor. These are the problem that you have that was the reason why we went for Active rectifiers or front end converters.

So, if you quickly look at what we are able to do is PWM converter a fixed DC bus voltage, is able to produce an output voltage of desired amplitude and desired phase. So, the amplitude and phase are such that you know there is a line inductor and it is able to control the power that flows through the line inductor. So, in Active rectifiers what do you have you essentially have a PWM converter with in line inductors in series now.

So, 1 side of the line inductor you have the mains voltage, the other side of the line inductor you have the PWM converter. So, this PWM converter applies a voltage of appropriate phase and amplitude such that the current that flows through the you know lines, that is through the inductor is of desired amplitude and desired phase or power is drawn at any desired power factor. So, you are able to control the power factor and you are able to draw near sinusoidal current through this, as we saw the fundamental current is being controlled and the harmonic voltages are there, but they get fairly filtered out by the line inductors and so the ripple current the harmonic currents are much lower in amplitude. Than the harmonic voltages as we saw some time back and the currents are near sinusoidal, apart from you know the fact that the power is being drawn at a high power factor now.

So, in Active rectifier what we saw was the power factor is being controlled to close to unity, rather you can make sure that the you know power factor is not unity, but it is 90 degrees the current is leading the voltage by 90degrees. If you do this you go into what is called as reactive current injection, now it is what you would call as reactive current injection. So, in this case of you know you may have other loads which are drawing a reactive power. So, what you try to do now is you supply reactive power through a voltage source convertor. So, you we know this are sometimes it is also called static compensator, I mean now we are we have particularly talking of reactive current compensation.

So, you may have other loads which draw a lot of reactive power. So, you have such a compensator available then you have much less, I mean this is supplying the necessary amount of reactive power. So, your overall power factor will be much better now and the most recent thing that we saw just a while back was harmonic current compensation or what is called as Active power filtering, this is Active filtering of power. So, you know you may have harmonics being drawn there what you are trying to do is if harmonic currents are required by certain load, you supply those harmonic currents and similarly if harmonic voltages are required let say the mains voltage available already is distorted.

So, what are trying doing is you inject in series with it certain harmonic voltages, which are out of phase with the harmonic voltages that are part of the mains voltage. So, the resultant will produce a waveform which is reasonably independent of all these kinds of distortion. So, these are the various applications that we saw and once again I would emphasize that is just an overview of these various applications, we have only seen the basic operating principles and you should look for the details in certain other courses that may be available for you.

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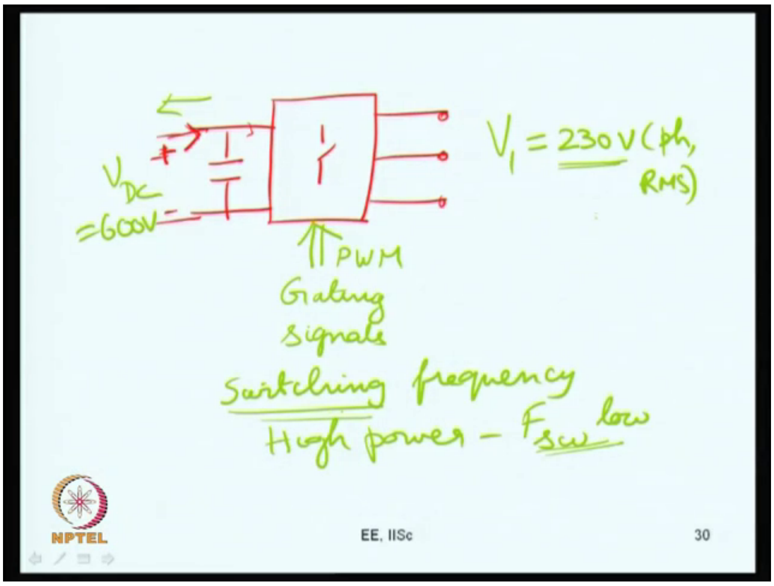

Now let us just sum up a few things so what is it that we saw in all these various situations what we had was a box, I mean a power converter and this power converter has DC on 1 side. So, it is fed from some DC power supply or whatever it may be or maybe the load is on this side or the source on that say we will come to that a little later and it has AC on the other. So, let us say it is a three-phase AC what does this come this box compress off it has several switches.

So, this is a power converter, now this produces three-phase AC on the other and what I would like to stresses this is really a bi directional power converter. So, power can flow in either directions, first if I say that the power is flowing in this direction let us say the current is flowing in this direction you know like here so; that means, power is flowing from the DC side to the AC side if this is reverted let me just change.

Now let us say in this the DC current is flowing in the other direction, what do you mean power is flowing from the AC side to the DC side. In the first case what is shown with the red ink power is flowing from DC to AC side, there if you look at the fundamental voltages and you look at the fundamental currents, they will be more or less in phase or the phase angle will be within 90 degrees. If you look at the second case that is the green ink 1 you have you know on the AC side three-phase voltages, the three-phase voltages have their fundamental and components the three-phase currents have their fundamental components. If you look at the fundamental voltage and fundamental current on the AC side they may have a power factor, I mean they may have a phase difference close to 180 degrees between something like 90 degree to 270 degree. So, let us say around 180degrees. So, if that is a situation where power is really flowing from 1 side to the other side now.

So, this converter could really be anything, it can be a 2 level converter or it can also be a 3-level converter so or it can be any other thing replace now. So, these are certain things which are applicable for any kind of converter which is DC on 1 side and the AC on the other side now. What will our focus be in subsequent lectures you can produce you know see you now all these applications require you to produce certain DC voltage, certain AC voltage given a particular kind of DC voltage, how do you do that by doing this pulsewidth modulation. You have a set of switches it may be a 2 level converter, it may be 3-level converter or whatever, but all that you have a set of switches. So, these switches have to be turned on and turned off in a particular fashion at particular instance and that we will have to result in the desired amount of fundamental voltage.

So, our issue focus is going to be on this PWM. So, what does it do it provides all the necessary gating signals for the devices. So, our job is to see how should you produce these gating signals or what kind of gating signals that you produce for a given amount of DC bus voltage and let us say given amount of fundamental voltage on doing this now. So, there are very standard methods of doing this and there are also certain modern methods are relatively less known methods available now. Our idea here will be to explore the various possibilities. So, let us say you have a DC bus voltage let us say this DC bus voltage is c equal to some 600 volts let me say this is 600 volts.

Let me say you need a fundamental voltage and that fundamental voltage is equal to should I say 230 volts phase RMS this is what you want now. So, this voltage 230 volts can be synthesized and out of this through very many methods. So, one of the constraints here is about the switching frequency, how fast you can switch an inverter now. So, the switching frequency has some relationship with the power level at which you are operating. So, far we have been dealing with only ideal switches, but the remember switches have non idealities, ideal switches have no dissipation whereas, non ideal switches are dissipation.

What are those dissipations one is conduction loss ideal switch has no forward drop where as a real switch has certain forward drop and therefore, certain amount of conduction loss and not only that an ideal switch turns on and turns off in no time, instantaneous switching transitions whereas, real switches take a finite amount of time to turn on and turn off and during the switching transitions what happens both the voltage and current are significant.

So, there are certain amount of switching energy lost ideally in a switch there is no loss at all power loss at all because in the forward state the voltage is 0, I mean in the on state in the off state the current is 0. So, the product VI is always 0. So, that is how you know you have very little loss in a switch. Whereas, you know while you are while a switch is undergoing a switching transition both the voltage and current could be substantial simultaneously and this produces certain amount of switching power loss over that interval. So, certain amount of energy gets lost every time you switch converter now.

So, if you are talking of high power converter this switching energy lost is going to be much higher. So, the overall power is product of the energy that we lose in every cycle multiplied by frequency. So, when you talk of high power the switching frequency is I let me call this as Fsw where the switching frequency is going to be low whereas, at lower power levels it could be high now. So, the switching frequency is also related to the power levels at which you are operating.

So, what I am trying to say is there are very many ways of producing the same 230 volts now and taking care of the switching frequency constraint, if you are talking of high power converter the switching frequency can be low even at a low switching frequency, it is possible to produce this desired fundamental voltage in multiple ways. So, what we will be exploring in this course is you know how you can produce the desired fundamental voltage out of a given DC bus voltage in multiple ways and if there are multiple ways, how you can go about evaluating the different options that are available. So, what could be the basis for evaluating various options and how you will be doing it? So, we will be doing this starting with we will be focusing just on a 2 level converter which is something there and then if we understand the modulation for a 2 level converter it should be reasonably easy for us to extend it to 3-level converter.

So, these are certain things that we will be doing in this course now and while coming to the PWM design 1 thing that is of importance is also the application, because as I mentioned a little earlier to you if you are looking at a motor drive the range of modulation, sometimes when you are close to the full speed of the motor your modulation index is very high. You are producing a fundamental voltage close to the full voltage if the motor drive is operating at a low speed, then the modulation or the AC side voltage is very low. On the other hand if you are talking of a line side converter a grid converter the modulation range is not very different. I mean the frequency of modulation is always the line frequency there is no variation and again the modulation index of the range of the fundamental voltage that you produce in this is not too very different it is within a finite range now.

The same way you know it depends on the application now and sometimes you know you may be drawing, if it is an Active rectifier this phase I mean the mains voltage and the current are in phase if it is a STSTCOM application, the phase I mean the current and the voltage are 90 degrees have a phase difference of 90 degrees, all these affect the losses particularly the switching losses etc. I mean the losses suffered by the inverter are affected now. So, we will be dealing with certain mean how do you evaluate losses in pulsewidth modulated converters that something will do and we will also look at is it possible to design converters such that, the losses can be reduced under given operating conditions that would again be another endeavor that we will have. So, we will be doing all this now.

So, henceforth our focus will move on to pulsewidth modulation. So, if you remember your first thing that is let me so if you go to their first slide what we have been looking at is pulsewidth modulation for power electronic converters. So, we have been dealing with power electronic converters all through these days now. So, what we will move on to will be pulsewidth modulation henceforth, we had a look at varied kinds of power electronic converter such as DC to DC and you know voltage source inverter current source inverter 2 level converter, multi level converter etc and then we looked at these various applications.

Now, we will be moving on from the next lecture onwards towards this modulation, towards pulsewidth modulation that is what we will be doing now. So, thanks for your interest and we hope to continue this in the next class, we will start looking at some fundamentals of pulsewidth modulation in the next lecture.

Thank you very much.